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Fatigue Strength of Riveted Connections.

Dauerfestigkeit von Nietverbindungen.

Résistance à la fatigue des assemblages rivés.

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Part B 5 of the Reports of the German Committee for Experimental Research on Steel Structures gives an account on Pages 42 *et seq.*, firstly, of the behaviour of rivited joints made of St. 52 when subjected to frequent alternations of tensile and compressive stresses.

In the Report in question attention is drawn to the fact that the amplitude of oscillation which a riveted joint is able to withstand due to alternating tension and compression effects is far greater than that which it can stand under varying tensile stresses. This fact is of great practical significance and its reason lies in the circumstance that the tensile stresses are transmitted according to Fig. 1, while the compressive stresses are transmitted as shown in Fig. 2. In the case of Fig. 1 it is the

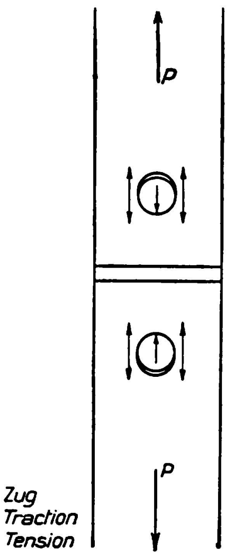


Fig. 1.

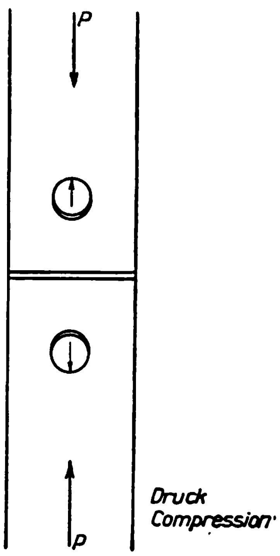


Fig. 2.

tensile stress of the material at the edge of the hole which is of a decisive influence; in the case of Fig. 2 the compressive load — apart from that portion of it which is transmitted by friction[1] — passes straight to the rivet. The stress at the edge

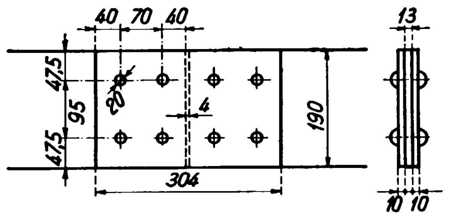
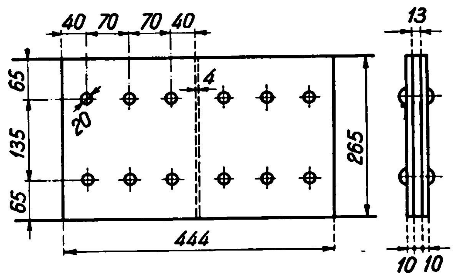
[1] It is not at all certain that friction is less with alternating tensile and compressive loads than for the tensile surge load. (Ursprungszugbelastung.)

of the hole due to alternating tensile and compressive loads are smaller than for tensile loads, with the same amplitude of oscillation.

Further it was necessary to investigate, if the resistance of rivet connections with different ratio $\sigma : \sigma : \tau$ (ratio of: tensile stress to bearing stress to shear stress) is influenced differently by repeated alternating tensile and compressive loads than it would be for repeated tensile effects only.

The results of experiments made with the joints shown in Figs. 3 and 4 have been described on Pages 42 to 47 of the above mentioned Report. The fatigue strengths determined by the experiments in question are given in Table 1. According to this

Table 1.

Series	Type of rivet connections $\sigma : \sigma_l : \tau = 1{,}0 : 1{,}9 : 0{,}8$	Fatigue strength for 250 000 loading repetitions: Tensile surge load σ_z kg/mm²	Tension-compression loading $+\sigma = -\sigma$ σ_w kg/mm²
2	 Fig. 3	20	14,5
5	 Fig. 4	18	13,5
1936	Fatigue tests for rivet connections. Plates of St 52, rivets of St 44.	Gf 4539	

the amplitude of stress oscillation which stood for 250 000 fluctuations alternating between tensile and compressive loads was considerably greater than that resulting from frequently repeated tensile loads, it was for instance:

for Row 2 — $2 \cdot 14{,}5 = 29$ kg/mm² as against 20 kg/mm²
for Row 3 — $2 \cdot 13{,}5 = 27$,, ,, ,, 18 ,,

Furthermore, the figures show that the two-row rivet joints were slightly stronger than the three-row rivet connections.

