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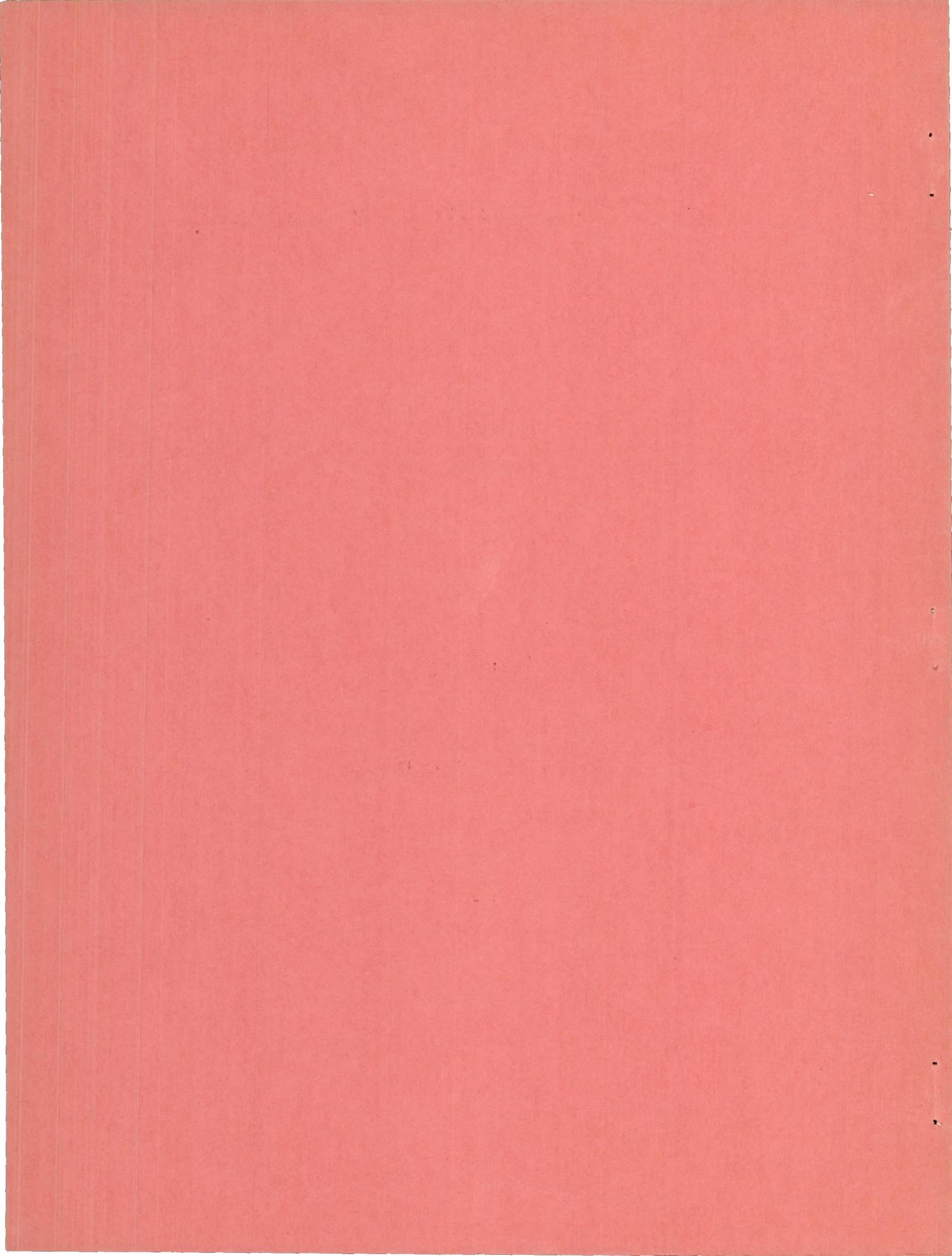
THE INFLUENCE OF NOTCHES UNDER STATIC STRESS

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THE INFLUENCE OF NOTCHES UNDER STATIC STRESS\*

By K. Matthaes

SUMMARY

The present report is a compilation of the experimental data obtained by Heinkel, the DVL, Focke-Wulf (J. Müller), and the Institute for Metallurgy of the Dresden T.H., in their studies of the influence of notches under static stress.

From the described experiments it is seen that notches are a potential source of strength decrease even under static stress, which the designer must take into consideration.

Section I is a general treatment of notch influence under the various types of stresses. It is proved that under tensile stress, steel of round or solid section always discloses an increase in strength, especially if the influence of the notch is confined to the outer zone of the piece. In the latter case, light alloys incur no loss of strength either. If the influence of the notch extends to near the center as, for example, with a transverse hole through a bar, steel evinces a very minor strength increase, but on light alloys it is already quite considerable. In the express notch sensitivity range at low temperatures, one must count with a considerable strength decrease due to notches even for steel.

Under flexural stress, notches effect an average strength decrease of 30 percent in any metal. Steel manifests a further severe drop in the notch brittleness range, that is, at low temperatures.

Notch effect and insufficient toughness of the material may become particularly serious if a section under

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\*"Die Korbwirkung bei statischer Beanspruchung." Luftfahrtforschung, vol. 15, nos. 1 and 2, January 20, 1938, pp. 28-40.

tension develops additional bending stresses due to an error as, for example, in fit or tolerance. This case is illustrated by an example on a bolted joint, where a slanting, compact surface of the nut lowered the strength of the bolt to a fifth.

Under twisting and compressive stress notches produce no strength decrease.

Section II treats the influence of notches in thin sheet as is used in airplane construction. It was found that with a hole diameter of around 12 percent of the strip width, a single centrally loaded hole already lowers the strength of light-metal strip by approximately 10 percent. The effect is less as the strip is narrower in relation to the hole. For equal ratio of hole diameter strip width the strength decrease rises with the hole diameter. For very small holes the strength decrease is disappearingly small. Steel manifests no such drop in strength.

If the stress is excentric, as with staggered rows of holes, for example, both the steels and the light-alloy metals undergo a marked strength decrease.

Simple rivet-joint tests proved the strength decrease in the range below crushing failure to be about as great as on specimens with simple holes.

Lastly, the strength of riveted joints in plate sections is investigated and compared with the strength of lap joints of equal rivet pitch and of correspondingly drilled strip. The experiments indicate that the force application in the back of the section or in the center of a plate joint is particularly unfavorable and that the transmissible strength becomes substantially greater if the force is applied near to the outer edge of the plate or in the side walls of the section.

## I. INTRODUCTION

### Effect of Notch Under Different Types of Stresses

On stressing a notched bar below its elastic limit, it is found that substantially higher stresses and strains occur in the effective range of the notch than in the un-

affected part of the bar (fig. 1). Since the maximum stress is decisive for the load capacity, we consequently find through notches in all these cases a marked decrease in strength in which failure is possible, within the elastic stress range - that is, chiefly under fatigue stresses, although it may equally occur under static stresses if the material is brittle.

Investigations into the effect of stress increases upon the static strength of iron, date back many years. Experiments by Kirkaldi in 1862, on drilled and notched test bars disclosed an increase in strength rather than a decrease. The well-known explanation for this phenomenon, found in the classic work of C. Bach, entitled "Die Maschinenelemente," 1911, is that, obstructing or partially restraining the transverse contraction of the bar reduces the elongation, and consequently, also increases the strength in materials which in the case of failure undergo a substantial transverse contraction.

Based upon this and similar experiments, the effect of notches on the static strength was then considered negligible for a long time.

But upon closer analysis of these conditions, especially on nonferrous metals, it is found that the strength-increasing effect, due to restrained transverse contraction, does not always outweigh the effect of the stress increase, but rather that it depends altogether upon the kind of notch and on the material as to whether an increase or a decrease of strength takes place.

## 1. Notch Effect Under Tensile Stress

a) Effect of depth of notch in steel.- Grooves (turned) on round steel specimens nearly always result in increased strength; it increases with the depth of the notch (figs. 2 and 3) (reference 1). It will be noted that the strength increase is almost proportional to the depth of the notch.

b) Influence of notch form and material.- Holes drilled through round steel bars also generally increase the strength. The result of a single test is illustrated in figure 4. The strength of the specimen without hole is 58.3 kg/mm<sup>2</sup>; and 61.0 kg/mm<sup>2</sup>, with hole. The remarkable fact is the simultaneously occurring complete change

in the aspect of the break, which is equally found on the round bars with the grooved notches (figs. 3 and 4). While the specimens without notches show a deep constriction and fibrous break, those with holes or deeply grooved notches manifest an almost pure granular break and very little constriction.

In order to afford a basis of comparison of the effect of notch form in different materials, table I, giving the results of various tests, has been compiled. According to these tests, the round bars with V-groove notches produced without exception a considerable strength increase. The strength of the notched bar of 0.64 carbon steel was 15 percent, of the soft ingot steel 63 percent, greater than that of the plain bar; for AZM elektron, the increase is 9 percent, for DM 31 duralumin 20 percent, and for pure aluminum (soft), even 77 percent. The square-section groove also was accompanied by an increase in strength. But it is much less in the aluminum base alloys than that for the V-notch.

On the bars with transverse hole the conditions are altogether different. Here the light alloys, with the exception of pure Al, disclose a considerable drop in strength. Even on the unusually tough, soft, pure aluminum the strength increase is a mere 3 percent. On steel the strength increase is also fairly small compared to the annular notches.

c) Effect of temperature in steel.— Steel manifests a recession in strength as a result of notches only in the stage of the very brittle break; that is, chiefly at low temperatures. Figure 5 illustrates the results of two test series by H. Flössner (reference 2) on round tensile test specimens with V and square notches. The material, SM steel, containing 64 percent C, had a tensile strength (smooth bar) of 86 kg/mm<sup>2</sup> at room temperature. It is seen that the notch tensile strength at higher temperatures is practically the same in all cases at around 105 to 108 kg/mm<sup>2</sup>. At temperatures below room temperature the bar with V notch discloses first a marked strength decrease; at -70° C. the tensile strength has dropped to 64 kg/mm<sup>2</sup> ! On the milder-acting square notch the strength did not drop until at lower temperature. At -70° C. the notch tensile strength still amounts to 93 kg/mm<sup>2</sup>. However, this drop in tensile strength at that temperature does not imply that the cleavage resistance drops with the temperature (experiments with plain bars prove just the oppo-

site) but that, through the stress increase in the notch, the actually higher cleavage resistance is prematurely exceeded. Equalization of stresses through local strains is either absent or very imperfect.

