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No. 597

RIVETING IN METAL AIRPLANE CONSTRUCTION

By Wilhelm Pleines

PART II

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PART II

Riveting Methods and Equipment (concluded)

Strength of Riveted Joints in Duralumin

D. Rivet Inspection and Inspection Equipment

The inspection of riveted joints is simple in all points accessible for hand riveting. In addition, the individual pieces can be inspected from one place so that only the final connections need be inspected by final assembly. At any rate, the inspection of individual parts can be made one by one and at one place, provided the subassemblies are handy for inspection, as the Rohrbach type, for example. Here the saving in inspection personnel is considerable as the types of inspection instruments used and their manipulation are simple and easy.

Defective seating of rivet heads is usually determined by thickness gauges (20 leaf from 0.02 to 0.2 mm thick). Places not visible to the eye are inspected by small mirrors and simple electric lamps. Defects which have to be done over are marked with black varnish which is removed with alcohol solution after the defective spot has been repaired and rechecked. The most common defects are slanted clinching of rivets, imperfect seating, shearing off of rivet head, damage around rivet head, stretching

*"Nietverfahren im Metallflugzeugbau." From Luftfahrtforschung, Vol. VII, No. 1, April 30, pp. 25-43. For Part I, see N.A.C.A. Technical Memorandum No. 596.

of metal strip in the rivet row, as well as all defects common to hand riveting (see Figure 11).

Much discussed is the problem of satisfactory rivet inspection of parts accessible from one side only, which are hard or even impossible to inspect without instruments. This problem is one of the most disputed points and constitutes one of the pet arguments put forth by the foes of inside tube riveting, and in fact against all riveting of parts accessible from one side only.

It has been doubted quite often, by misconstruing the actual facts, that it is at all possible to check and inspect inside tube rivet operations satisfactorily, such as Junkers has applied for a decade or more, although no convincing reasons for this doubt have ever been given. The precautions taken by the Junkers company to this end are so extensive and thorough that doubts in every case are unwarranted. Already the undisputed fact, that defects in riveting never once were due to technical disarrangements, proves the extensive safeguard of the riveting devices and methods by ample inspection.

For inspecting the inside riveting and the rivet heads in tubing a small electric lamp was previously used even for long tubing (6 - 8 m long, 30 - 50 mm diameter). Defects in head shape or driving can be detected quite satisfactorily, although inspection calls for great practice and conscientiousness on the part of the inspector. On the other hand, inspecting by eye alone is very strenuous; the lamp on the inside is blinding, and defective riveting is almost impossible to detect without magnifying the individual spots and reflecting them so as to be seen from the outside. After many experiments the Junkers company, in collaboration with its inspection personnel, succeeded in developing an optical inspection device, which is inexpensive, yet simple to operate. (See Figure 68.)

It consists of an oblique mirror S set in a telescopic tube, and illuminated by two 12-volt lamps. The connection of the cables in the tube is parallel with the bayonet socket through a spring contact.

The most remarkable feature of this instrument is the different arrangement of the light source, set before a plane mirror adjusted to 45°. Figures 69 to 71 show the method of using this instrument and illustrate the image of the rivet in the telescope.

The advantages of this instrument are:

1. Indisputable inspection of all tubular spars from smallest to largest diameter over the entire length as to riveting, and aspect of inside, - defects due to riveting, material defects (blisters, hairline seams, corrosion, etc.).

2. Its shape permits free movement in the spar for inspecting splices, joints, etc.

3. Any practical worker, without special skill, can operate it satisfactorily.

4. All delicate parts of the instrument are recessed to pro-

tect them from possible damage, thus increasing the life of the instrument.

5. The telescope requires no resetting except when lengthening or shortening it.

6. The entire tube width comes into the field of vision.

7. It is inexpensive and all parts are interchangeable.

The instrument is made in three sizes:

Size	I	for	30 - 40 mm	inside	tube	diameter
"	II	"	40 - 60 "	"	"	"
"	III	"	60 - 100 "	"	"	"

Interchangeable for these three sizes are:

1 telescope,

1 constant piece,

1 three-wire cable about 26 ft. long with screw plug,

1 transformer.

Comparative tests made on old and new riveting with this instrument are remarkable in their evidence of improved riveting practice.

The instrument has been recorded under a trade mark. Through subsequent improvements and development, the point has been reached now where one size can be used for all practical tube diameters.

E. Dural and Iron Rivets used in Metal Airplane Construction

Specifications for rivet sizes in metal airplane construction are imperative in order to be able to manufacture the heads of dollies and backing-up tools by pattern (standardization of tools). The head sizes usually prescribed were, aside from purely practical considerations, (headed on rivet machine), the result of the corresponding rivet joints from the strength standpoint (contact surface in thin plates, avoidance of too long rivet shanks, saving in time and labor, etc.).

a) Rivet Head and Closing Head (round)

1. Sizes of closing heads of rivets used by Junkers but furnished heat-treated (by other firms). (Fig. 72.)

Head Shape the Same for Hand or Machine riveting, which means:

d - diameter of rivet body

D - head diameter

h - height of head

r - radius

δ - hole diameter

TABLE II

Sizes of heads for dural rivets (Junkers)

d mm	2.0	2.5	3.0	3.5	4.0	5.0	6.0
r mm	2.4	3.0	3.6	3.5	4.0	5.0	6.0
D mm	4.4	5.5	6.6	6.65	7.6	9.5	11.4
h mm	1.4	1.75	2.1	2.45	2.8	3.5	4.2
δ mm	2.1	2.6	3.2	3.7	4.2	5.2	6.2

For rivets of 3 mm diameter and over:

$$D = 1.9\ d; \quad r = 1.0\ d; \quad h = 0.7\ d; \quad \delta = d + 0.2\ \text{mm}$$

For rivets of less than 3 mm diameter:

$$D = 2.2\ d; \quad r = 1.5\ d; \quad h = 0.5\ d; \quad \delta = d + 0.1\ \text{mm}$$

TANLE III

Size of heads for iron rivets (Junkers)

d	mm	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0
r_1	"	2.0	2.5	3.0	3.5	4.0	4.5	5.0	6.0	7.0	8.0
r_2	"	2.2	2.75	3.3	3.85	4.4	4.95	5.5	6.6	7.7	8.8
h_1	"	1.2	1.5	1.8	2.1	2.4	2.7	3.0	3.6	4.2	4.8
h_2	"	1.0	1.25	1.5	1.75	2.0	2.25	2.5	3.0	3.5	4.0
D	"	3.6	4.5	5.4	6.3	7.2	8.1	9.0	10.8	12.6	14.4
δ	"	2.1	2.6	3.2	3.7	4.2	4.7	5.2	6.2	7.2	8.2

a) For rivet head:

$$D = 1.8\ d; \quad r_1 = 1.0\ d; \quad h_1 = 0.6\ d;$$

b) For second head:

$$D = 1.8\ d; \quad r_2 = 1.1\ d; \quad h_2 = 0.5\ d;$$

c) Or size of both heads like δ as for dural rivets.

2. Rivet sizes (Rohrbach) made in own shops.

TABLE IV

Size of heads for dural rivets (Rohrbach)

d	mm	1.5	2.0	2.5	3.0	4.0	5.0	6.0	8.0	10.0
R	"	2.25	3.0	3.75	4.5	6.0	7.5	9.0	12.0	15.0
r	"	0.75	1.0	1.25	1.5	2.0	2.5	3.0	4.0	5.0
D	"	3.0	4.0	5.0	6.0	8.0	10.0	12.0	16.0	20.0
h	"	0.75	1.0	1.25	1.5	2.0	2.25	3.0	4.0	5.0

Generally:

$$D = 2\ d; \quad r = 0.5\ d;$$

$$R = d + r = 1.5\ d;$$

$$h = 0.5\ d$$

$$\delta = d + 0.1\ \text{mm}$$

$$\text{for} \quad d = 3.0 \text{ to } 6.0\ \text{mm}$$

$$\delta = d + 0.2\ \text{mm}$$

$$\text{for} \quad d = 8.0\ \text{mm}$$

It remains to be explained why different firms use different rivet-head sizes, and whether the question of strength is the cause of the difference in shapes.

3. Sizes of duralumin rivets (Dornier, Figure 74, Table V).

Dimensions given in Figure 74 and in parts list for plain rivets; d to apply about 2 mm from the head. The rivets are made of wire, 0.1 mm less than the rivet diameter.

The rivet heads are the same for all riveting tools.

Foreign countries are also at present working on new standards. The S.A.E. Standards Committee is sponsor for the forms of the rivets which will be considered standard within range of sizes covered up to 11 mm (7/16 in.) body diameter (Fig. 75).

A - flat head	E - truss head
B - round "	F - tinners' rivet
C - countersunk head	G - coopers' rivet
D - pan or oval head	H - belt rivet

4. Rivet head eccentricity.- The gratifying tendencies toward standard rivet sizes have finally made it possible to define the permissible eccentricity of the rivet head with respect to the body of the rivet within definite limits.

The discrepancies in eccentricity in heat-treated rivets are often so pronounced that separation as to quality and rejection is necessary. Too much eccentricity leads to stresses, particularly in machine riveting, which are bound to result in incorrect clinching of the rivets, due to controlled symmetrical guiding of the dolly and bucking-up tool. A perfect fit is impossible unless body and head of the rivet are concentric.

Junkers prescribes a tolerance of less than 5% of the body diameter, with 0.3 mm as maximum (in machine riveting where upper and lower header movements are controlled). Measurements made of rivets in stock and for ordinary use are reproduced in the table, showing their respective rivet-head eccentricity. However, the investigations regarding a detailed explanation of permissible head eccentricities have not yet been concluded.

TABLE V

Duralumin Rivet Dimensions (Dornier)

Rivet diameter (nominal diameter for manufacturer and user)	d	2	2.5	3	3.5	4	5	6	7	8
Driven rivet diameter (hole diameter) decisive for calculation	d_i	2.1	2.6	3.1	3.6	4.1	5.1	6.1	7.1	8.1
R o u n d h e a d										
Rivet head	$D = R = 1.8\ d$	3.6	4.5	5.4	6.3	7.2	9	10.8	12.6	14.4
	$k = r = 0.5\ d$	1	12.5	1.5	1.75	2	2.5	3	3.5	4
	$r_o = 0.05\ d$	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4
Closing head	$D_i = R_i = 1.6\ d$	3.2	4	4.8	5.6	6.4	8	9.6	11.2	12.8
	$k_i = r_i = 0.45\ d$									
F l a t h e a d										
Rivet head = closing head	$D = R = 1.8\ d$	3.6	4.5	5.4	6.3	7.2	9	10.8	12.6	14.4
	$k = 0.275\ d$	0.6	0.7	0.8	1	1.2	1.4	1.7	2	2.3
	$r = 0.125\ d$	0.3	0.3	0.4	0.4	0.5	0.6	0.8	0.9	1
C o u n t e r s u n k										
Rivet head = closing head	$D = 2d$	4	5	6	7	8	10	12	14	16
	k	0.8	1	1.2	1.4	1.6	2	3	3.5	4
	α	105°					90°			

TABLE VI

Rivet head eccentricity

Rivet diameter	Head eccentricity in majority of measured rivets	Some showed eccentricity of:
3	3.3% to body diam. = 0.1 mm	8.4% to body diam. = 0.25 mm
4	3.7% to body diam. = 0.15 mm	8.8% to body diam. = 0.35 mm
5	4% to body diam. = 0.20 mm	8% to body diam. = 0.4 mm
6	5% to body diam. = 0.30 mm	5.8% to body diam. = 0.35 mm

b) Closing Head (Flat head - Junkers riveting)

For flat heads, as used for inside riveting of tubing, the standard sizes corresponding to Figure 76 and Table VII are prescribed.