About the longitudinal deformations in connections full informations are given in the above mentioned reports. The experiments revealed how necessary it is to investigate the method of execution of the joints so as to reduce to a minimum the shifting (give) which occurs when the load is increased or when it is frequently applied.

Since those experiments were carried out the joints seen in Figs. 5 and 6 (Rows 3 and 4) have been tested[2]. While the tests shown in Table 1 (Figs. 3 and 4, Rows 2 and 5) were based on: $\sigma:\sigma_l\,\tau = 1:1.9:0.8$, in other words, stresses approximately corresponding tho the limits laid down in the Regulations, we have the later experiments with the testpieces of Figs 5 and 6, are based on ratios: $\sigma:\sigma_l = 1:1.5$ and $1:2.5$, respectively. The ratio $\sigma:\tau$ remained $1:0.8$ as determined by the earlier experiments.

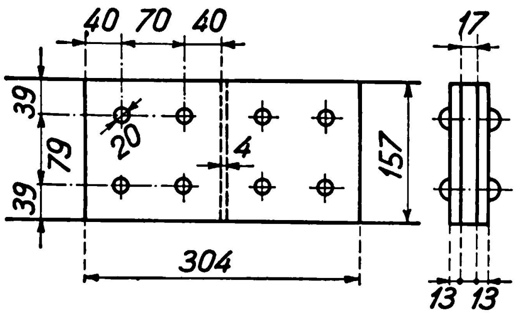


Fig. 5.

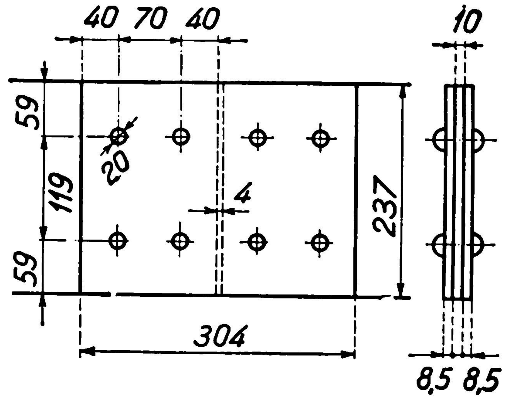


Fig. 6.

The standard kind of tensile test, carried out on steel plates 17 mm thick for Row 3 gave the following figures:

Yield limit	35.6 kg/mm²
Tensile strenght	52.4 ,,
Rupture point elongation	24.6%
Reduction for rupture section	65 %.

The figures for the 10 mm gauge sheet metal of Row 4 were:

Yield limit	39.6 kg/mm²
Tensile strength	54.0 ,,
Rupture point elongation	25.8%
Reduction for rupture section	59 %.

Ball thrust resistance (Brinell) of normally annealed rivets (supplied as rivets of St. 44) was determined as being 137 kg/mm^2.

When comparing the experiments described below with those referred to in Table 1 it should be noted that the steel used in the later experiments was supplied specially for that purpose.

All the steel plates and rivets were supplied free of charge by the Oberhausen Factory of the Gutehoffnung-Hütte.

The riveted connections were manufactured by the Material Testing Laboratory of the Institute of Technology at Stuttgart. The holes were drilled — simultaneously for both plates and straps — to a diameter of 19.5 mm and then enlarged to 20.0 mm by using a cylindrical reamer. The edges of the holes were lightly machined on the contact surfaces, while on the outer surfaces of the straps they were countersunk by bevels of 1 to 1.5 mm.