Metals with a tendency to cold brittleness - that is, all unalloyed, or lightly alloyed, steels, alloys of zinc, and alloys of magnesium - must therefore be approached with the possibility of strength decrease due to notches in mind, if the particular structural part is to be safe against failure at low temperatures.

## 2. Effect of Notch Under Bending Stress

In bending the conditions are substantially different than in tension. Here the notch under static stress, even for steel, always results in a decrease of strength. This is probably due to the fact that in the bending test the strength is not governed by the constriction as in the tensile test. For this reason, the restrained constriction itself cannot have the strength-increasing effect to that extent, and the influence of the stress increase becomes more prominent. It is the reason why, in the bending test, all brittleness effects are more prominently displayed than in the tensile test (notch impact test!).

a) Effect of notch depth.- Figure 6 illustrates the notch-depth effect on the flexural strength in 4 percent C steel, 47 percent C steel (reference 1), and an aged aluminum-base alloy with 4.28 percent Cu and 99 percent Si (reference 3). The ratio: "notch-bending strength/flexural strength of the non-notched bar" is plotted against the ratio: "notch depth/height of bar." The greatest decrease in strength occurs with a notch depth of about 10 to 20 percent of the bar height, and steel does not show up any better than the light alloys.

b) Effect of notch form and material.- The notch-form effect in DM 31 duralumin and AZM elektron was ascertained from several other tests; the results are shown in table II. Here the hole effects a smaller decrease in strength than the notch. This accordingly corresponds to the smaller stress increase at the hole.

c) Dimensions of parts subject to bending stress.- The marked decrease in flexural strength caused by notches even under static stresses, makes allowance for notch effect im-

perative when establishing the dimensions of structural parts subject to flexural stress. The proper way is to proceed on the basis of the notch-bending strength established on a flexural bar of rectangular section having a depth of notch equal to 20 percent of the bar height (fig. 6, table II).

d) Effect of temperature and rate of strain in steel.

The strong influence of the brittleness in bending stress causes in steel a further important decrease of notch-bending strength in the stage of notch brittleness; to be sure, only the stage where the energy absorption has already largely declined and the whole surface of the fracture indicates separation failure.

Figure 7 portrays the results of notch-bending and notch-impact tests with annealed tool steel of 9 percent C, the bending strength being plotted against temperature for different rates of bending (reference 1). On the slowly bent specimens the strength decreases considerably below about  $+50^{\circ}$  C. temperature, while for the impact specimens it already decreases when the temperature falls below  $+230^{\circ}$  C. But in every case the flexural strength drops by about 30 percent if this temperature is around  $100^{\circ}$  C. less. The flexural strength of the plain specimen is substantially higher with  $135 \text{ kg/mm}^2$  at room temperature, and discloses no decrease even at temperatures as low as  $-50^{\circ}$  C.

The results of similar tests made with 5-percent C steel (reference 1) are shown in figure 8. At slow rate of bending, about  $1 \text{ mm/min.}$ , the notch-bending strength gradually increases with decreasing temperature from  $+200^{\circ}$  C. to  $-50^{\circ}$  C. At high rate of bending (= rate of impact, approximately  $200,000 \text{ mm/min.}$ ) the flexural strength increases with temperature dropping from  $+230^{\circ}$  C. to  $+80^{\circ}$  C.; but from then on it decreases sharply with decreasing temperature. At  $+18^{\circ}$  C. it is already less than on the slowly bent bar. The experiments indicate that still another significance attaches to the brittleness than is usually conceded, in the evaluation of notch-impact tests only for energy absorption. In reality, bending stresses in the expressed brittleness zone are accompanied by quite a substantial strength decrease, which is especially effective at higher stress rates.

### 3. Notch Effect Under Combined Tensile and Bending Stress

Other than the simple tensile and bending stresses the case of combined stress must also be considered. Many times, for example, it happens that in the design and stress analysis a tensile stress is assumed while in reality, supplementary bending stresses due to assembly errors, irregularities of fitting surface, etc., occur which are not allowed for. In very many cases it is utterly impossible to make an exact mathematical allowance for such influences, since the magnitude of the inaccuracies depends on chance alone. With minor notch effect or sufficiently tough material, no allowance for such supplementary stresses under static stress is, as a rule, necessary, since the appearing flow (strain) voids the supplementary stresses. But this so-called "artfulness of the material" can only be relied upon when the material is tough enough.

One frequently encountered case of that kind is the bolted structure under tensile stress, when the area of contact of the bolts or nuts is uneven or not parallel to each other, or when, on a tight-fitting bolt, the area of contact of the head or the nut is not exactly perpendicular to the bolt axis. To ascertain this effect on the strength of bolted structures, a series of tests were made. Heat-treated bolts of alloy steel with a tensile strength of around 130 kg/mm<sup>2</sup> were used as described in figure 9. Following the test in a tensile-test machine, tensile-test bars and notch-impact specimens were taken from all bolts and tested. It was found that the bolts could be classed into:

- a) those with a notch toughness of 2 mkg/cm<sup>2</sup>
- b) those with a notch toughness of 4 mkg/cm<sup>2</sup>
- c) those with a notch toughness of 10 mkg/cm<sup>2</sup>

The results of the tests, given in figure 10, show the ratio "bolt strength/tensile strength of material" plotted against the contact angle of the washer. Even a small angle of contact produces a marked decrease of strength, particularly on the bolts of steel with low-notch toughness. The failing load of the bolt, 40 tons under central loading, is reduced to 24 tons when the washer has a 3° slope, and to 9 tons for a contact area equivalent to a 7° slope. With greater notch toughness the conditions are

much improved. There is a "high" in strength for small contact angles, followed by an abrupt drop in strength and, finally, a "low" in strength at greater contact angles of washers. At small contact angles the bending stress is obviously almost completely equalized by the twisting of the bolt end in the threaded part. At greater contact angles the toughness of the material is no longer adequate to effect this equalization, as a result of which the strength decreases very sharply as the angle increases. At great angles of contact the nut itself rests on one side only, thus creating in this zone an additional bending moment which is unaffected by any further increase in contact angle.

According to the experiments, the toughness of the material itself must be allowed for in greater measure with respect to the strength under static stress, while for the highly stressed parts in airplane design, the problem of fit and tolerances can only be attacked with due allowance for the effect on the strength conditions.

On the basis of the results of these experiments, a simple and at the same time reliable method for the acceptance testing of vital bolts, was inaugurated. It was based on the following arguments: The designer introduces the material strength in the stress analysis and refers this strength to the minimum section - that is, the core section of the thread, or the barking-off. Under the influence of the notch effect, the strength of the bolt is substantially greater under central load, and does not decrease until additional bending stresses caused by oblique contact areas, occur. So, up to a certain slope of contact area, and provided the toughness is adequate, the computed bolt strength prevails. This must be proved in the acceptance test. The bolts are simply torn between oblique contact areas, as in the described test, while the bolt shank itself is guided cylindrically. Since failures can occur at the bolt head also, an oblique contact area is provided as for the nut. The contact angle is  $4^{\circ}$ . At this angle, bolts of tempered steel still have a failing stress equal to the strength of the material provided the toughness is adequate. If, in the acceptance test, the stipulated figure is not reached, notch-impact samples are taken and the cause of the inferior bolt strength ascertained.

#### 4. Notch Effect Under Static Twisting Stress

Since in shearing and twisting stresses, even with stress reversals, the notch effect is substantially less than in normal stress, the effect of notches will be relatively small, even under static shearing and twisting stress.

We made no notch-effect tests under static twisting stress since this subject has been adequately covered in the static and impact tests of E. Stille (reference 4), and E. Fischer (reference 5), whose findings, so far as they pertain to the effect of notches on the static strength, are appended in table III. The tests disclose a 4- to 7-percent strength increase through the annular notches. The bars with collar manifested practically no influence on the strength. Transverse holes and longitudinal grooves lowered the ultimate twisting moment. But, taking the cross-sectional reduction into consideration, there is hardly a reduction - but rather a slight rise - in the existing nominal stresses. The impact-twisting tests disclosed the ultimate twisting moment to be only very little affected by the rate of strain, averaging for impact stress, about 6 percent higher than for static stress.

#### 5. Notch Effect in Compressive Stress

No reduction of strength due to notches is expected under compression, because the section in the notch base is supported by the greater sections over it. Aside from that, substantially less significance attaches to the notch effect in compression, for the reason that the compressive strength of metal materials can - excepting cast iron - as a rule, not be utilized, because it lies substantially above the tensile strength, and the strains induce failure long before failure in compression takes place.

Individual compressive tests were foregone and recourse had to Sach's experiments (reference 6) on cylindrical samples of cast iron with annular notch of varying depth in the center. The results of these tests are shown in figures 11 and 12. The obtained failing stress rises in proportion to the ratio of "outside diameter to diameter at notch base"; i. e., on materials as brittle as cast iron, the notch effects a substantial strength increase. The notch effect here is more properly looked upon as sup-

porting action of the specimen center due to the tapered notch flanks; that is, an additional effect. (The conditions would probably be less propitious if the notch sloped at  $45^\circ$  to the axis, or in axial direction.

## II. THE NOTCH EFFECT OF HOLES IN THIN SHEET

Whereas the first part of this article was confined to the effects of notches under various types of stresses, in general, the following treats the notch effects on thin sheet, corresponding to the special conditions encountered in airplane design, where the holes constitute the most general type of notch form. (These experiments were prompted by the work of J. Müller-Bremen. His findings, not published so far, were graciously put at our disposal. Only a portion of his extensive experiments is quoted.) The studies therefore treat primarily the effects of holes of different sizes and locations (centric and excentric), as well as of rows of holes and riveted joints in light metal and high-tensile steel. The fundamental investigations were largely made on specimens of AZM elektron.

### 1. Effect of Single Central Hole

a) Influence of sectional weakening through one hole in AZM elektron.— Müller's tensile-test experiments on AZM elektron strip with 3 mm diameter holes, disclosed a decrease in strength varying in amount with the width of the strip. The greatest decrease occurred on the strip with width  $b$  equal to eight times the diameter  $d$  of the hole ( $d:b = 12.5$  percent). The strength then amounted to only 83 percent of a standard 10 mm wide tensile test bar. For narrower strip, the strength decrease is less.