TABLE VII

Rivet diameter d mm	D mm	D in d	h mm
2.0	3.8	1.90	1.1
2.5	4.6	1.84	1.3
3.0	5.5	1.83	1.6
3.5	5.5	1.57	1.7
4.0	6.0	1.50	2.0
4.5	6.8	1.51	2.2
5.0	7.6	1.52	2.5
6.0	9.2	1.53	2.9
7.0	10.6	1.51	3.5
8.0	12.2	1.52	4.0

h (mm) = height of rivet head
D (mm) = closing head diameter

c) Body Dimensions

1. Body diameter.- To conform with the mode of riveting on the riveting machine, the body of the rivet is slightly conical. (See table for dimensions and size of cone shape.) The tolerance in body diameters is important when deciding on the required hole diameter for drilling, and the diameter at the end of the rivet is likewise of importance because the necessary volume for forming the second head and filling the hole depends on the actually selected raw rivet material.

Ordinarily the hole diameter is drilled 1/10 mm larger than the nominal body diameter of the rivet, which means that this rule applies principally to hand riveting only. Based upon the decisions of all airplane factories, the following list of tolerances was established:

Rivet hole			Screw hole		
For rivet diameter	Hole diameter	Symbol	For screw diameter	Hole diameter	Symbol
2.0 mm	2.1 mm				
2.5 "	2.6 "				
3.0 "	3.1 "	3			
4.0 "	4.1 "	4	4.0 mm	4.2 mm	
5.0 "	5.1 "		5.0 "	5.2 "	
6.0 "	6.1 "		6.0 "	6.2 "	
8.0 "	8.2 "		8.0 "	8.2 "	
			10.0-30.0 mm	screw diam. +0.2 mm	Ø

TABLE VIII

Rivet tolerances (see also Fig. 77)

Hole diameter	Body diameter	Tolerances from +	to −
2.1	2.0	0.03	0.03
2.6	2.5	0.05	0.05
3.1	3.0	0.05	0.06
4.1	4.0	0.05	0.08
5.1	5.0	0.05	0.08
6.1	6.0	0.06	0.10
8.1	8.0	0.08	0.12
10.2	10.0	0.10	0.12

2. Length of body.- which is important for the respective rivet diameter and thickness of the metal sheet. Above all, the calculated sizes for body lengths, as they would result without anything further from the required volume, must not be taken as basis. There is always a certain compression of material connected with the amount of clinching, so that the calculated body lengths, found on a series of rivet experiments, are too small, even when enlarging of the hole diameter during clinching, is avoided. (Sheet iron was used.) The body lengths required for the respective plate thicknesses are computed as follows:

Using Figure 78 as basis, the volume is

$$V_1 = \frac{\pi}{4} a \left(d_1^2 - d_2^2\right)$$

$$V_2 = \frac{\pi}{4} d_2^2 a$$

$$V_3 = \pi h \left(\frac{D^2}{8} + \frac{h^2}{6}\right)$$

$$V_4 = V_1 + V_2 + V_3 = \frac{\pi}{4} d_2^2 s_g$$

We have for whole body length

$$s_g = \frac{4\ V_4}{\pi\ d_2^{\ 2}}\ (\mathrm{mm})$$

and for free body length

$$s_{fr} = (s_g - a)\ (\mathrm{mm})$$

Figure 79 shows the computed necessary rivet body lengths plotted against the rivet thickness for different rivet diameters.

By 1/10 mm larger drill hole in plate thicknesses up to 5 mm, a margin of from 0.2 to 0.5 mm must be added to the computed body length in most cases; for riveting with the Junkers eccentric press, from 1.0 to 2.0 mm must be added to the calculated body length, because the rivet is more thoroughly compressed, and the rivet hole edges yield more on account of the strong pressure - 6000 kg (13,230 lb.).

As a rule the rivets carried in stock with over 10 mm body length, are graded for every 2 mm; not all intermediate sizes are carried, although in the future all lengths in 1 mm sizes are to be furnished according to an agreement with supply firms. Of the experiments to determine the rivet body lengths for machine riveting, we shall speak later. A compilation of rivet weights made by the Rohrbach company is shown in Table IX.

TABLE IX

Dimensions and weight per 100 (in kilograms) of duralumin rivets, according to Rohrbach

Thickness and length	
2.0 x 6 mm = 0.012 kg	5.0 x 10 mm = 0.165 kg
2.0 x 8 " = 0.014 "	5.0 x 12 " = 0.176 "
2.0 x 10 " = 0.016 "	5.0 x 14 " = 0.187 "
2.0 x 12 " = 0.018 "	5.0 x 16 " = 0.198 "
	5.0 x 18 " = 0.210 "
2.5 x 6 " = 0.022 "	5.0 x 20 " = 0.220 "
2.5 x 8 " = 0.024 "	5.0 x 22 " = 0.232 "
2.5 x 10 " = 0.027 "	5.0 x 24 " = 0.242 "
2.5 x 12 " = 0.031 "	5.0 x 26 " = 0.253 "
	5.0 x 28 " = 0.264 "
3.0 x 8 " = 0.039 "	5.0 x 30 " = 0.275 "
3.0 x 10 " = 0.044 "	5.0 x 34 " = 0.296 "
3.0 x 12 " = 0.048 "	5.0 x 40 " = 0.332 "
3.0 x 14 " = 0.051 "	
3.0 x 16 " = 0.056 "	
3.0 x 18 " = 0.060 "	6.0 x 16 " = 0.316 "
3.0 x 20 " = 0.064 "	6.0 x 18 " = 0.333 "
3.0 x 26 " = 0.075 "	6.0 x 20 " = 0.350 "
	6.0 x 24 " = 0.375 "
	6.0 x 28 " = 0.412 "
4.0 x 10 " = 0.092 "	6.0 x 32 " = 0.439 "
4.0 x 12 " = 0.098 "	6.0 x 36 " = 0.470 "
4.0 x 14 " = 0.105 "	6.0 x 40 " = 0.501 "
4.0 x 16 " = 0.113 "	
4.0 x 18 " = 0.120 "	
4.0 x 20 " = 0.127 "	8.0 x 30 " = 0.874 "
4.0 x 22 " = 0.134 "	8.0 x 32 " = 0.902 "
4.0 x 24 " = 0.141 "	8.0 x 34 " = 0.930 "
4.0 x 26 " = 0.148 "	8.0 x 36 " = 0.952 "
4.0 x 30 " = 0.162 "	8.0 x 40 " = 1.014 "

Weight of rivet heads for parts list weights (each 200 rivet heads) = 100 rivets (in kg)

2.0	diam.	= 0.007 kg
2.5	"	= 0.014 "
3.0	"	= 0.024 "
4.0	"	= 0.050 "
5.0	"	= 0.110 "
6.0	"	= 0.190 "
8.0	"	= 0.480 "

F. Method of Treatment and Tensile Strength Specifications for Dural Rivets

The special kind and quality of the rivet material calls for special rules with respect to strength characteristics and method of treatment.

The rivets are stocked annealed, and the stockroom issues daily supplies to the heat-treating crew, which treat just the amount required for one day's use. The most favorable period for using heat-treated rivets is from four to five hours. All rivets left over must be returned to the heat-treaters.

Generally it needs no check in enforcing these rules because the rivets, used after the 5-hour period, become hard to hammer and to head, and mechanical defects (shearing off of head, etc.) are apt to occur in subsequent work. The annealing process requires great care on account of the exact maintenance of the annealing period, which on the average is from 10 to 15 minutes (according to Junkers' rules for heat treating). After delivery of the treated rivets, it is advisable to have the inspection section make some strength tests, such as Rohrbach prescribes, where one or two rivets of each batch is shear-tested. This method is particularly advisable when continuous supervision of the man doing the annealing, is impossible; for example, by automatic pyrometer setting, etc., such as Junkers uses (see Fig. 80, Junkers annealing plant). Of late, Junkers also uses rivets which are annealed at much lower temperature (420°C) than usual (500 to 520°C). But these rivets are used only for emergency repair, where annealing is impossible. A rivet treated at 420°C retains its malleability regardless of the time in stock. These rivets are painted red and therefore called "red rivets." Of course, it remains a question whether these soft rivets (420°C) are as rust-resisting as those treated at 520 to 520°C. It would perhaps be better to give these soft rivets a special shaped head in place of the red paint, because after a coat has been given the whole assembly, it is impossible to tell the softer from the harder rivets.

More detailed rules and regulations on heat treating, aging, furnaces, and baths are given in the 1928 Specifications of the D.V.L.

With the exclusive use of duralumin as structural material in light metal construction, and the prevailing thicknesses of the structural components, the rivets are comparatively thin (1.5 to 8 mm), and 5 to 8 mm rivets are seldom used. One of the greatest differences between riveting in machine construction and riveting in metal airplane construction lies in the entirely different relation of rivet diameter to sheet thickness. The pulled-in rivets do not only fill the rivet holes completely, but even enlarge them when driven too much, so that the danger of damage to the metal strip at the hole edges must always be reckoned with. The rivets are nearly always slightly conical (cone averaging 1.25 : 100) and shape themselves around the head end under pressure on the plate edges. The drilled holes usually have a diameter of from 0.1 to 0.25 mm greater than the nominal body diameter of the rivet. The rivet is driven cold, set with light hammer blows (100 to 500 g hammer weight, depending on rivet size) and headed.

With P_s as the shear by failure, we have

$$P_s = \frac{\pi}{4} d^2 p_s.$$

p_s is usually assumed at 25-28 kg/mm², and the crushing pressure by failure (safety factor = 2) at about 60 kg/mm². Here it should be noted that the nominal rivet diameter is always used. Because the body diameter is considerably compressed while being hammered down, a safe margin is ensured. Riveting of cold-driven rivets is naturally expensive and requires great care. According to Bach, the amount of slippage is of first importance in strength considerations of hot-riveted joints, and shear is second. In cold-riveted joints as used in German metal airplane construction, the strength calculations are based on the shearing strength of the rivet body and also include slight bending stresses (this applies to lap riveting).