To ascertain the effect of the hole diameter and of the strip width in their combined influence on the strength decrease, a large number of tests were made on specimen bars of different width and different size holes. The material consisted of AZM elektron sheet of 1 mm thickness. Its strength factors were  $\sigma_{0.2} = 19.9$  kg/mm<sup>2</sup>,  $\sigma_B = 31.2$  kg/mm<sup>2</sup>,  $\delta = 17$  percent. The microstructure, as shown in figure 13, discloses zone-like, arranged marked differences in grain size. The specimens were so taken as to exclude as far as possible any influence on the result due to

the strength scattering in the sheet. The obtained values (averages from three to five samples) are given in table IV, while figure 14 shows the strength of the perforated bars plotted against the bar width and the hole diameter. It readily reveals the strength decrease with increasing specimen width and the effect of the hole diameter. The various influences are individually emphasized in figures 15 and 16, which show the strength of the specimens against the ratio: "hole diameter/strip width" ( $d:b$ ). The curves in figure 15, referring to bars of different width and equal hole diameter, stress the influence of the strip width. With decreasing ratio  $d:b$ , the strength decreases almost linearly. Comparing the different curves, the strength decrease is seen to become so much greater as the hole diameter is increased. The curves in figure 16 refer to bars of the same width and show the influence of the hole diameter. As the ratio  $d:b$  increases, the strength of the holed tensile test bar drops very rapidly to a lower limit value and then increases again gradually as the ratio  $d:b$  increases. This gradual rise rests on the same phenomenon as that of the curves in figure 15.

The remainder of the section adjoining the hole must be looked upon as a tension bar with so much greater local taper as the hole is smaller. With large holes the tension bars formed on the sides are comparatively small and bounded on one side by a hole of relatively large radius - hence, subject to little notch effect. The fact that with small holes the influence on the strength diminishes again and almost disappears for very tiny holes, is readily understood when proceeding from the premise that every material has minor defects which, similar to a tiny hole, locally act as notches. A notch effect of the same order of magnitude as such defective spots can therefore have no influence on the strength. Naturally this influence of the ratio  $d:b$  prevails only when the hole diameter decreases with the ratio  $d:b$  and not, if, as in figure 15, the decrease in  $d:b$  is attributable to an increasing strip width  $b$ . In that case, as is seen in figure 15, there is no second rise in strength even for very small values of  $d:b$ .

Figure 17 illustrates the influence of the hole diameter on the tensile strength for constant ratio  $d:b = 5, 10, 20, \text{ and } 40$  percent. For constant  $d:b$  the strength decreases with increasing hole diameter throughout the entire range. The same results were obtained by Muller in

his experiments with a 1 mm AZM elektron sheet, which disclosed even greater notch sensitivity (fig. 18).

TABLE IV

Influence of Hole on Tensile Strength of AZM Elektron of Various Widths  
 Material, 1 mm sheet:  $\sigma_{0.2} = 19.9 \text{ kg/mm}^2$ ,  $\sigma_B = 31.2 \text{ kg/mm}^2$ ,  
 $\delta_{10} = 17$  percent. Average from 2 to 6 samples

Specimen width mm	Stress with a hole diameter of ... mm in $\text{kg/mm}^2$							
	0	0.625	1.25	2.5	3	5	10	20
6.25	31.5	29.7	29.7	30.9	31.8	--	--	--
7.5					30.9			
10					29.6			
12.5	31.1	29.3	28.2	28.9	--	29.7	--	--
15					28.5			
20					28.4			
25	30.2	28.7	--	27.2	27.4	27.7	28.6	--
30					27.5			
37.5					26.9			
50	29.9	28.5	26.4	26.1	26.6	26.5	--	26.8

b) Influence of sectional weakening and material.— The effect of holes was further explored on other materials (table V). The specimens were 10 mm wide strips of 1 mm sheet with a 0.9 mm diameter hole in the center. On the steel specimens the hole increased the strength by 4 to 7 percent, while lowering it on brass, duralumin, hydronalium, and elektron. Müller's experiments were made on strip of various widths and a 3 mm hole in the center. Figure 19 shows the strength ratio against  $d:b$ . While AZM elektron discloses a strength decrease in the range of  $d:b = 0$  to 46 percent, this range extends to  $d:b = 36$  percent for duralumin, and to  $d:b = 24$  and 22 percent for hydronalium. Rather than a decrease, there is a distinct increase in strength for the steels, above  $d:b = 10$  percent.

(See tables I, II, III, and VII, at end of report.)

TABLE V

Strength Decrease Due to Single Centric Holes in Specimens of Varying Materials  
 Specimen: bar, 10 mm wide of 1 mm sheet, 0.9 mm transverse hole in center; 10 mm wide tensile test bars included for comparison

Material	$\sigma_B$ kg/mm <sup>2</sup>	$\delta_{10}$ percent	$\sigma_{BL}$ kg/mm <sup>2</sup>	$\sigma_{BL}/\sigma_B$ percent
Mn steel Acro 50	60.3	23	62.9	104
Cr-Ni steel VCN 35	112.4	6	116.8	104
Stainless Cr steel, hardened	180.2	1	192.2	107
Ms 63 brass	34.9	55	33.3	95
Hy 9 hh hydronalium	40.4	17	38.7	96
681 B duralumin	44.7	--	41.9	94
DM 31 duralumin	50.3	12	47.8	95
AM 503 elektron	23.7	6	23.5	99
AZM elektron	30.6	--	27.3	89

In order to determine the influence of d:b ratio on the plated duralumin (aircraft material 3116) now commonly used in airplane design, some further experiments were made. The test specimens were 1 mm gage duralplat sheet in original condition and in heat-treated condition. One series of tests each was devoted to the specimens of varying widths fitted with 3 mm diameter transverse hole in the center. The results are given in figure 20. Again, there is a fairly uniform drop in strength as the ratio d:b decreases. The loss of strength due to the perforation in the heat-treated sheet exceeds that of the sheet in original condition. Another series of tests was made on specimens with different hole diameters, but with the same ratio d:b, namely, 12.5 percent, or specimen width equal to eight times hole diameter. The results are shown in figure 21, where the tensile strength of the perforated bar in relation to the tensile strength of a standard tensile test specimen 12 mm wide, is plotted against the hole

diameter. The influence of the hole diameter for holes of less than 3 mm diameter on the reduction of strength, is strongly noticeable. With larger diameters the strength does not vary. The reduction in strength then amounts to 8 percent for sheet in original condition and 12 percent after heat treatment.

c) Scatter of notch factor on the same material.— In the application of these notch factors, it naturally is very important whether or not approximately the same notch factor can be counted upon for one and the same material and notch form, or whether considerable scattering of the notch factor occurs on the same material. It is a question of deciding whether the notch figure is a quality characteristic of the type of material or whether this quality, as a kind of "brittleness," primarily hinges upon the pretreatment received by the material and consequently becomes utterly different, depending upon fabrication and delivery. For these reasons, a number of 1 mm gage sheets of 681 ZB duralumin (from different deliveries) were investigated. The specimens from each sheet consisted of two 10 mm width strips and two specimens each without holes for comparison. The frequency curve (fig. 22) represents the test data from 50 sheets. The tensile strength of the sheets was:  $\sigma_B = 41.0$  to  $46.1$ ; of the specimens with holes,  $\sigma_{BL} = 39.1$  to  $43.8$  kg/mm<sup>2</sup>; the ratio,  $\sigma_{BL}/\sigma_B = 91$  to  $98$ , or  $94.4$  percent on the average. The scatter of the strength values respectively, amounted to  $\pm 5.8$  and  $5.7$  percent, against  $\pm 3.7$  percent for  $\sigma_{BL}/\sigma_B$ . This indicates that the notch figure is a material property little affected by pretreatment, at least, as far as aluminum alloys are concerned. Allowance for notch sensitivity in the design is hereby rendered decidedly easier. Other tests on aluminum 681B, 681 ZB 1/3 alloys plated and DM 31 yielded the same notch figure.

## 2. Influence of Several Holes and Edge Notches in AZM Elektron

Concerning the influence of a row of successive holes (as in a single-row rivet seam), the test data of J. Muller are available. His tests were made on 1 mm gage AZM elektron sheet specimens of different widths and 3 mm diameter holes. The results are shown in figure 23. Here  $d$  denotes the sum of the three hole diameters. It will be noted that the reduction in strength for  $d:b = 12$  percent, is

equally as great as for the single hole, but that at higher values of  $d:b$ , the strength decrease abates much quicker, and at still higher values a marked strength increase (9 percent for  $d:b = 50$  percent) occurs. Müller also investigated the influence of two half-round notches of 1.5 mm radius, drilled in opposite edges of the specimens on the strength. His obtained curve included in figure 23, attests to a smaller reduction in strength and to a stronger increase in strength at higher values of  $d:b$ . This obviously relates to the fact that on failure of a flat bar, the break always starts at the center. As a result of this, the presence of a hole in the center must have the greatest strength-reducing influence.

### 3. Effect of Excentric Holes

With unsymmetrical holes, such as excentric holes in strip, for example, the conditions become substantially more unfavorable. The tensile stress is then accompanied by an additional bending stress which can only be canceled by considerable plastic strain. Notch effects of this kind appear, for instance, on multi-row riveted joints, and the thereby induced local bending stresses are usually ignored mathematically. The effects of such notches were observed at the DVL during the investigation of a flying boat which after an accident had been lying for some time under water (reference 7) and as a result the wing spars had become considerably corroded, in part intercrystallized. The plain test specimens taken from the spar flange showed a tensile strength of 36 kg/mm<sup>2</sup>, while specimens taken at places where the flange had been weakened through staggered rows of rivet holes, and therefore contained these series of holes in longitudinal direction, disclosed a tensile strength of 27 kg/mm<sup>2</sup> only. Prompted by these findings, the brittleness testing was carried out with the specimen form illustrated in figure 24.

a) Influence of excentricity.— A comparative tabulation of the strength of specimens with central holes and of specimens with excentric holes, is contained in table VI. It is seen that all materials with excentric holes undergo a marked reduction in strength. On steel it amounts to 51 percent, against an increase of 7 percent for the centric hole. For duralumin and AZM elektronik, the reduction is also considerable.