G. Dimensions of Heading Tools, Dolly Bars, Riveting Sets, etc.

a) For duralumin rivets.- The rules governing the size of rivet heads apply in most cases to the sizes of the heading tools as well. Tables X to XIII give a descriptive picture of the shape and size of principal heading tools used chiefly for hand riveting. Of course, there are times when the shape of a particular piece calls for a differently shaped heading tool from those shown here, as, for instance, for riveting at the edge of a section, by grinding off one side, or half-round grinding for riveting corrugated strips, etc. The heading tools must be smoothly polished, particularly as used by Rohrbach, while in the Junkers type riveting this is not so carefully enforced because, there it is simply a matter of setting the heading tool on top of the rivet head. Moreover, it is recommended not to make the heading tool exactly like the closing-head tool, or the final closing head shape becomes too high. As a rule the dolly is kept a little lower because there is always some burring left, and the dolly must in no case touch the metal strip. A certain tool steel "Durax W" is generally used. (Heading tools used as dies for riveting machines are described under "Machine Riveting" (See Part I of this article - N.A.C.A. Technical Memorandum No. 596, page 26.)

b) For iron rivets.- Here the same rules apply as for G, a) (above).

TABLE X

Riveting Set (Durax W Tool Steel) (See Fig. 80,a)

d	D	d_1	d_2	t	R	d_3	l
2.	12	2.25	4.25	6	6	7.75	15.2
2.5	12	2.75	5.25	7.5	6	8.75	11.6
3	15	3.25	6.25	9	7.5	9.75	18.7
3.5	15	3.75	7.25	10.5	7.5	10.75	15.2
4	15	4.25	8.25	12.0	7.5	11.75	11.6
4.5	18	4.75	9.25	13.5	9	12.75	18.7
5	18	5.25	10.25	15	9	13.75	15.2
6	20	6.25	12.25	18	10	15.75	15.2

TABLE XI

Heading Tool for Iron Rivets (Durax W Tool Steel)
(See Fig. 80,b)

d	D	R	t	r	d_1	d_2	l
2	12	1	2.2	3.7	4.7	6	7.6
2.5	12	1.25	2.75	4.6	5.6	6	6.1
3	15	1.5	3.3	5.5	6.5	7.5	10.1
3.5	15	1.75	3.85	6.5	7.5	7.5	8
4	15	2	4.4	7.4	8.4	7.5	6.5
4.5	18	2.25	4.95	8.4	9.4	9	10.6
5	18	2.5	5.5	9.2	10.2	9	8.5
6	20	3	6.6	11.1	12.1	10	9.2

TABLE XII

Heading Tool for Dural Rivets
(See Fig. 80,c)

Diameter of body of rivet d mm	Diameter of heading tool D mm	d_1 mm	d_2 mm	Recess for rivet head D mm	Recess for rivet head h mm	Recess for rivet head r mm	R mm	L mm
2	12	5.4	8.28	4.4	1.0	3	6	13.25
2.5	12	6.5	9.38	5.5	1.25	3.75	6	9.3
3	15	7.6	10.48	6.6	1.5	4.5	7.5	16.1
3.5	15	7.65	10.53	6.65	1.75	4.2	7.5	15.96
4	15	8.6	11.48	7.6	2.0	4.8	7.5	12.57
5	18	10.5	13.38	9.5	2.5	6	9	16.5
6	20	12.4	15.28	11.4	3.0	7.2	10	16.85

TABLE XIII

Heading Tool and Dolly for Duralumin and Round-Headed Iron Rivets
(See Figs. 80,d and 80,c)

Duralumin Rivets									Iron Rivets								
Rivet head annealed					Dolly and heading tool alike				Rivet head annealed					Dolly and heading tool alike			
d	D	h	r	L	d	D	h	r	d	D	h	r	L	d	D	h	r
2-3	2.2	0.7	1.2	2-2.5 d+0.1	2-3	2.2	0.5	1.5	2	1.8	0.6	= d	2-2.5 d+0.1	2	1.8	0.5	1.1
3.5-6	1.9	0.7	= d	3-6 d+0.2	3.5-6	1.9	0.5	1.2	8	1.8	0.6	= d	3-6 d+0.2	8	1.8	0.5	1.1
Head Form the Same for Hand and Machine Riveting																	
2	4.4	1.4	2.4	2.1	2	4.4	1.0	3	2	3.6	1.2	2	2.1	2	3.6	1.0	2.2
2.5	5.5	1.75	3	2.6	2.5	5.5	1.25	3.75	2.5	4.5	1.5	2.5	2.6	2.5	4.5	1.25	2.75
3	6.6	2.1	3.6	3.2	3	6.6	1.5	4.5	3	5.4	1.8	3	3.2	3	5.4	1.5	3.3
3.5	6.65	2.45	3.5	3.7	3.5	6.65	1.75	4.2	3.5	6.3	2.1	3.5	3.7	3.5	6.3	1.75	3.85
4	7.6	2.8	4	4.2	4	7.6	2.0	4.8	4	7.2	2.4	4	4.2	4	7.2	2.0	4.4
5	9.5	3.5	5	5.2	5	9.5	2.5	6	4.5	8.1	2.7	4.5	4.7	4.5	8.1	2.25	4.95
6	11.4	4.2	6	6.2	6	11.4	3.0	7.2	5	9	3	5	5.2	5	9	2.5	5.5
									6	10.8	3.6	6	6.2	6	10.8	3.0	6.6

H. Principles and Strength Requirements in Riveted Joints for Light Metal Construction

Aside from welding, riveting is the most important and widely used technical means of making permanent (nondetachable) joints in machine construction. So the question of the strength of a riveted joint plays a prominent role in all branches of machine construction, regardless of the kind of materials used.

In light metal construction, and particularly in airplane construction, riveting is resorted to exclusively. Welding of structural components has not been found satisfactory because of the special kind of light metal used (principally duralumin), so its use has been restricted. Moreover, while in iron construction, particularly iron bridge construction, hot riveting was used, the construction of light metal aircraft is confined to cold riveting, and may be considered as the most perfect and economical method.

The use of cold riveting as such in the construction of metal airplanes (duralumin) was based upon the following reasons:

1. The type of stress in riveted joints on the main structural components of an airplane, such as fuselage and wings, would make cold-riveting appear advantageous. These components are nearly all exposed to high alternating stresses, for which Bach (See C. v. Bach, "Festigkeitslehre," p. 197) claims the hot inserted rivet is inadmissible, because such rivets, after cool-

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six hours, can be safely used again.

3. Cold riveting is preferable to hot riveting on account of the unavoidable temperature effect of hot-driven rivets on other surrounding parts which, if likewise of duralumin, may have under some circumstances a deteriorating effect on the strength characteristics of these components, particularly on those of the entire riveted joint.

Here we point to some hot-riveting experiments of R. Beck, Düren (See Zeitschrift für Metallkunde, 1927, No. 12), made to determine whether the hot-driven rivet remains too soft and therefore has insufficient shear and tensile strength, and whether the heat transmitted by the rivet raises the temperature of the plate in the rivet row so as to lower the strength characteristics. These experiments were made with 22 mm duralumin rivets (alloy 681a). The rivets were heated for about twenty minutes in the salt-bath heater at 500-520°C. Any salt adhering to the rivet was knocked off. Immediately after hammering the rivet - clinching and head-forming were quickly accomplished with hot rivets - rivet and plate were plunged in cold water. After aging 5 days, the rivet was sawed in two and the Brinell hardness determined. The results showed slight hardness discrepancies in the hot- and cold-hammered rivets, that is, less hardness and greater spread at the rivet heads and splices of the hot-driven rivets. The obtained values proved that hot-riveting, although possible, depends to a much greater extent on the reliability and skill of the worker (exact temperature and immediate dousing with water) than cold riveting. From the figures of the obtained Brinell hardness it was concluded that the hot rivet, inserted at 500-520°C in the rivet hole has no detrimental effect on the metal plate.

Accordingly, the mass of the rivet was too small to transmit any detrimental heat to the strip. Nevertheless, Beck insists always with respect to the annealing, not to omit the cooling. A really enlightening explanation, however, is to be obtained only by very exhaustive strength experiments. We might also mention that Beck's assertion that the rivet inserted at about 500°C has no detrimental effect on the plate or the adjacent rivets, agrees with Bohner and Westlimming's* experiments only under certain conditions. According to these tests it concurs in all probability for individual rivets, but not for rows of rivets. Upon comparing these two experiments as to amount of hardness of adjacent, hot-inserted dural rivets, it was found that a reduction in hardness, due to the increased heat emission by increasing the number of rivets occurs in the riveting material as well as in the sheet metal strips.

In consequence the principal advantages of cold-riveting in light metal construction, with dural as material, may be summed up as follows:

a) Riveting can be done at ordinary temperatures;

b) Satisfactory malleability of the rivets due to the advantages of annealing without lowering the strength character-

*Bohner and Westlimming, "Riveting of Heat-Treated Aluminum Alloys." Zeitschrift für Flugtechnik und Motorluftschiffahrt, June, 1928, No. 6.

istics;

c) Considerably higher strength and reliability in the riveted joints in contrast to hot riveting (See paragraph 3, page 23);

d) Repeated usefulness of rivets not used within specific time, by second annealing, without detrimental effect on the existing qualities of the material.

Disadvantages: The trend in recent shop technique toward standardizing the working processes and cutting down the individual work periods may result in a disadvantage, in so far as it concerns an increase in demands made thereby on continuous heat treatment of rivets and the careful supervision of all processes connected with it. In this connection, it is again referred to the thorough and consequently remarkable supervision carried on in all leading German metal airplane factories.

The rivets reach the stock-room heat-treated. The stock-room in turn issues, daily or weekly, as the case may be, a definite number of rivets to the annealing room, where the amount likely to be needed for one day is annealed and turned over to the receiving section, whose province it is to see that only annealed rivets are used. All such rivets not actually used within the prescribed period of four to six hours, must be returned.

In a well running shop, supervision of these rules is unnecessary, due to the fact that the rivets are hard to drive, and any hardened rivet can easily cause mechanical defects. Of course, handling of the rivets while annealing calls for strict attention, the annealing process taking from 10 to 15 minutes, varying with the rivets, which are from 2 to 6 mm. To assure exact temperature and correct timing in annealing, clocks or automatic pyrometers are used. Lacking these, it is advisable to make strength tests.

Strength of Dural Rivets and Dural Strips

Before going into detail on the strength of dural rivet joints, we shall make some statements regarding the general strength requirements of the structural material and structural components where riveting is used.