TABLE VI

Strength of Specimens with Excentric Rows of Holes and of Specimens with Single Centric Holes  
 Specimen form: tensile test bar of 1 mm gage sheet; standard tensile test bar 10 mm wide; perforated tensile test bar 10 mm wide with central hole of 0.9 mm diameter; bar with excentric rows of holes is shown in figure 24.

Material		Stainless Cr steel air- hardened	Heat- treated 681 B duralumin	AZM elektron
Normal tensile test specimen	$\sigma_B$ kg/mm <sup>2</sup>	180.2	43.3 40.7	28.9
Tensile test specimen with hole	$\sigma_{BL}$ kg/mm <sup>2</sup>	192.2	41.3	24.4
	$\sigma_{BL}/\sigma_B$ %	107	95	84
Specimen with excentric rows of holes	$\sigma_{BL_{ex}}$ kg/mm <sup>2</sup>	92.1	30.2	19.3
	$\sigma_{BL_{ex}}/\sigma_B$ %	51	74	67

b) Influence of strength and age-hardening in steel.

It was desirable to ascertain the amount of strength decrease in steels of different tensile strength. The tests were made on specimens from 0.5 and 1 mm gage sheet steel with from 53 to 192 kg/mm<sup>2</sup> tensile strength.

The strength of the perforated specimen is plotted against that of the plain specimen for different steels in figure 25. Up to a tensile strength of around 100 kg/mm<sup>2</sup> the strength of the perforated specimen is fairly consistently 80 (to 90) percent of the strength of the plain specimen. At higher values the excentric holes cause a somewhat greater strength reduction. Raising the strength values above 150 kg/mm<sup>2</sup> through heat-treating, brings out the brittleness in considerable scattering of the values.

The conditions become plainer if the analysis is confined to one material that has been hardened and annealed to suit the different strength values.

In figure 26 the strength of the plain specimen ( $\sigma_B$ ) and of the perforated specimen ( $\sigma_{BL_e}$ ) is plotted against

the annealing temperature for stainless Cr steel. When these temperatures exceed  $250^{\circ}$  C., the two curves are almost parallel; but at low annealing temperatures the strength of the perforated specimen shows a steep drop, while that of the plain specimen still increases. The high brittleness of the unannealed specimens makes itself felt here by the fact that the narrow strips between hole and edge on one specimen developed premature cracks and then only did the specimen absorb the maximum load.

Figure 27 shows the ratio  $\sigma_{BL_e}/\sigma_B$  against the tensile strength of the plain specimen for Cr-Ni W steel. The specimens are air-hardened at  $840^{\circ}$  and tempered at 100, 250, 350, 500, and  $630^{\circ}$  C. (The specimens with 182 strength were not tempered.) The ratio  $\sigma_{BL_e}/\sigma_B$  decreases fairly uniformly with increasing strength. For the mild treatment to 95 kg/mm<sup>2</sup> the conversion factor is 85 percent, in contrast with only 73 percent for the hardened specimen of 182 strength.

c) Influence of corrosion.— It was also desirable to ascertain whether the corrosion effect increased the brittleness and whether this becomes noticeable on specimens with excentric rows of holes. The corrosion tests were made in the salt-spray tester of the DVL. Figures 28 to 31 show the tensile strength and the notch tensile strength against the corrosion period. Figure 32 gives the values for Cr-Ni steel specimens of different gage sheet. The plotting against the ratio: "corrosion period/gage of sheet" affords a better comparison. It is seen that the manner of strength decrease on the standard test specimen and on the perforated specimen is the same. The corrosion effect is not much greater, as a rule, on the perforated than on the standard test specimen. The difference is probably due to the fact that owing to the rims of the holes, more unprotected edges are exposed to corrosion. (On all specimens the corrosion attack had a preference to start at the specimen edges.) It is surprising that even on the stainless Cr steel of figure 30, which had lost its corrosion stability through unfavorable heat treatment, none of the rising brittleness, indicated by the perforated test specimen, could be observed (although this might be expected with intercrystalline corrosion).

## III. STRENGTH DECREASE IN RIVETED CONNECTIONS

## AND AT JOINTS

The effect of holes on the strength is of particular concern with respect to the conditions at riveted joints. Since the decrease of strength in light metals occurs chiefly when the hole diameter is small relative to the specimen width, this range will largely govern riveted joints as well. Such conditions are encountered on larger, load-transmitting sections when smaller forces are locally applied as, for instance, at joints of diagonals, uprights, web plates, etc. In many cases the force introduced in the rivet is then not in the direction of the principal stress of the structural part itself, hence the influence of the local force introduction is probably comparatively small. But, between the simple hole and the rivet hole, there is that difference that the rivet hole cannot deform itself freely at the edge. To ascertain this influence, a number of tests have been made by J. Müller, in which the deformation of the holes was prevented by the insertion of blind rivets of 3 mm shank diameter - some with flat head, some with half-round snaphead. The test specimens themselves, of 1 mm gage AZM elektron, were of different widths. The results of these experiments are given in figure 33. The strength decrease is less than on the specimens with open holes (without rivets). At higher  $d:b$  the strength also increases more rapidly again. The influence is greatest on the rivets with half-round heads.

## 2. Effect in Simple Riveted Joints

At joints and corners the total force to be absorbed by the sheet is frequently introduced through the riveting. This makes the influence exerted by the force-transmitting rivet a matter of vital importance. This problem was also treated by J. Müller. His specimens of 1 mm gage AZM elektron consisted of two strips riveted together lengthwise, using 1 to 4 rivets per row of 3 mm diameter. The criterion of the strength decrease due to the holes is the value at which the crushing pressure at the side of the hole does not exceed a certain limiting value ( $p = 41.5 \text{ kg/mm}^2$ ) as otherwise the failure occurs as pure crushing pressure failure, or is at least, seriously affected by the high crushing stress. Smaller values of  $d:b$  are therefore obtainable only on specimens with several holes. On the

specimens with 3 and 4 rivets, the ratio  $d:b$  could only be lowered to 17 and 20 percent (lower values would necessitate a study of a still greater number of rivets whereby, however, the nonuniform support of the individual would more and more have affected the result). The findings are shown in figure 34. The reduction is about as much as on the specimens of the same material but with open holes, or greater than on the specimens with holes closed by blind rivets.

Inasmuch as the tests with load-transmitting rivet are in any case less favorable than with the blind rivet, the strength decrease ascertained here will have to be given careful consideration on every riveted joint through single rivets or several lengthwise-arranged rivets, at least.

### 3. Strength of Centrally and Excentrally Joined Sheet Sections

If joints of sheet and strip sections are used in combinations, as is customary in airplane design, the conditions are substantially more involved, especially so if the joints themselves are excentrical. Of the many experiments made by the EHF, only a few can be described here. Table VII illustrates several types of attachment of light-metal C sections and the obtained strength values in comparison to the strength of the same kind of joints but developed from flat sheet. The strength of specimens with simple holes made from the same sheet are also included. The sections were so jointed as to place the last rivets near to the edge, and the next time to place the last rivets toward the center of the specimen. The same experiments were repeated on the joints of the (profile developments) flat-sheet strips. (The influence can also be studied in the test of a sheet strip with a series of holes corresponding to the rivet pitch when the strip is suitably widened out at the points of marked strength reduction, so that failure occurs in the desired cross section.) According to table 7, favorable forms of attachment make it possible to utilize 90 percent of the tensile strength, against only 55 percent if the joint is unfavorable. The introduction of the force in the section back of, or in the center of the developed strip is singularly unfavorable, while the force introduction in the side walls of the section or at the edges of the sheet strip (development) is especially propitious.

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## FIGURE LEGENDS

- Figure 1.-- Stress increase at edge of hole rendered visible through brittle paint. (Specimen much overstressed for better visualization.)  
Specimen: 1 mm gage duralumin sheet, 40 mm wide, 8 mm diameter hole; painted with a solution of rosin in acetone and dried for 3 days at 30° C. Under a 6 kg/mm<sup>2</sup> stress in the perforated section, cracks appear at edge of hole; under 10 kg/mm<sup>2</sup> stress, cracks appear in the unweakened section.
- Figure 2.-- Effect of notch depth on notch strength of steel specimen: round, 18 mm diameter, 45° Vee notch of from 0.4 to 4 mm depth.  
Ingot metal:  $\sigma_s = 30.6/29.4$  kg/mm<sup>2</sup>,  $\sigma_B = 43.9$  kg/mm<sup>2</sup>,  $\delta_4 = 19\%$ ,  $\psi = 61\%$ ; 0.17 C steel,  $\sigma_s = 29.6/28.7$  kg/mm<sup>2</sup>,  $\sigma_B = 47.7$  kg/mm<sup>2</sup>,  $\delta_4 = 21\%$ ,  $\psi = 55\%$ .
- Figure 3.-- Aspects of breaks of notched tensile test specimens (Cf. fig. 2). The deeply notched bars disclose separation failure, the others slippage failure.
- Figure 4.-- Effect of hole in tensile test. Specimen: section of bar, 3 mm diameter hole. Material: smooth-drawn, round steel 5011, of 15 mm diameter. The specimens without hole disclose slippage failure and severe constriction; those with hole, separation failure and minor constriction.
- Figure 5.-- Effect of temperature on tensile strength of notched bars (Flossner's experiments).  
Specimen: 18 mm diameter round bar; type of notches: 4 mm square notch, 45° V notch, 4 mm deep. Material: 0.64 C steel,  $\sigma_s = 44.2/43.6$  kg/mm<sup>2</sup>,  $\sigma_B = 85.8$  kg/mm<sup>2</sup>,  $\delta_4 = 16\%$ ,  $\psi = 31\%$ .

Figure 6.- Reduction of bending strength due to notches.

Material: 0.04 C steel with  $\sigma_s = 23.3/22.5$  kg/mm<sup>2</sup>,  $\sigma_B = 37$  kg/mm<sup>2</sup>,  $\delta_s = 34\%$ ,  $\psi = 74\%$ ; 0.47 C, 0.6 Mn steel,  $\sigma_s = 44.5$  kg/mm<sup>2</sup>,  $\sigma_B = 69.8$  kg/mm<sup>2</sup>,  $\delta_w = 19\%$ ,  $\psi = 44\%$ ; Al alloy with 4.28 Cu and 0.99 Si, heat-treated,  $\sigma_{0.2} = 20.5$  kg/mm<sup>2</sup>,  $\sigma_B = 35.9$  kg/mm<sup>2</sup>,  $\sigma_{10} = 19\%$ ,  $\psi = 26\%$  (bending strength and notch bending strength referred to section modulus  $W = \frac{b \cdot h^2}{6}$ ). Allowance for change in bending moment with deep deflection of bar.