In contrast to a flat bar without holes and evenly loaded at both ends by force P (Fig. 81), which in its cross section undergoes (aside from that near the restraint) an evenly distributed stress σ, we take two metal strips held together by a rivet (Fig. 82,a), where the stress in one flat strip is transmitted by means of the rivet to the second flat strip like a bolted joint. While, remote from the rivet, the stress due to force P is nearly uniformly divided as tension along section a-a, we have in cross section b-b, a basically different load distribution for flat bar and rivet, which is

α) The rivet cross section in its symmetrical plane (b-b) - ignoring in first approximation a bending stress in the body of the rivet due to moment P s, as it actually occurs in single-shear lap rivet joints - is loaded in shear, hence stressed in shear (Fig. 82,b). In a single rivet, single-shear joint, the force P now is taken up by the cross section of the loaded rivet according to equation

$$P = \frac{\pi}{4} d^2 \sigma_S$$

where

P (kg) denotes the shear,

d (mm) the body diameter of the rivet, and

σ_S (kg/mm²) the shearing strength of the rivet material.

Accordingly, we have for a multi-rivet, single-shear joint,

$$P = i \frac{\pi}{4} d^2 \sigma_S$$

where i represents the number of rivets, and for a multi-rivet, double-shear joint,

$$P = 2 i \frac{\pi}{4} d^2 \sigma_S \qquad (1a)$$

β) Assuming frictionless riveted joints, the total stress in the rivet plate in section b-b comprises the following individual stresses;

β_1) Section (s d) of the rivet plate on the side of the hole below the rivet body is under compression, hence under crushing pressure (Fig. 83).

In a single rivet, single shear riveted joint in consequence the stress P acting on the face of the hole is taken up by the cross section of the shaded sides of the hole in the projection according to equation

$$P = d\ s\ \sigma_L \qquad (2)$$

where

P (kg), the crushing pressure,

d (mm), the diameter of the body of the rivet,

s (mm), thickness of plate,

σ_L (kg/mm²), crushing strength of plate.

Hereby it should also be noted that the crushing strength is always contingent on the edge distance e, because:

The cross section of the plate, in addition to stress P, is subjected to a stress in shear in section (s e) (Fig. 84), for which equation (3) is valid:

$$P = 2\ e\ s\ \sigma_S' = \frac{\pi}{4}\ d^2\ \sigma_S \qquad (3)$$

with e (mm), distance from edge, and

σ_S'(kg/mm²), shearing strength of the plate.

Now in machine construction, we generally write $\sigma_S' = 0.8 \times \sigma_S$ and, instead of $(e + d/2)$, we base the calculation on distance e.

β_2) The cross section of the model plate in b-b is, moreover stressed in tension in the direction of force P. (Fig. 85). Ordinarily we now assume that the tension stresses in this section, weakened by the rivet hole, are uniformly distributed over the cross section - assuming that the safe tension remains far enough below the yield limit, just as the safe crushing pressure remains below the crushing strength, for only then are equally high degrees of safety* valid for all individual structural components. The equation reads

$$P = (b - d)\ s\ \sigma_Z \tag{4}$$

where

b (mm), width of plate,

σ_Z (kg/mm²), tensile strength of plate

and by arrangement of several rivets

$$P = (b - i\ d)\ s\ \sigma_Z \tag{4a}$$

with

i = number of rivets.

*Weidmann bases the validity of a lower safety factor for the permissible crushing pressure than for the tension plate on the following: 1) the stress, in contrast to the free plate loaded over its whole cross section, is here distributed over a comparatively small portion of it; 2) the crushing or crumpling of the sides of the hole upon reaching or after exceeding the crushing strength is small and locally confined, and spreads only a little within the structural material; 3) this crushing produces a certain material hardening at the hole edge, while in the free plate it spreads over the entire cross section and for a considerable length. (See Erwiderung Weidmann, Die Bautechnik, No. 7, February 17, 1928.)

According to previous experiments, it is not to be assumed that the stress distribution over the cross section weakened by the rivet hole, is uniform within the entire range of deformation. For instance, according to Preuss' experiments (Zeitschrift des Vereines deutscher Ingenieure, 1912, p. 1780, etc.) on stress distribution of uniformly stressed-in-tension iron bars of the same width and different hole diameters, he found, for the cross section most weakened by the hole within the elastic range of deformation, that the maximum stress σ_{max} at the edge of the hole reaches 2.1 to 2.3 times the value of mean stress σ by assumed uniform stress distribution over this section.

An approximate picture of the stress distribution is seen in Figure 86. It was, moreover, ascertained that the effect of the hole diameter is practically nil as far as this distribution is concerned. The stress and the stress distribution of the rivet plate in section b-b is in our case much more complicated, but at any rate there is the possibility that the distribution in this cross section is perhaps wholly similar.

Bleich, like Preuss, after mathematical calculations on stress distribution in riveted joints*, came to the conclusion that the dimensions should be such that the calculated hole edge stresses do not exceed the elastic limit. According to his calculations the values for σ_{max} were four to five times greater than σ.

*Bleich, "Theory and Calculation of Iron Bridges," page 260.

Now the conditions are not quite as simple in a material such as duralumin; the requirement, after exceeding the elastic limit cannot be so quickly complied with because there is no expressed yield and proportionality limit. In soft iron, for example, the stress-strain curve shows a wholly different aspect for a certain stress and at a certain point, either by a drop or jump in the curve, so that the stress at that particular point can be designated as "yield" or "flow" limit. According to the standardized "Form 1602, Material Testing," the "yield" or "flow" limit is always the stress at which the testing machine indicator stops registering or goes back, even though the length changes in the test specimen continue.

The stress-strain curve shows directly that, upon reaching the respective strength, the curve of the deformations has a clearly defined bend or jump, or in other words, above this point the deformations increase more rapidly and are more irregular.

Conditions are different with duralumin which, like all aluminum alloys and nonferrous metals, does not show any expressed elasticity even under minimum loads and stresses. For that reason it was decided to take as limit of safe stress that limit at which the form changes assume a certain amount. So, for instance, we speak of a "0.2 limit," which means that stress at which the permanent elongation is 2% of the measured length, and of a "0.02 limit," as the "elastic limit" which is the strain where a permanent elongation of 0.02% of the measured length remains. However, it should be remembered that these figures are arbitrarily agreed upon and do not wholly interpret the correct meaning of elastic limit of soft iron, for example, because this definition presupposes that the respective material roughly follows Hooke's Law. This, however, is not the case in duralumin. More than in any other material the 0.2% or 0.02% limit is not a constant characterizing its actual character. It simply represents a temporary load figure, i.e., a value for the continuously more-or-less pronounced curvature of the stress-strain curve.

One general requirement in machine construction is that, exceeding the elastic limit of any structural component, while in operation, is prohibited. This requirement alone can undoubtedly never be complied with in light metal airplane construction. P. Brenner* points to the generally accepted and recognized fact that this request is, as a whole, impossible to accede to, because the elastic limit, particularly of light metal, is comparatively lower and its acceptance as safe limit would in many cases lead to too heavy structures. Then inasmuch as the operating conditions assumed in the strength calculation of airplanes hardly occur in normal operation, and merely distinguish the extreme and most unfavorable conditions, Brenner holds it to be justified in allowing a slightly higher stress between the 0.02, and the 0.2 limit. Farther on, Brenner writes: "Any at-

*P. Brenner, "Lautal as Structural Material for Airplanes," Luftfahrtforschung, Vol. I, No. 2.)

tempt to definitely place this safe limit at present, is premature, because of our lack of accurate data on the magnitude and kinds of stresses occurring in flight, and our insufficient research on the behavior of the structural materials under such stresses. But it may be stipulated that the yield limit should not be exceeded in operation, else we would invite form changes which might endanger the safety and reliability of an airplane structure."

But far more complicated and debated were these questions of deformations at the inauguration of the strength specifications for riveted joints.

With respect to strength in riveted joints in metal airplane construction, particularly duralumin, the question remains the same as for riveting iron metal joints: Are permanent deformations of the whole riveted joint and local deformations admissible or not? Schaechterle, in summarizing the results of extensive tests in iron bridge construction, stated that local deformations would have to be taken into the bargain (this applies particularly to hot riveting) if riveting was to gain a foothold. The same applies to duralumin in airplane construction, although a perfect fit of the rivets is generally obtained by cold riveting. The size of these deformations is left for future tests, to which we shall refer again.

In the following we give various strength factors used in German metal airplane construction with duralumin as material.

1. The ultimate shearing strength of rivets is expressed as

$$\sigma_{S\ Br} = 24 \text{ to } 26 \text{ kg/mm}^2$$

and the shear at failure as

$$P_{Br} = \frac{\pi}{4}\, d^2\, \sigma_{S\ Br} = (18.85 \text{ to } 20.4)\, d^2 \text{ (kg)}$$

Assuming a mean ultimate shearing strength $\sigma_{S\ Br}$ of 25.0 kg/mm², P becomes

$$\boxed{P_{Br} = (i)\,\frac{\pi}{4}\, d^2\, 25 = (i)\ 19.64\, d^2 \text{ (kg)}}$$

i = number of rivets.

Table XIV shows the safe shear at failure computed for different rivets. These values for shear P were computed with the nominal diameter of the rivets as basis. The increase in body diameter, due to clinching and filling of the rivet hole, which usually is 0.1 to 0.25 mm larger in diameter, yields a margin of safety for the strength of rivet joints, which is not further considered in the calculation.

According to another rivet table used in metal airplane construction, the shear P is found for different rivet diameters (Table XV). The ultimate shearing strength of the rivets is given as $\sigma_{S\ Br} = 19$ to 25 kg/mm².

TABLE XIV

Shearing Strength at Failure for Different Rivets

Rivet diameter d mm	2.0	2.5	3.0	4.0	5.0
Rivet cross section $\left(\frac{\pi}{4}\ d^2\right)$ mm²	3.1416	4.9087	7.0686	12.5664	19.6450
Shear at failure P_{Br} single shear kg	78.5	113.0	177.0	314.0	490
Shear at failure P_{Br} double shear kg	157.0	226.0	354.0	628.0	980

TABLE XIV (cont.)

Rivet diameter d mm	6.0	8.0	9.0	10.0
Rivet cross section $\left(\frac{\pi}{4}\ d^2\right)$ mm²	28.2743	50.2655	63.6173	78.5398
Shear at failure P_{Br} single shear kg	707	1257	1390	1963
Shear at failure P_{Br} double shear kg	1414	2514	3180	3926

TABLE XV

Shear at Failure for Different Rivets

Rivet diameter d mm	2.0	2.5	3.0	4.0	5.0	6.0	8.0
Shear at failure P_{Br} single shear kg	80	110	160	270	400	570	950
Shear at failure P_{Br} double shear kg	160	220	320	540	800	1140	1900

That is, decreasing as the size of the rivet increases, as shown in Table XVI, and Figure 87.