Figure 7.- Effect of temperature and rate of strain on the notch bending strength of 0.9 C steel.

Material: 0.9 tool steel, annealed,  $\sigma_s = 31.2$  kg/mm<sup>2</sup>,  $\sigma_B = 61.8$  kg/mm<sup>2</sup>,  $\delta_s = 32\%$ ,  $\psi = 60\%$ . Specimen section: 20 x 26 mm (bent flat edge); triangular notch, 45°, 7 mm deep, with 0.5 mm rounding off radius at tip; support spacing, 120 mm; rate of flexure, 1 mm/min; rate of impact bending, about 200,000 mm/min.

Figure 8.- Effect of temperature and rate of bending on notch bending strength of 0.5 C steel.

Material: 0.51 C steel,  $\sigma_s = 40.7/37.0$  kg/mm<sup>2</sup>,  $\sigma_B = 68.1$  kg/mm<sup>2</sup>,  $\delta_s = 25\%$ ,  $\psi = 43\%$ ,  $\sigma_B' = 154$  kg/mm<sup>2</sup>. Specimen: 20 x 20 mm (bar section). Notch: 8 mm deep, 45° triangular, with 0.5 mm rounding off radius at tip. Support spacing, 120 mm.

Figure 9.- Testing device for threaded bolts.

- a) device for clamping in testing machine.
- b) spacing disks.
- c) fitting bolt.
- d) oblique washer.
- e) duralumin holder.

Figure 10.- Effect of oblique support on strength of heat-treated steel bolts of different notch toughness. Material: Cr-Ni steel and Cr-Ni-Mo steel.

## Figures

- 11 & 12.- Notch effect in compression test (Sach's experiments). Material: cast iron.
- Figure 13.- Microstructure of elektron sheet, etched with 1 percent alcoholic phosphoric acid.  $V = 150$ .
- Figure 14.- Effect of specimen width and hole diameter on tensile strength of AZM elektron (thickness = sheet thickness = 1 mm).
- Figure 15.- Effect of ratio: "hole diameter/specimen width" on tensile strength of AZM elektron. Curves for equal hole diameter but different specimen widths.
- Figure 16.- Effect of ratio: "hole diameter/specimen width" on tensile strength of AZM elektron. Curves for equal specimen width but different hole diameters.
- Figure 17.- Effect of hole diameter on tensile strength of AZM elektron. Curves for constant ratio: "hole diameter/specimen width".
- Figure 18.- Effect of hole diameter on tensile strength of AZM elektron, 1 mm sheet with  $\sigma_{0.22} = 16.7$  kg/mm<sup>2</sup>,  $\sigma_B = 28.3$  kg/mm<sup>2</sup>,  $\delta_{10} = 15\%$  (Müller's experiments).
- Figure 19.- Effect of "hole diameter/specimen width" on strength ratio " $\sigma_{BL}/\sigma_B$ " of different metals. Hole, 3 mm. The values refer to tensile strength of 10 mm wide tensile test specimens. Material: Steel St C 25.61 with  $\sigma_B = 49.8$  kg/mm<sup>2</sup>; Cr-Mo steel with  $\sigma_B = 83.8$  kg/mm<sup>2</sup>; hydronalium Hy 7 with  $\sigma_B = 36.2$  kg/mm<sup>2</sup>; hydronalium Hy 9 with  $\sigma_B = 37.6$  kg/mm<sup>2</sup>; duralumin 681 B with  $\sigma_B = 40.5$  kg/mm<sup>2</sup>; AZM elektron with  $\sigma_B = 28.3$  kg/mm<sup>2</sup> (Müller's data).

Figure 20.-- Effect of ratio: "hole diameter/specimen width" on tensile strength of duralplat; hole, 3 mm. Material: 1 mm strip of 3116.5 with  $\sigma_{0.2} = 31.6$  kg/mm<sup>2</sup>,  $\sigma_B = 43.9$  kg/mm<sup>2</sup>; identical strip heat-treated, with  $\sigma_{0.2} = 26.7$  kg/mm<sup>2</sup>,  $\sigma_B = 41.7$  kg/mm<sup>2</sup> (showed considerable coarse grain after treatment).

Figure 21.-- Effect of hole diameter on tensile strength of duralplat for constant ratio,  $d/b = 0.125$ . Material: 1 mm strip of 3116.5 with  $\sigma_{0.2} = 31.6$  kg/mm<sup>2</sup>,  $\sigma_B = 43.9$  kg/mm<sup>2</sup>; identical strip heat-treated, with  $\sigma_{0.2} = 26.7$  kg/mm<sup>2</sup>,  $\sigma_B = 41.7$  kg/mm<sup>2</sup> (showed considerable coarse grain after treatment).

Figure 22.-- Frequency curve against ratio  $\sigma_{BL}:\sigma_B$  for duralumin 681 ZB; 1 mm gage sheet and strip. Specimen: 10 mm wide strip, center hole 0.9 mm diameter. Comparative specimens: 10 mm wide; averages from two tests each.

Figure 23.-- Effect of several holes and edge notches on crushing strength for 1 mm gage AZM elektron,  $\sigma_{0.2} = 16.7$  kg/mm<sup>2</sup>,  $\sigma_B = 28.3$  kg/mm<sup>2</sup>,  $\delta_{10} = 15\%$ . Averages of two tests each (Müller's data).

Figure 24.-- Specimen with excentric holes.

Figure 25.-- Strength of steel strip with excentric holes against tensile strength of plain specimens. Material: 0.5 mm and 1 mm gage sheet and strip of alloyed and unalloyed steel.

Figure 26.-- Effect of annealing temperature on tensile strength of specimens with excentric holes. Material: 1 mm gage stainless Cr steel, with 0.34 C, 13.6 Cr, air-hardened from 1020° C.

Figure 27.-- Effect of heat treatment on ratio  $\sigma_{BL}:\sigma_B$ . Specimen strips with excentric holes of 1 mm Cr-Ni-W steel sheet with 0.36 C, 1.05 Cr, 4.0 Ni, 0.95 W air-hardened from 840° C. not annealed and annealed at 100-250-350-500-630° C.

## Figures

- 28 to 31.- Effect of corrosion tensile strength of specimens with excentric holes compared with 10 mm wide tensile test specimens. Specimen thickness, 1 mm; corrosion in salt-spray tester of DVL.
- Figure 29.- Cr-Ni-W steel with 0.4 C, 1.1 Cr, 4.5 Ni, 0.9 W, air-hardened from 840° C.; annealed at 250° C.
- Figure 30.- Stainless Cr steel, with 0.34 C, 13.6 Cr, air-hardened from 1020° C.; annealed at 530° C.
- Figure 31.- Duralumin 681 B.
- Figure 32.- Effect of corrosion period on tensile strength of specimens with excentric holes for different specimen thickness. Material: Cr-Ni steel, with 0.28 C, 0.7 Cr, 3.3 Ni. Corrosion in DVL salt-spray tester.
- Figure 33.- Effect of blind rivets on tensile strength of elektron specimens. Material: 1 mm gage AZM elektron with  $\sigma_{0.2} = 16.7 \text{ kg/mm}^2$ ,  $\sigma_B = 28.3 \text{ kg/mm}^2$ ,  $\delta_{10} = 15\%$ . Hole and rivet diameter = 3 mm. Specimen width changed. (Muller's test data.)
- Figure 34.- Effect of riveted joints on the tensile strength of 1 mm AZM elektron sheet, with  $\sigma_{0.2} = 16.7 \text{ kg/mm}^2$ ,  $\sigma_B = 28.3 \text{ kg/mm}^2$ ,  $\delta_{10} = 15\%$ . Rivet diameter = 4 mm. Rivets of magnalium. with 5 Mg. joint formed with from 1 to 4 rivets in a row.

TABLE I. Tensile Strength of Notched Bars

Specimen shape								
	$\sigma_B$	$\sigma_{BK}$	$\frac{\sigma_{BK}}{\sigma_B}$	$\sigma_{BK}$	$\frac{\sigma_{BK}}{\sigma_B}$	$\sigma_{BL}$	$\frac{\sigma_{BL}}{\sigma_B}$	
Material	kg/mm <sup>2</sup>	kg/mm <sup>2</sup>	percent	kg/mm <sup>2</sup>	percent	kg/mm <sup>2</sup>	percent	
Ingot steel	43.9	69.1	163	--	--	--	--	
O.17 C steel	47.7	65.2	137	--	--	--	--	
O.35 C steel	58.3	--	--	--	--	61.0	105	
C.64 C steel*	85.8	98.6	115	105.5	121	--	--	
Aluminum								
Al 98/99	9.9	17.5	177	13.5	136	10.9	103	
Duralumin								
DM 31	51.5	61.8	120	51.8	101	46.1	89	
Elektron								
AZM	31.4	34.3	109	34.1	109	28.9	92	
Elektron								
AZF								
sand cast	15	17	114	15	100	14	93	

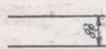
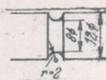
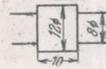
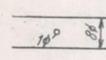
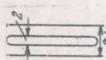
\*Flössner's test data.

TABLE II. Bending Strength of Notched Bars

Material								
	$\sigma_B$	$\delta_{10}$	$\sigma_B'$	$\sigma_{BK}'$	$\frac{\sigma_{BK}'}{\sigma_B'}$	$\sigma_{BL}'$	$\frac{\sigma_{BL}'}{\sigma_B'}$	
	kg/mm <sup>2</sup>	percent	kg/mm <sup>2</sup>	kg/mm <sup>2</sup>	percent	kg/mm <sup>2</sup>	percent	
O.04 C steel	38	--	~90	58	65	--	--	
O.47 C steel	70	19	134	93	70	--	--	
Al alloy+4.3 Cu	36	19	69	52	75	--	--	
Duralumin								
DM 31	52	14	93	66	70	77	83	
Elektron								
AZM	31	11	60	37	62	45	75	
AZF	15	--	23	17	74	--	--	

\* Specimen width, 10 mm.

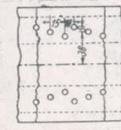
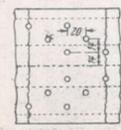
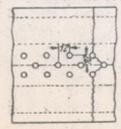
TABLE III. Notch Effect on Twisting Strength  
(Stille and Fischer's test data)

Material		0.05 C steel	0.16 C steel	1.04 C steel	0.64 C steel		Al alloy + 4% Cu heat-treated
					normal-ized	tem-pered	
Strength	$\sigma_{Bo}$ kg/mm <sup>2</sup>	31.1	40.5	37.6	44.2	71.5	$\sigma_{0.2} =$
	$\sigma_{Bt}$ "	29.9	36.7	--	43.6	69.3	19.2
	$\sigma_B$ "	42.0	50.3	56.5	79.3	84.4	36.9
	$\delta_{10}$ percent	31	27	17	16	13	21
	$\psi$ "	72	67	43	31	56	33
	$M_{Do}$ cm kg	565	574	683	770	780	375
	$T_B'$ kg/mm <sup>2</sup>	56.2	57.1	67.9	76.6	78.4	37.3
	$M_d$ cm kg	--	600	728	797	--	--
	$\frac{M_d}{M_{Do}}$ percent	--	105	107	104	--	--
	$M_d$ cm kg	--	568	--	--	--	--
	$\frac{M_d}{M_{Do}}$ percent	--	99	--	--	--	--
	$M_d$ cm kg	490	538	564	700	680	373
	$\frac{M_d}{M_{Do}}$ percent		94	83	91	87	99
	$M_d$ cm kg	560	536	--	765	730	--
	$\frac{M_d}{M_{Do}}$ percent		94	--	99	94	--

Depth of groove 0.7 mm

TABLE VII. Strength Section and Sheet Joints

Material: 1 mm duralplat, aircraft material 3116.5, with  $\sigma_{0.2} = 27.5$  kg/mm<sup>2</sup>,  $\sigma_B = 39.6$  kg/mm<sup>2</sup>. The dimensions of the joints are such as to insure the same tensile and crushing strength as with  $\sigma_B = 39$  kg/mm<sup>2</sup>,  $p = 70$  kg/mm<sup>2</sup>.

Section joint	Hole arrangement (development)	Specimen form	Strength in percent of sheet strength	
			Last rivets outside	inside
		Plate with holes	93	92
		Plate joint	91	96
		Section joint	85	90
		Plate with holes	96	--
		Plate joint	66	63
		Section joint	77	80
		Plate joint	--	64*
		Section joint	--	55*

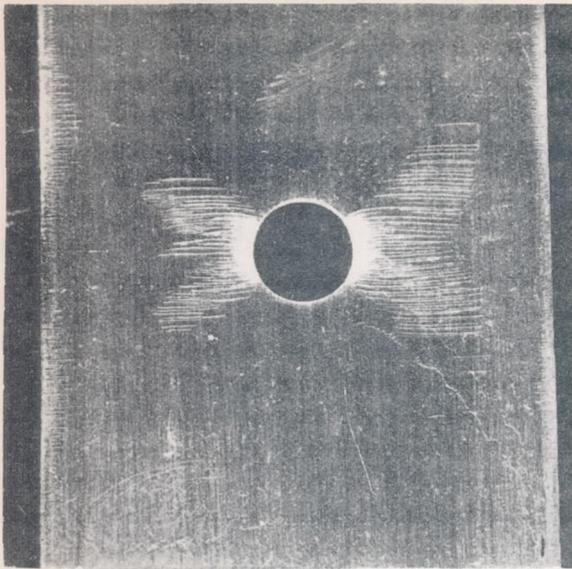


Figure 1.



Figure 13.

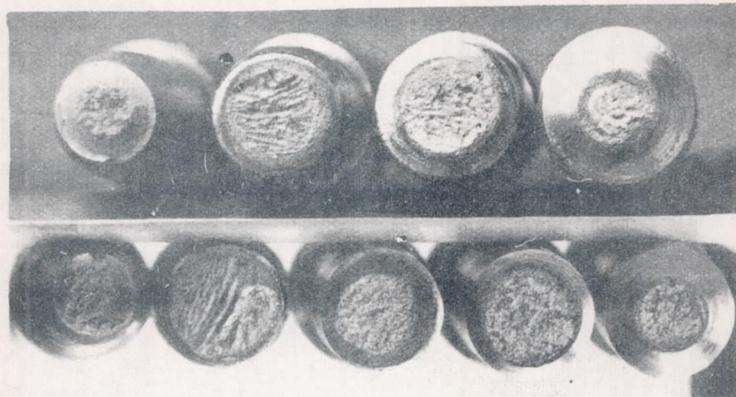


Figure 3.

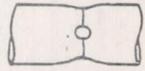
Specimen	Without hole	With hole
Failure stress, $\text{kg/mm}^2$	58.3	61.0
Constriction %	58	21
Type of failure	Slippage failure	Separation failure
Shape of break		
Aspect of break		

Figure 4.

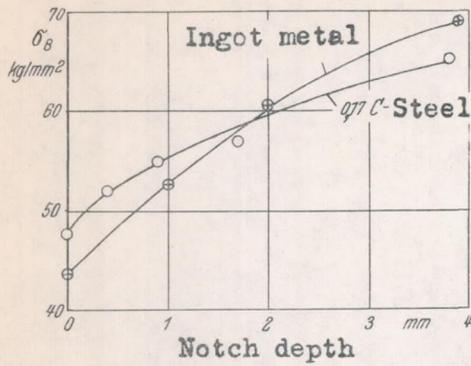


Figure 2.

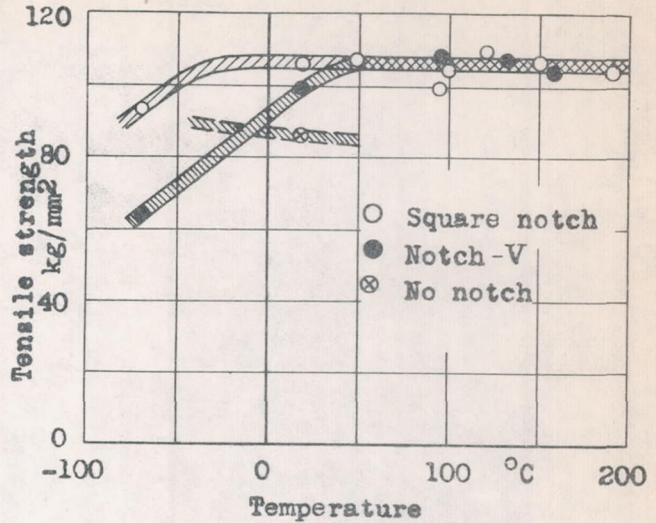


Figure 5.

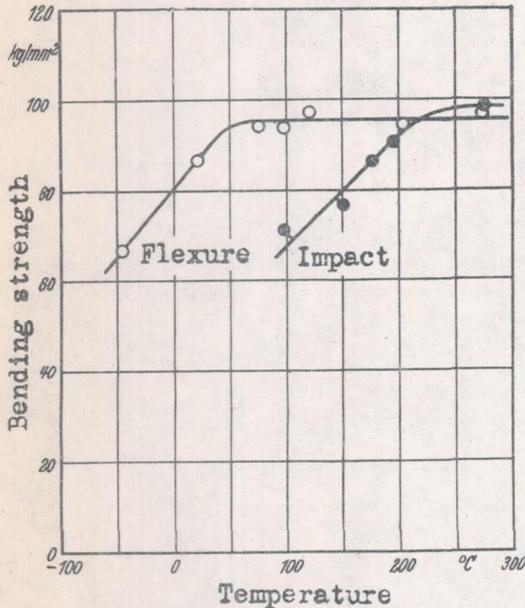


Figure 7.

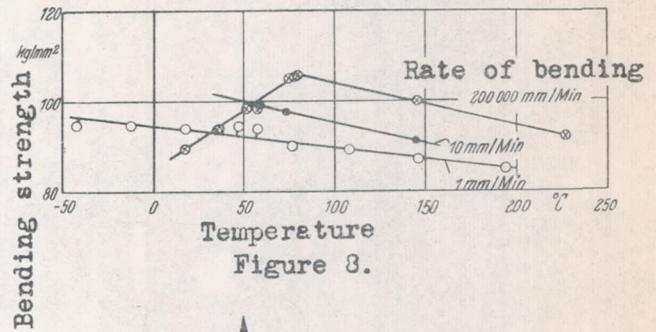


Figure 8.

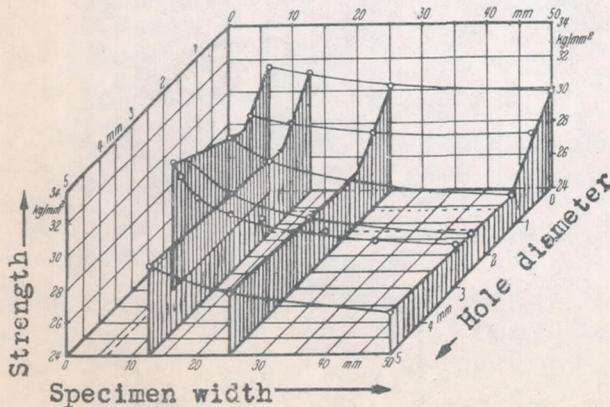


Figure 14.

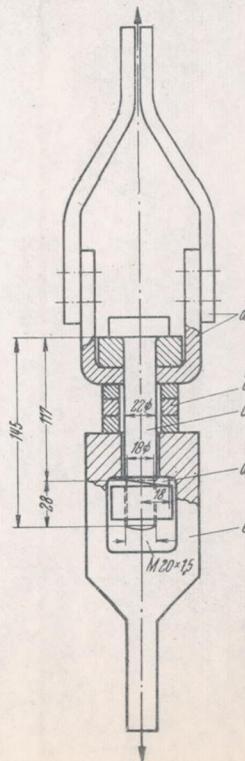


Figure 9.