TABLE XVI

Ultimate Shearing Strength of Different Size Rivets

Nominal diameter d mm	2.0	2.5	3.0	4.0	5.0	6.0	8.0
$\sigma_{S\ Br}$ kg/mm²	25.5	22.5	22.5	21.5	20.4	20.2	18.9

Taking into account the changes in shearing strength, Table XVII shows for shear P the following:

TABLE XVII

Ultimate Strength in Shear Depending on Rivet Diameter

Rivet diameter d mm		2.0	2.5	3.0	4.0	5.0	6.0	8.0
Shear at failure P_{Br}	single shear kg d²	20	17.6	17.7	17	16	15.8	14.8
	double shear kg d²	40	35.2	35.4	34	32	31.6	29.6

The selection of lower shearing strength values by increasing rivet diameter may be based on the fact that, by increasing the rivet diameter the relation of cross-sectional areas of driven to plain rivets becomes smaller when - as is mostly the case - the rivet hole is drilled 0.1 mm larger than the described rivet diameter. As a result the body cross section resulting from clinching becomes smaller with respect to the nominal cross section (from 1.1 at 2 mm rivet diameter, to 1.04 for 5 mm rivet diameter). The safety margin is lowered.

This decrease in shearing strength values by increasing the rivet diameter can also be based upon the lesser malleability of the rivet as its diameter increases.

Figure 88 shows the shear at failure P for single and double shear riveted joints plotted against the rivet diameter, i.e., for ultimate shearing strength $\sigma_{S\ Br}$ = 25 kg/mm² = constant, and $\sigma_{S\ Br}$ = 19 to 25 kg/mm² (variable).

2. The crushing strength for a duralumin plate is usually expressed as (with $\sigma_{L\ Br}$ = 60 kg/mm² for ultimate crushing pressure)

$$P_{Br} = s\ d\ \sigma_{L\ Br}$$

where s (mm) = plate thickness, d (mm) = hole diameter. Now the crushing pressure at failure reads as

$$\boxed{P_{Br} = 60\ s\ d\ (kg)}$$

By equally good use of a riveted joint as to crushing and shear at failure, we have

$$P_{Br} = s\ d\ \sigma_{L\ Br} = \frac{\pi}{4}\ d^2\ \sigma_{S\ Br}$$

Given the rivet diameter and a rivet hole equal to the rivet diameter, we have for single shear rivet joints

$$P_{Br} = 60\ s\ d = 19.6\ d^2\ (kg)$$

α) when $\sigma_{L\ Br}$ = 60 kg/mm²

and $\sigma_{S\ Br}$ = 25 kg/mm²

Then the minimum plate thickness s for different hole diameters d becomes

$$\boxed{s = \frac{19.6\ d}{60} \geqq 0.325\ d\ (mm)}$$

β) When $\sigma_L = 60$ kg/mm², and $\sigma_g = 19$ to 25 kg/mm², different for different rivet diameters, according to Table XVI, the equation for the minimum plate thickness s for different rivet diameters reads:

$$\boxed{s \geqq \frac{(20.0 \text{ to } 14.8)\ d}{60}\ (\text{mm})}$$

Table XVIII shows the minimum plate thicknesses for different rivet diameters and the respectively different σ_g values.

TABLE XVIII

Minimum Plate Thickness for Different Rivet Diameters and Shear Values

Rivet diameter d mm	2.0	2.5	3.0	4.0	5.0	6.0	8.0
Shear at failure P single shear kg d^2	20	17.6	17.7	17	16	15.8	14.8
Minimum plate thickness s mm d	0.333	0.293	0.295	0.283	0.266	0.263	0.247

If, as is common practice, the diameter of the rivet hole is larger than that of the rivet, the hole diameter is used for computing the plate thickness s. If s is known and it is desired to find the respective rivet diameter, we have

$$\boxed{d = \frac{60\ s}{19.6} \leqq 3.0\ s\ (\text{mm})}$$

α) when $\sigma_{L\ Br} = 60$ kg/mm², and $\sigma_{g\ Br} = 25$ kg/mm² for the required rivet diameter by given plate thickness s, and

$$\boxed{d \leqq \frac{60\ s}{20.0 \text{ to } 14.8}\ (\text{mm})}$$

β) when $\sigma_{L\ Br} = 60\ kg/mm^2$, and $\sigma_{S\ Br} = 19$ to $25\ kg/mm^2$ for different rivet diameter (variable) according to Table XVI.

The required rivet diameters d conjugated to the different plate thicknesses s are compiled in Table XIX.

TABLE XIX

Different Plate Thicknesses and Respective Rivet Diameters According to Shear Values of Table XVI

Diameter of rivet hole d = mm	2.0	2.5	3.0	4.0	5.0	6.0	8.0
Shear at failure P_{Br} single shear kg d^2	20	17.6	17.7	17.0	16.0	15.8	14.8
Rivet diameter $\frac{d}{s}$ ≤ mm	3.0	3.41	3.39	3.53	3.75	3.8	4.0

TABLE XX

Shear and Crushing Pressure at Failure for Different Rivet Diameters and Plate Thicknesses

Rivet diameter		2.0 mm	2.5 mm	3.0 mm	4.0 mm	5.0 mm	6.0 mm	8.0 mm
Shearing strength $\sigma_{S\ Br}$ = 19 to 25 kg/mm² — At failure	P_{Br} single shear kg	80	110	160	270	400	570	950
	P_{Br} double shear kg	160	220	320	540	800	1140	1900
Shearing strength $\sigma_{S\ Br}$ = 25 kg/mm² — At failure	P_{Br} single shear kg	78.5	113	177	314	490	707	1257
	P_{Br} double shear kg	157.0	226	354	628	980	1414	2514
Crushing pressure P_{Br}, at failure (in kg) for $\sigma_{L\ Br}$ = 60 kg/mm² by a sheet thickness s (mm) of:	0.2	24	30	36	48	60	72	96
	0.3	36	45	54	72	90	108	144
	0.4	48	60	72	96	120	144	192
	0.5	60	75	90	120	150	180	240
	0.6	72	90	108	144	180	216	288
	0.7	84	105	124	168	210	252	336
	0.8	96	120	144	192	240	288	384
	0.9	108	135	162	216	270	324	432
	1.0	120	150	180	240	300	360	480
	1.2	144	180	216	288	360	432	576
	1.4	168	210	252	336	420	504	672
	1.6	192	240	288	384	480	576	768
	1.8	216	270	324	432	540	648	864
	2.0	240	300	360	480	600	720	960
	2.4	288	360	432	576	720	864	1152
	2.8	336	420	504	672	840	1008	1344
	3.2	384	480	576	768	960	1152	1536
	3.4	408	510	612	816	1020	1224	1632
	3.6	432	540	648	864	1080	1296	1728
	3.8	456	570	684	912	1140	1368	1824
	4.0						1440	1920
	4.2							2016
	4.4							2112
	4.6							2208
	4.8							2304
	5.0							2400
	5.2							2496

Figure 88 shows the P values plotted against plate thickness s for $\sigma_{L\ Br} = 60\ kg/mm^2$, and for different rivet diameters, or better, rivet hole diameters d. It also shows the respective diameter d and plate thickness s for the best riveted joint. Table XX is a compilation of the crushing and shear at failure for various rivets and plate thicknesses.

In computing the shear values $\sigma_{S\ Br} = 25\ kg/mm^2$ is used if the size of the rivets is the same, or $\sigma_{S\ Br} = 19$ to $25\ kg/mm^2$ if the size of the rivets increases from d = 2.0 to 8.0 mm diameter. The respective minimum plate thicknesses s ascribed to the P values are marked by the heavy blank line.

Tests on riveted joints of duralumin plate have also been made in other countries, and particularly in the United States by the Department of Mechanical Engineering of the Massachusetts Institute of Technology. From the data by H. F. Rettew and C. Thumin: "Tests on Riveted Joints in Sheet Duralumin," published as N.A.C.A. Technical Note No. 165, 1923, we abstract the following: The experiments consisted of twenty-six tension tests on various forms of single-riveted lap-joints. Three thicknesses of duralumin sheet were used: 0.5 mm (.020 in.), heat-treated; 1.0 mm (.040 in.) heat-treated; and 2.4 mm (.095 in.) annealed. While making the tests the slippage of the joints was measured at three points across each joint. In addition, stress-strain curves were plotted for plain (unriveted) tension specimens, and a chemical analysis was made of the metal sheet, although the rivets were not analyzed. The rivet material was annealed duralumin wire; the heads were swelled before riveting.

The test of the used material in tension has been compiled in Table XXI.

TABLE XXI

Tensile Tests of Rivet Plate, According to Rettew and Thumin

		Heat-treated		Annealed
Plate thickness s	mm	0.50	1.00	2.40
Elongation (203.2 mm = 8 in.)	%	12.67	19.53	12.55
Elongation (50.8 " = 2 ")	%	14.83	24.25	17.75
Yield point σ_{st}	kg/mm²	19.50	18.40	9.70
Tensile strength σ_B	kg/mm²	39.80	39.80	22.30
Modulus of elasticity E	kg/cm²	795200	787500	686900
Reduction of area ψ	%	15.33	19.97	34.48
Ratio of yield point to tensile strength $\frac{\sigma_{st}}{\sigma_B}100$	%	49.10	45.60	43.70

TABLE XXII

Comparison of Tensile Strength Values of Riveted Joints with Commercial Material and According to Rettew and Thumin

	Commercial values	Values from Rettew & Thumin	
		Computed	Suggested for design of joints
Tearing σ_Z kg/mm²	39.0	38.0	35.0
Crushing σ_L kg/mm²	32.0	74.4	70.0
Shear σ_S kg/mm²	18.0	28.0	28.0

The most surprising results of these tests were the unusually high σ_L and σ_S values for rivets and plates, which far exceed the basic tensile strength figures and are attributable in part to the friction of the riveted plates and reinforcement of the rivet heads. In Table XXII we show the obtained strength values compared to the ordinary test values, along with the recommended strength values for future calculations. The recommendations made by Rettew and Thumin are tabulated below and plotted in Figure 89.

Table for Tearing and Shear by Failure of Riveted Joints in Duralumin Sheet (according to Rettew and Thumin).

English Rivet Strength Values

K_Z = 3500 kg/cm³
K_L = 7000 "
K_S = 2800 "
d = rivet diameter (mm)
s = plate thickness (mm)
t_N = pitch
P_S = failure by shearing (single shear) = 22.0 d^2 (kg)
(double ") = 44.0 d^2 "

P_L crushing = 70.0 d s (kg)
P_Z tearing = 35.0 s (t_N - d) (kg)
Critical rivet diameter (single shear) d_K = 3.2 s (cm)
(double ") d_K = 1.6 s (")
Critical pitch (single row) t_K = 3 d (cm)
(double ") t_K = 5 d "
(triple ") t_K = 7 d "
Lap = (2.5 to 3.0)d (cm)
Distance between rows (staggered) = (1.0 to 1.5) t (cm)

The strength values appearing in Figure 89 are based upon the following equations.

a) Shear by failure:

$$P = \frac{\pi}{4} d^2 \sigma_S = 22\ d^2 \text{ (single shear) (kg)}$$

$$P = \frac{\pi}{2} d^2 \sigma_S = 44\ d^2 \text{ (double shear) (kg)}$$

b) Crushing by failure of rivet plates:

$$P = s\ d\ \sigma_L = 70\ s\ d \text{ (kg)}$$

c) Critical rivet diameter:

$$P = (b - d)\ s\ \sigma_Z = 35\ s\ (b - d) \text{ (single riveting) (kg)}$$

$$P = (b - i\ d)\ s\ \sigma_Z = 35\ s\ (b - i\ d) \text{ (multi-riveting) (kg)}$$

where

d (mm) = driven diameter of rivet,

s (mm) = thickness of plate,

b (mm) = plate width,

i = number of rivets.

In reading the chart one usually starts with the plate thickness s and finds the intersection with one or the other of the shear curves P for this s, depending on whether it is a single or double shear riveted joint. This intersection point gives the critical rivet diameter. As a rule the somewhat larger (preferably) nearest available rivet diameter is chosen and the shearing strength P is read on the scale of the ordinates. If the chosen rivet diameter is above the critical figure, the ordinate of the plate thickness line is used; if below the critical figure, the ordinate of the shear parabola is chosen. To find the pitch, read down from the chosen diameter and take the nearest convenient pitch, but larger than that given by the graph, for reasons of safety. (See example in Fig. 88)

The critical rivet diameter, according to Rettew and Thumin, is:

$$d = 3.2\ s \quad (\text{for single shear rivets})$$
$$d = 1.6\ s \quad (\text{" double " "})$$

and the critical pitch:

$$t = 3\ d \quad (\text{for single riveting})$$
$$t = 5\ d \quad (\text{" double "})$$
$$t = 7\ d \quad (\text{" triple "})$$

It is good practice to have the lap from 2.5 to 3.0 d and the distance between rows in double riveting (staggered), from 1.0 to 1.5 t.

All of the tension failures in the riveted joints and in the plain (not riveted) specimens occurred as shear along a 45° angle. The crushing failures appeared to be crushing of the plate edges and not of the rivets, although the heat-treated plate has the higher theoretical strength of the two. The shear failures were instantaneous while the distortion which preceded a failure by crushing or tearing was gradual.

One noteworthy result of the tests for slippage of the rivet joints is that in nearly every case a redistribution of load takes place at the lower stresses; in general, the slippage is small and unimportant.

However, the American tests were made with the driven diameter of the rivet as basis, while in general it is customary to apply it to the nominal diameter, i.e., the plain (not driven) rivet without considering the resulting clinching owing to the slightly larger hole diameter. It must therefore be expressed as unusual if the American tests use the driven diameter of the rivet as basis. Aside from the fact that the quality of clinching always hinges on contingencies, as well as on the dexterity of the worker, such method renders comparison with the usual strength figures unfeasible for the reason that the rivet holes, due to too much clinching, quite often have enlarged nominal diameters, a fact which surely is not conducive to increased strength in riveted joints. In a later section we shall refer to this again.

I. Tests to Determine the Crushing Strength of Riveted Joints in Duralumin

Object of tests.- It is common practice to define the crushing strength of plates on riveted joints, and then to determine the crushing strength from the amount of mutual slippage and deformations of the plates and butt straps. This method is used very successfully in iron bridge construction, where hot riveting is used, and which recently was made the object of a series of tests to determine the safe crushing pressure on riveted joints.* Here the crushing strength denotes that crushing pressure per cm² (in kilograms) at which the bearing capacity of the sides of the holes becomes exhausted.

By the large sizes of riveting joints used for iron and steel, with 12 mm plate thickness, 18 mm butt straps, and 23 mm rivet diameter, it was possible to note the limit of the safe crushing strength from the distinct bend in the curves. In these tests the curvature was measured and plotted against the crushing pressure as ordinate, with

$$\alpha = \frac{\text{crushing strength } \sigma_L^2}{\text{safe strength } \sigma_{zul.}(\text{safe})}^{**} \text{ as ordinate.}$$

This bend in the curve says that the deformations are accelerated and more erratic as soon as a certain stress is reached. In Figure 90a, where we reproduced several of these test data in graphs, the respective bends are readily apparent. The points in three test plates, each from a different test laboratory, were combined for one common average, because the individual figures checked very closely.

*Weidmann, "Versuche über den zulässigen Lochleibungsdruck an Nietverbindungen." Die Bautechnik, No. 46, Oct. 21, 1927.
**For example, for steel 48: $\sigma_{zul} = 1820$ kg/cm² ($\sigma_B = \sim 5340$ kg/cm²) $\sigma_{str} = 3380$ kg/cm². For steel 37: $\sigma_{zul} = 1400$ kg/cm² ($\sigma_B = \sim 3760$ kg/cm²) $\sigma_{str} = 2420$ kg/cm².

The crushing strength and the safe crushing pressure were determined in two different laboratories and by a second method of measurement. The plate elongations δ were measured with Martens' optical instrument over a distance equal to rivet distance s plus a distance x, with x as width of plate b (Fig. 90c). The lines showing the δ values (Fig. 90b) plotted against the above relation α as ordinate, show a close agreement with the curves for the curvature measurements and the bend in the curve, which at the same time characterizes the safe crushing pressure, is at about the same height as that of the curvature measurements.

These tests, made in three different laboratories, proved that the safe crushing strength $\sigma_L = 2.5\ \sigma_{safe}$, as specified for German railroads, is justified for the reason that the crushing strength lies at decidedly higher σ_L values of 3.0 to 4.0 σ_{safe}.

Now in the construction of light-metal airplanes the rivets are handled cold. Through more or less heavy clinching the body of the rivets fits closely to the sides of the holes. Quite frequently the sides are subjected to such enormous pressures - if too much clinching pressure is used - that the holes become larger before the riveting is completed. This fact was established by measuring the rivet diameter and the hole diameter directly after clinching. The rivets are hand-driven, as usual, by an experienced riveter shortly after heat-treating, and then inspected with the normal shop microscope. The results, tabulated in Table XXIII, obviously show the enlargements in rivet body and hole diameter.

TABLE XXIII

Rivet Diameter and Hole Diameter before and after Clinching

Before clinching		After clinching		Enlargement of	
Nominal rivet diameter d_N mm	Hole diameter d_L mm	Rivet diameter d_N mm	Hole diameter d_L mm	d_N %	d_L %
2.00	2.10	2.42	2.42	21.0	15.2
2.50	2.60	2.84	2.84	13.5	9.3
3.00	3.10	3.55	3.55	18.5	14.5
4.00	4.10	4.33	4.33	8.5	5.6
5.00	5.10	5.40	5.40	8.0	6.0

The occurrence of such hole enlargement falsifies the interpretation of the test data, when the cross section of the plain rivet body and the original size of the drilled hole is the basis for calculating the specific stresses.

The test results, for instance, of riveted joints of duralumin, with respect to safe crushing strength as compared to other joints - say, bolted joints, which merely serve to test the crushing strength - are erroneous for various reasons. They are principally due to

1. Different size enlargement of holes, caused by too heavy clinching, and which is hard to determine;
2. Slippage;
3. Reduced plate thickness underneath the rivet head caused by tightening of rivet, particularly in thin plates;

4. Poor fit of plates with resultant less effectiveness against slippage, particularly in large rivets;

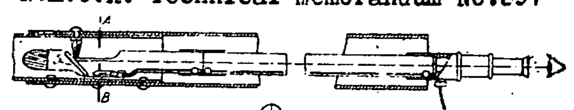
5. Possible bulging of sides of hole and surrounding plate, prior to reaching crushing pressure;

6. Variation in crushing pressure at the different plate hole edges, due to plastic deformation of rivet body.

(The relation between depression of the rivet or rivet body on the sides of the hole and the pressure ensuing upon exceeding the elastic limit, are factors about which we know very little.)

For these reasons and with the object of clearing up the effects of some of the factors mentioned above, it was intended to make some tests on bolted and on riveted joints. In the following Memorandum (No. 598, Part III) we begin with tests on simple bolted joints to determine the pure crushing strength by failure for duralumin plates of different thicknesses s, and different edge distances e, perpendicular, and r, parallel to the direction of tension.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.



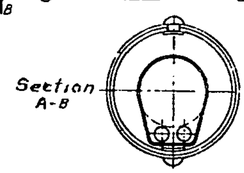


Fig.68 Optical rivet inspection device,(Junkers type).

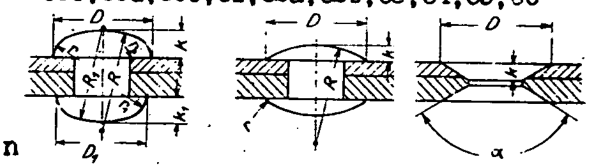


Fig.74 Rivet head,(Dornier)

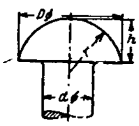


Fig.72 Rivet head, (Junkers)

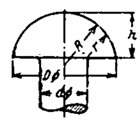


Fig.73 Rivet head, Rohrbach)

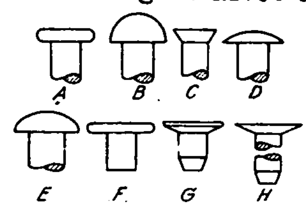


Fig.75 Standarized head shapes according to S.A.E. Standards Committee.

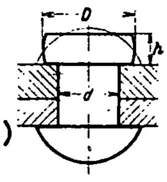


Fig.76 Flat closing head (Junkers) preliminary data on head sizes of flat closing head, (Junkers)

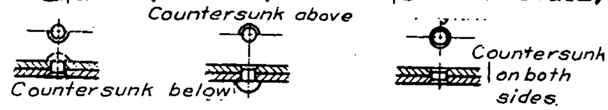


Fig.77 Designations for rivets and screws,(Rohrbach)

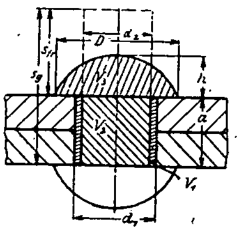


Fig.78 Division of rivets for computing the desired lengths of rivet body.

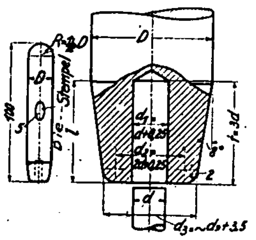


Fig. 80a

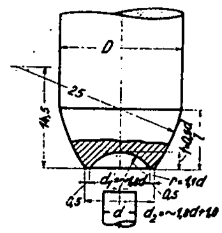


Fig.80b

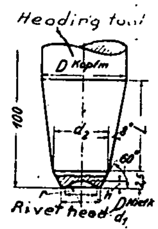


Fig.80c

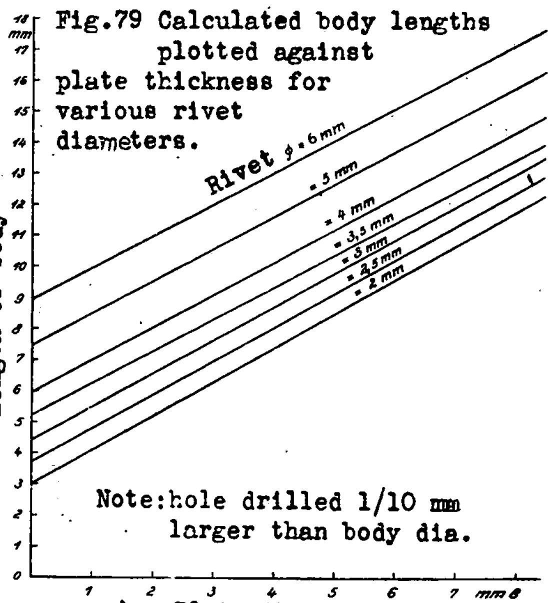


Fig.79 Calculated body lengths plotted against plate thickness for various rivet diameters.