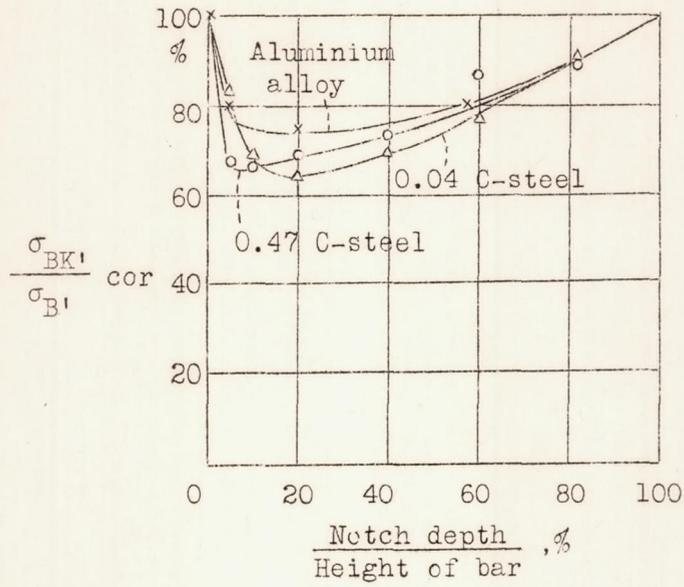


Figure 6.

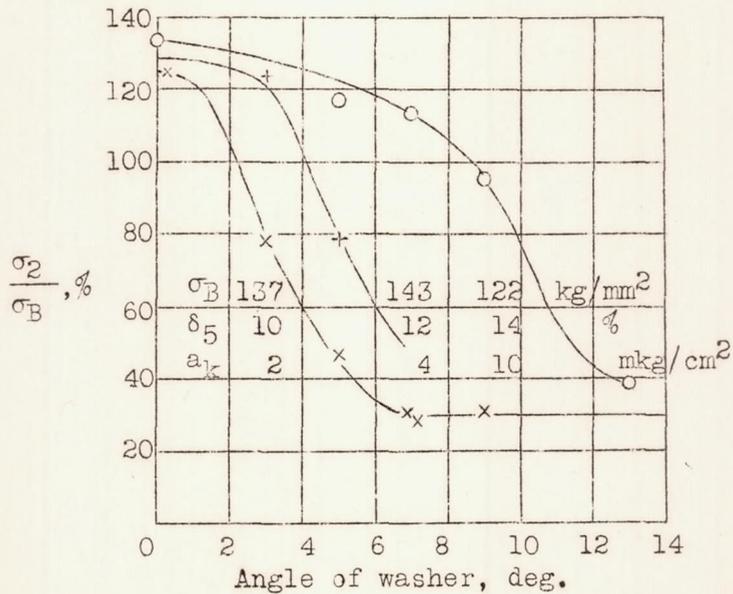


Figure 10.

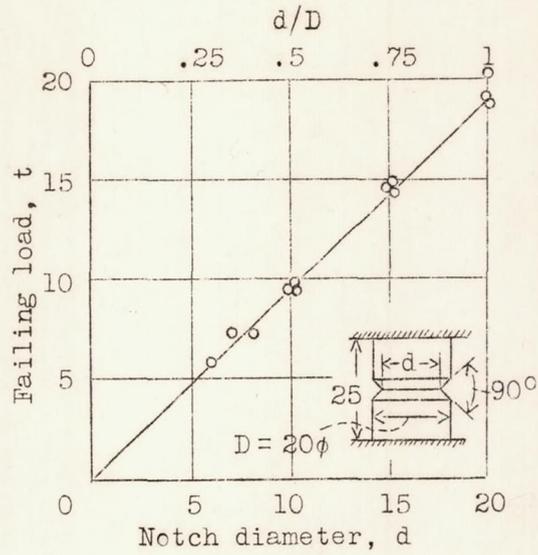


Figure 11.

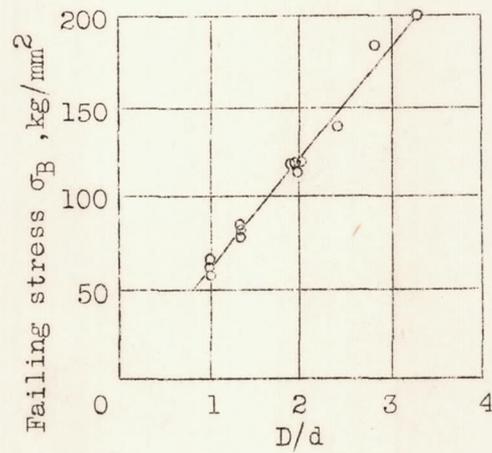


Figure 12.

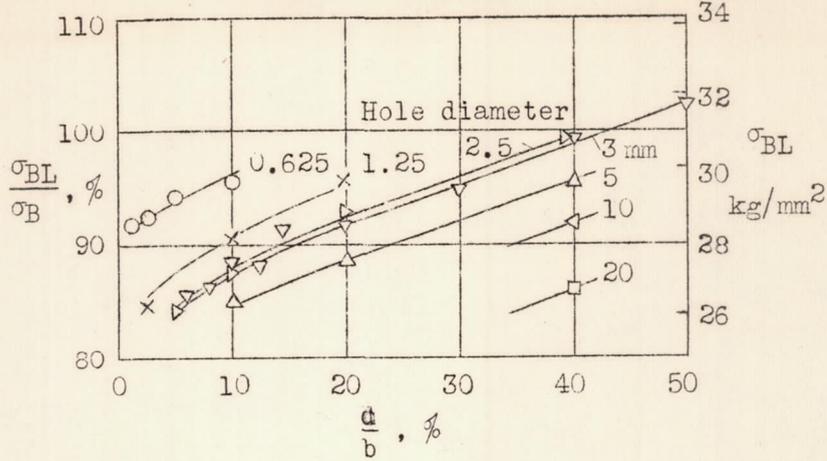


Figure 15.

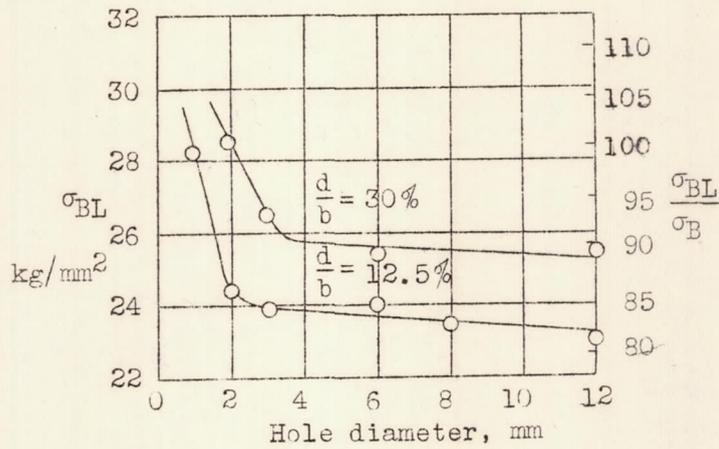


Figure 18.

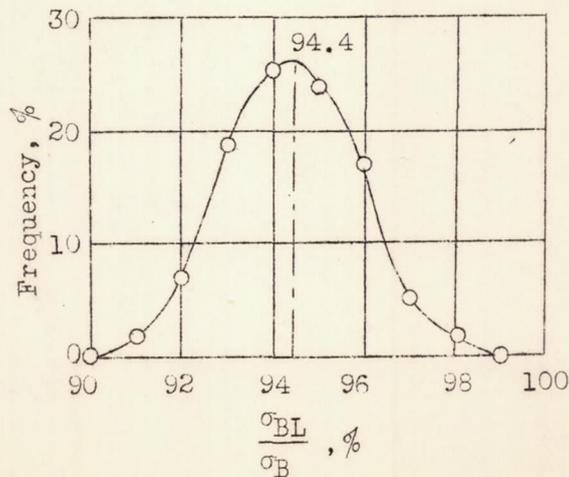


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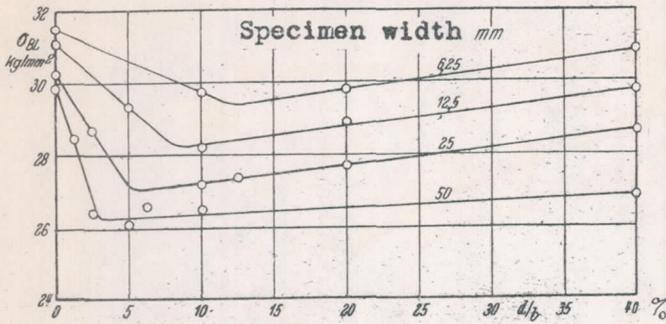


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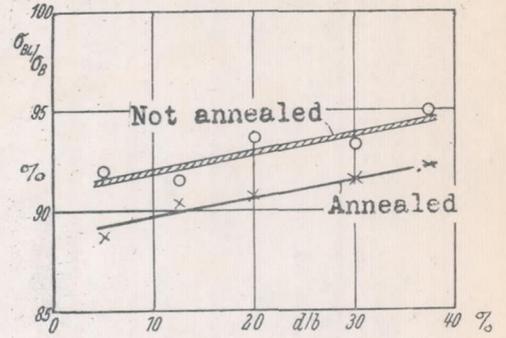


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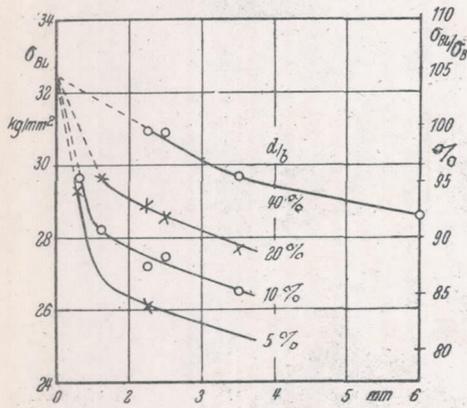


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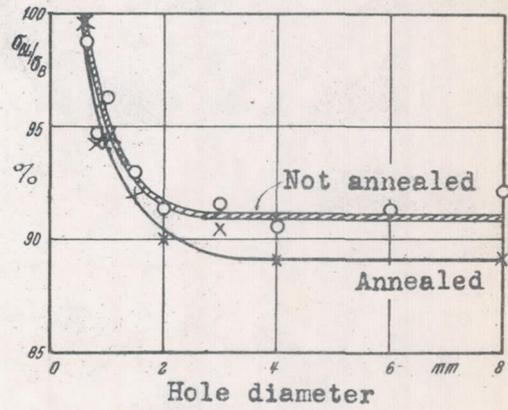