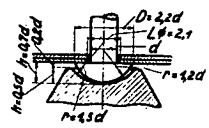


Fig.80d

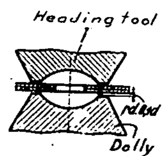


Fig.80e

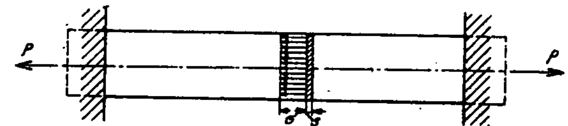
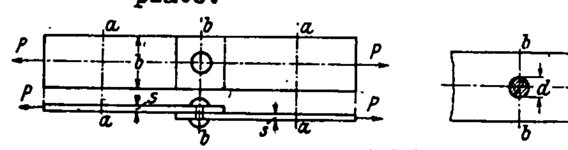


Fig.81 Evenly stressed plain tension plate.



Figs.82a,b Flat plates connected by one rivet.

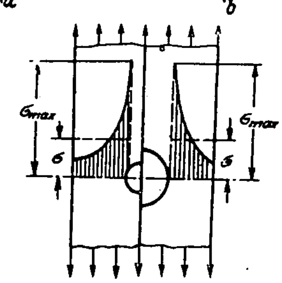


Fig.86 Stress distribution in weakened cross section of plate with hole.

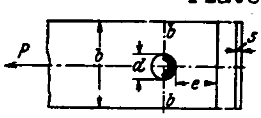


Fig.83 Stress of rivet hole due to sides of hole.

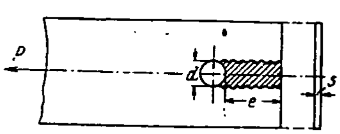


Fig.84 Shear in hole walls of rivet joint.

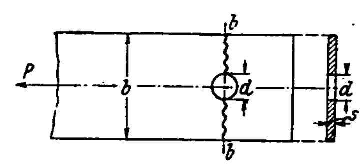


Fig.85 Tearing stress of plate with rivet hole.

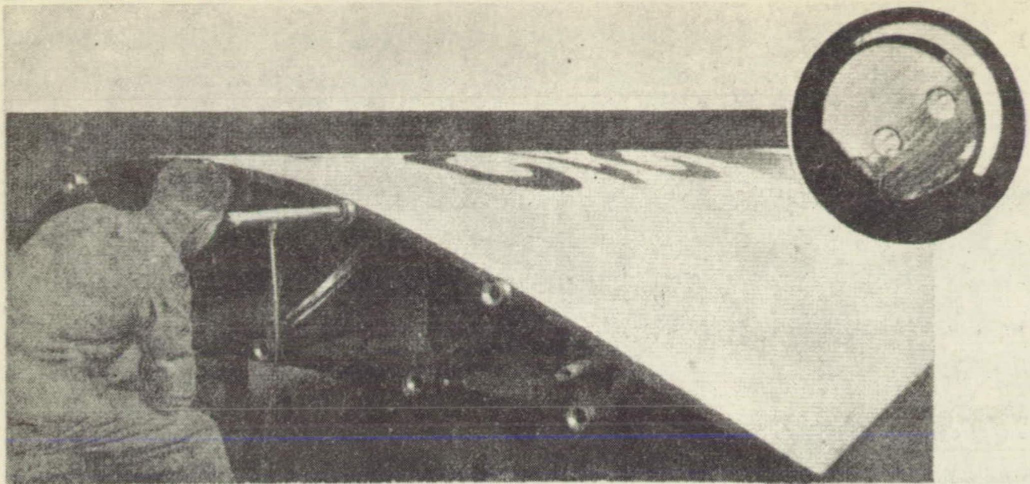


Fig.69 Spar telescope reflecting rivet heads, (from Junkers report 1928, No.4)

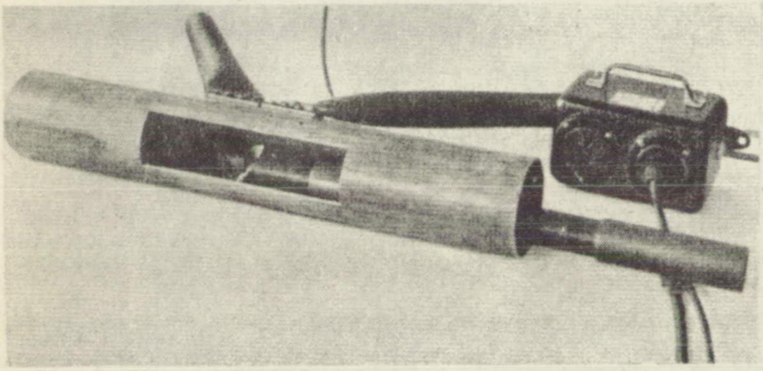


Fig.70 Position of instrument in tubular spar.

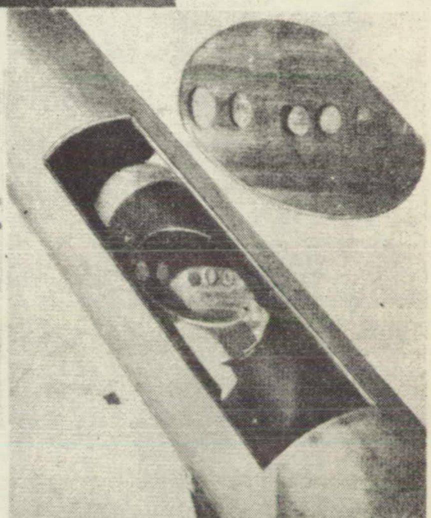


Fig.71 Rivet heads reflected by spar telescope.

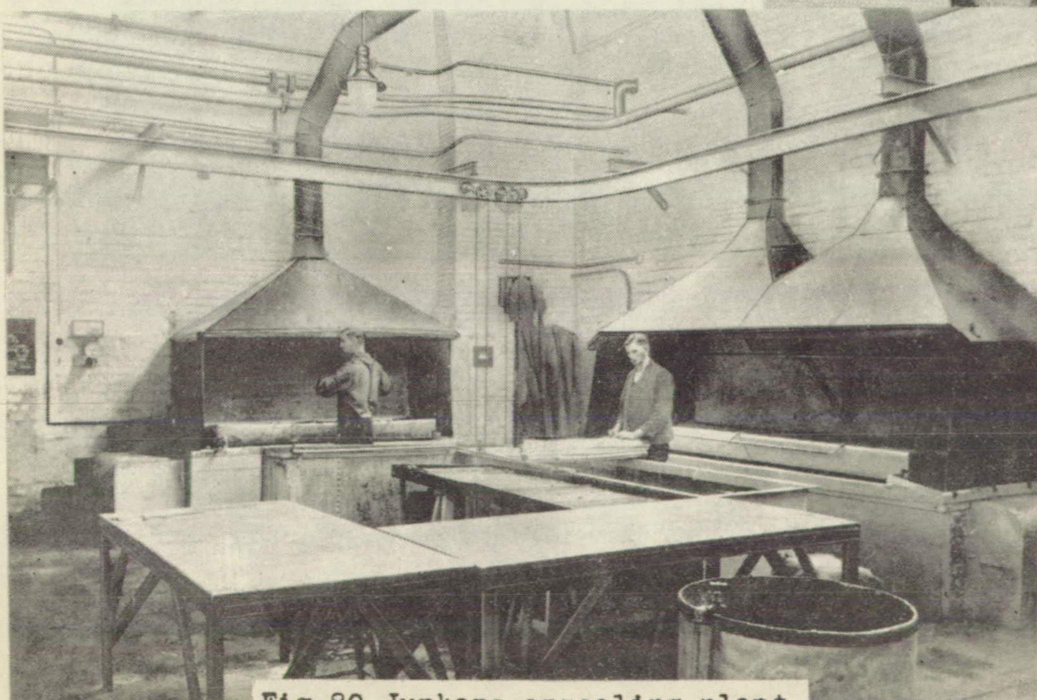


Fig.80 Junkers annealing plant.

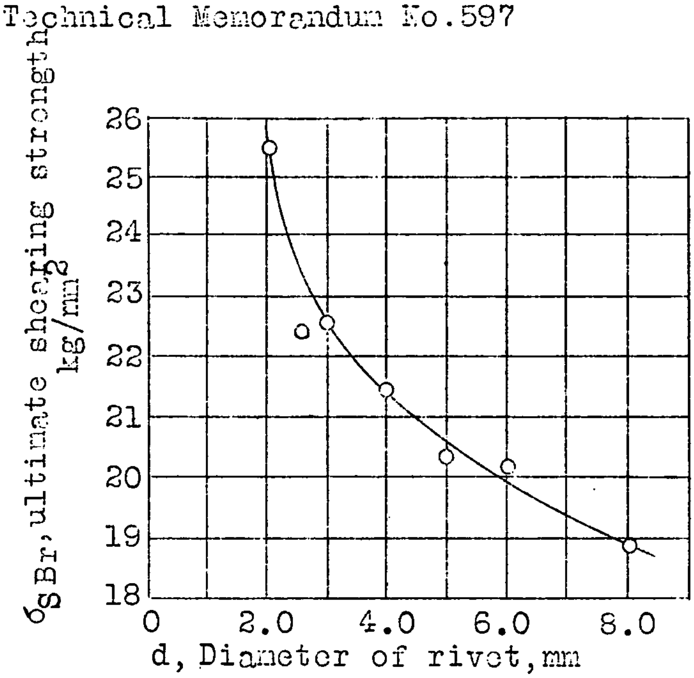
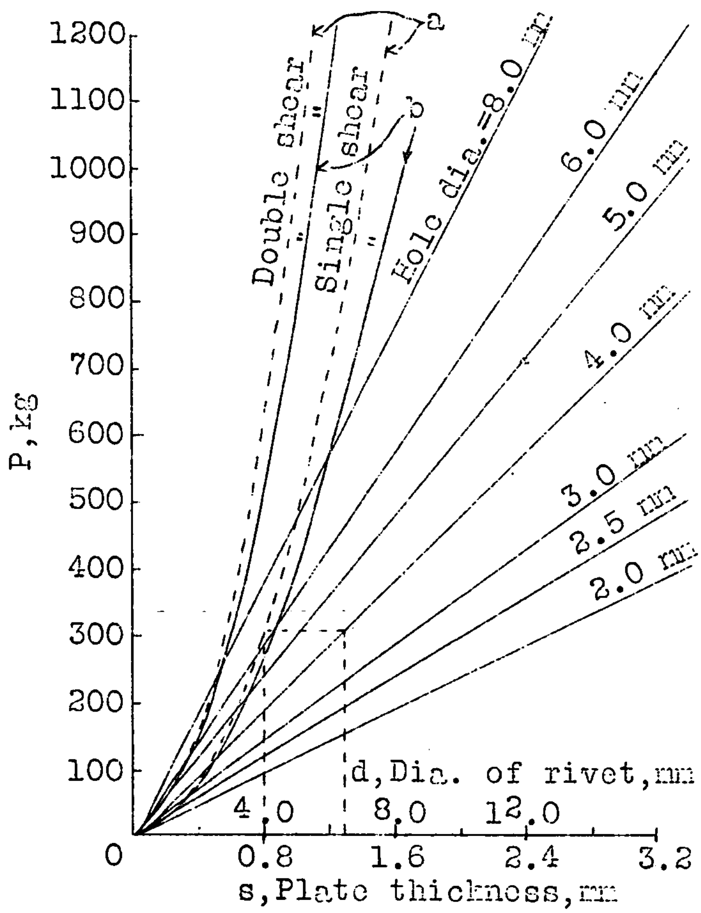


Fig.87 Ultimate shearing strength depending on diameter of rivet.



a, σ_S=25.0 kg/mm^2= constant

b, σ_S= 19÷25 kg/mm^2 =inconstant

Fig.88 Shear and crushing pressure by failure in duralumin rivet joints, (Germany).