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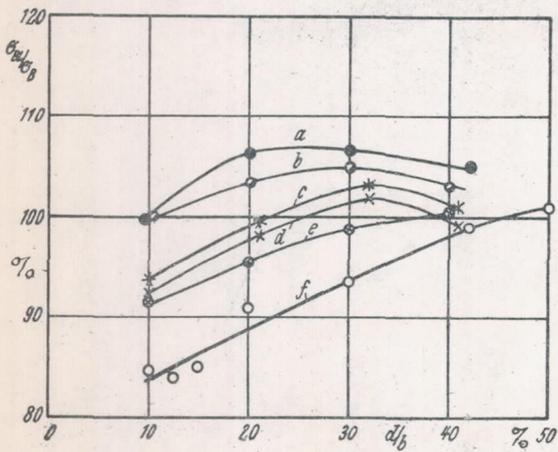


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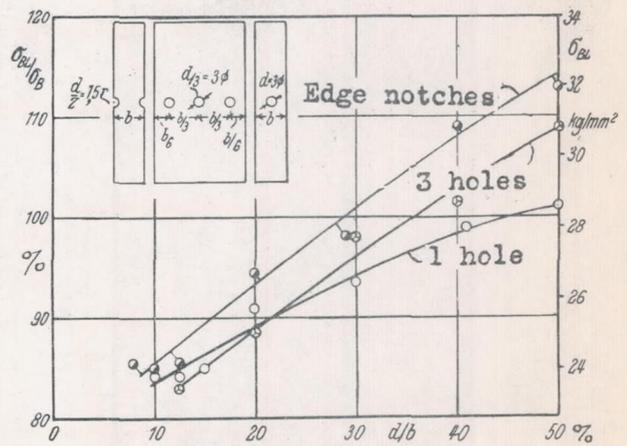


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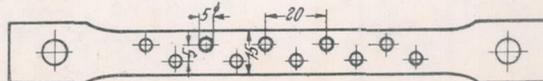


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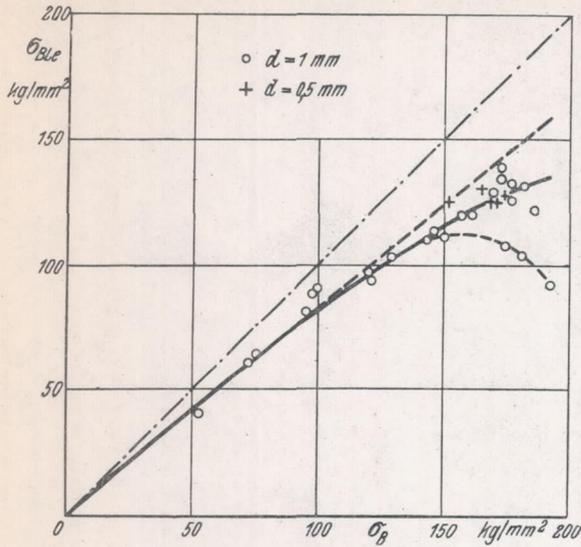


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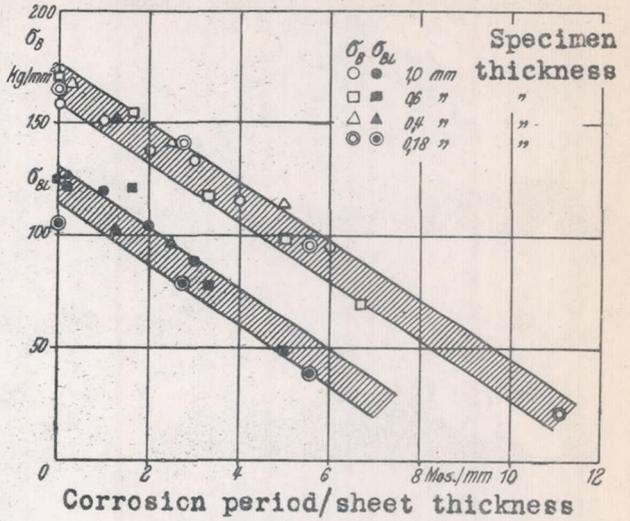


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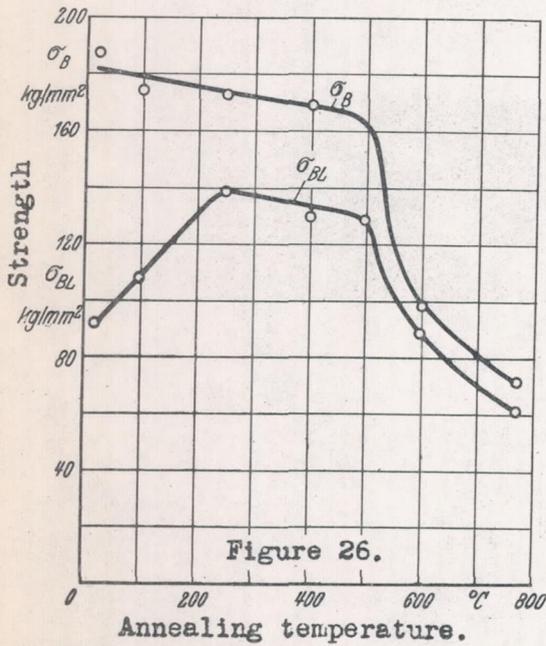


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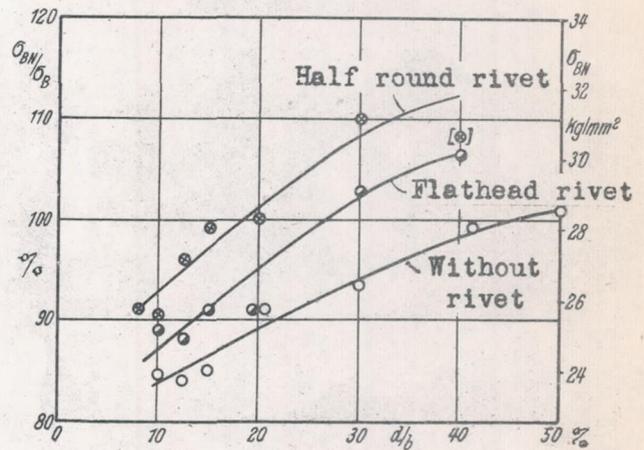


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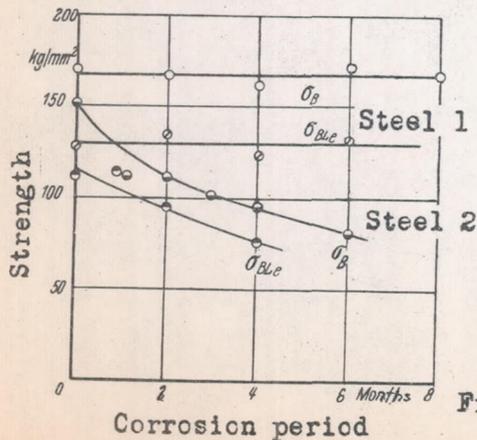


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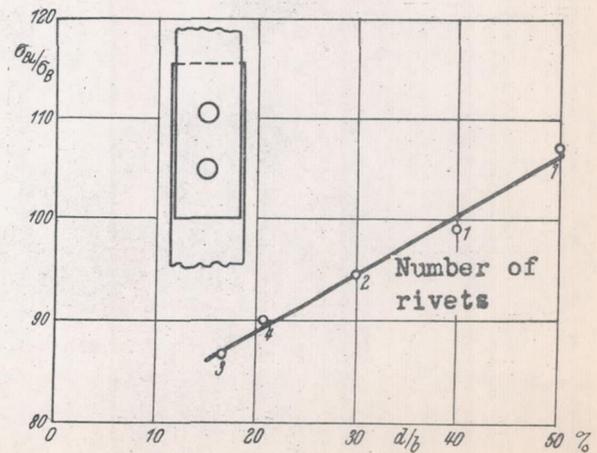


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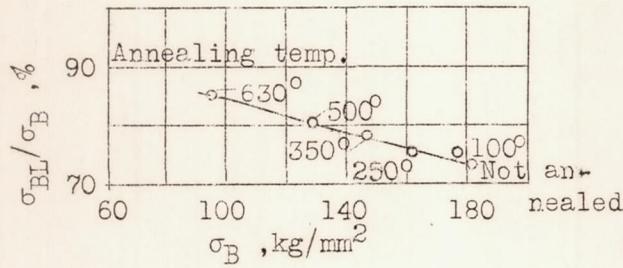


Figure 27.

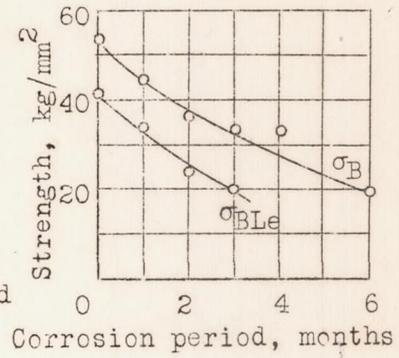


Figure 28.

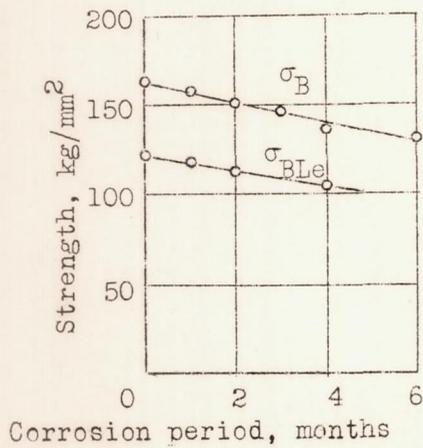


Figure 29

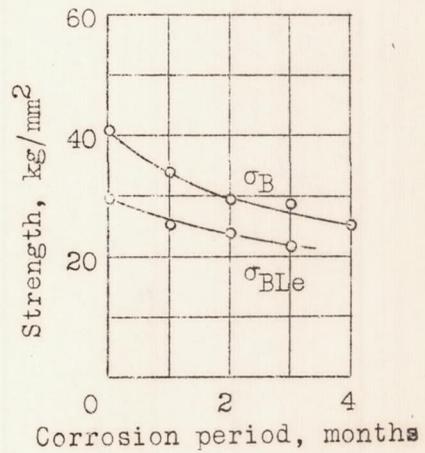


Figure 31.