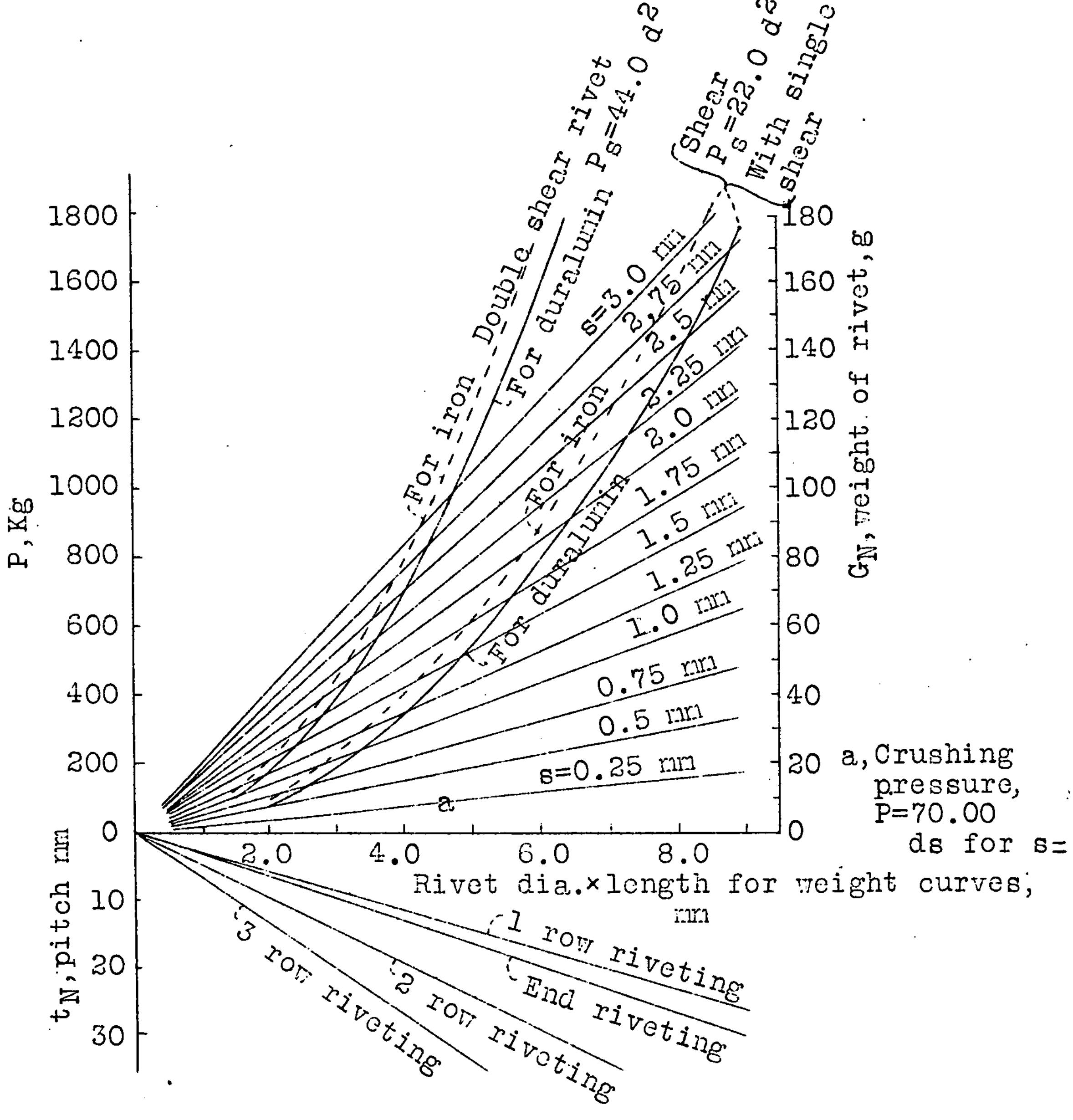
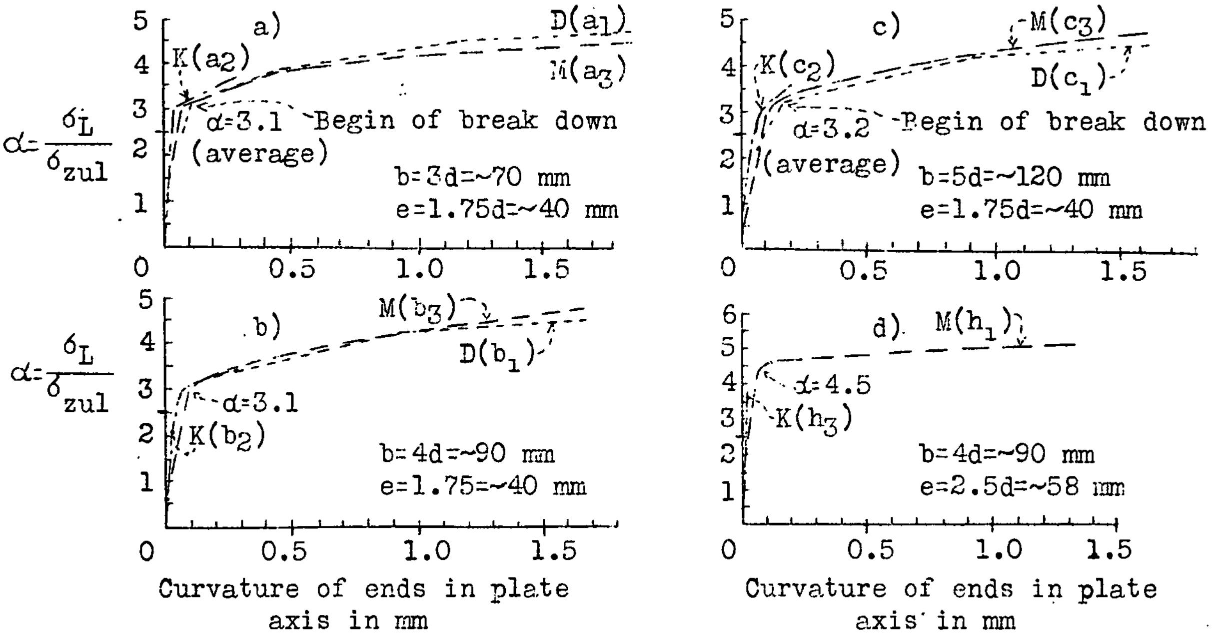


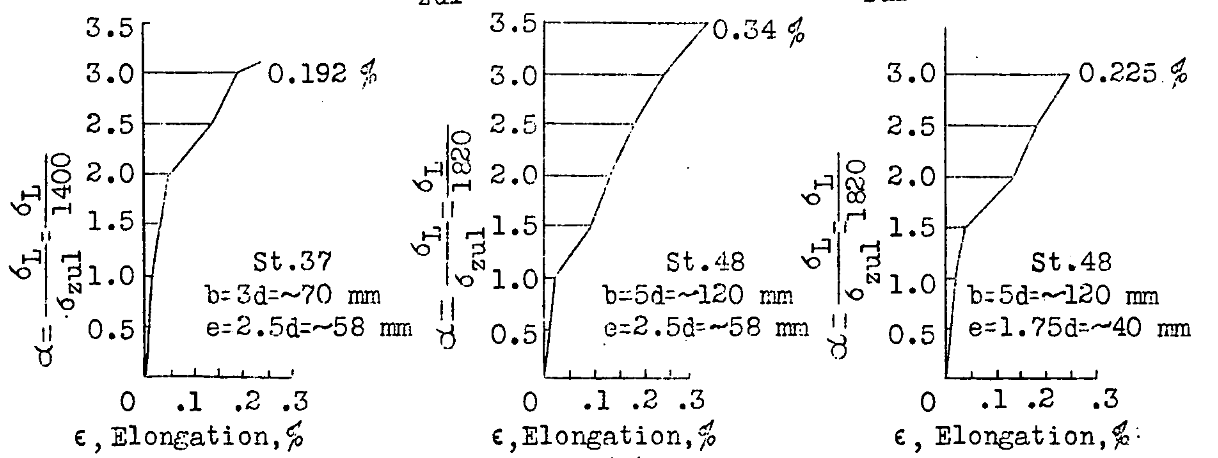
Fig.89 Table of shear and crushing pressure by failure in riveted joints of duralumin, (according to Rettew and Thumin).

(a)

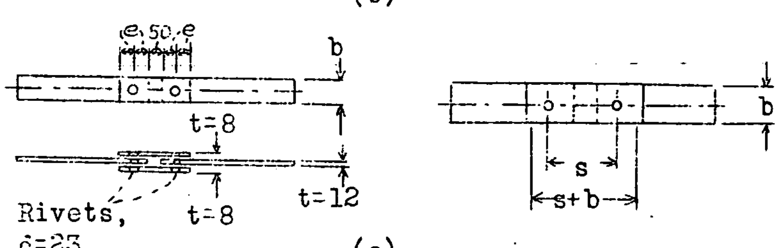


Tests in Technical High School {München — — — M, Dresden - - - - - - D, Karlsruhe — - - — K} Rivet diameter in all tests, d 23 mm; Plate thickness " " ", t 12 mm

a÷c = St.48 (σ_{zul}=1820 kg/cm^2) d = St.37 (σ_{zul}=1400 kg/cm^2)



(b)



(c)

Fig.90a,b,c Test data on crushing pressure in riveted joints.