The contact surfaces of the plates and straps were carefully treated with benzine

[2] Mr. *Munziger* was entrusted with the execution of the experiments.

before riveting so as to remove all grease. In accordance with the Regulations then in force, they were not given a coat of red lead. Compressed air tools were used for riveting and a hammer designed by the Frankfort Construction Company Ltd.,

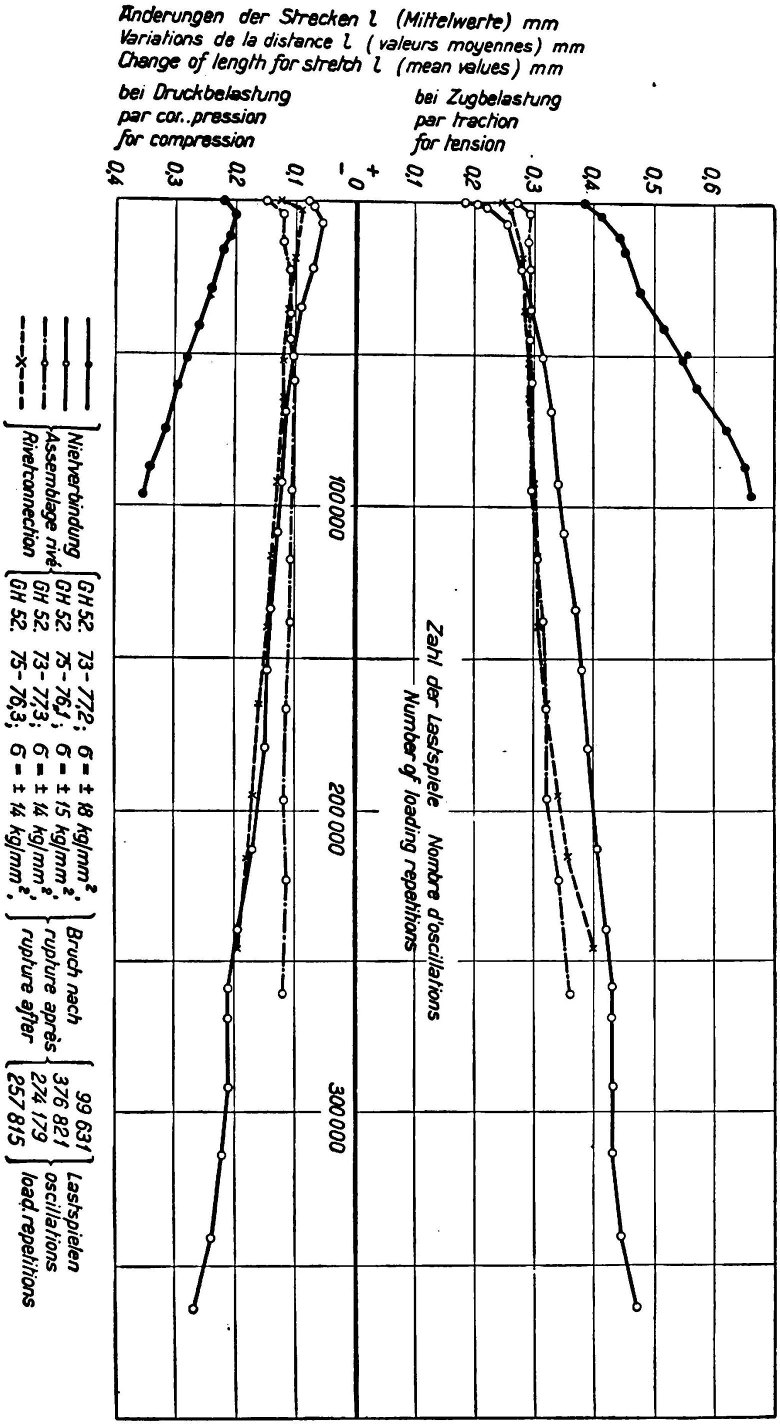


Fig. 7.

Fatigue tension-compression tests connections of St 52 with two rivet lines

$\sigma : \sigma_1 : \tau = 1{,}0 : 1{,}5 : 0{,}8$

successors to Messrs Pokorny & Wittekind, and known as Type N 80 (weight 13.3 kg, weight of die 1.33 kg was used. The pressure of the compressed air was 6 to 7 atm.

When starting riveting operations, the glowing rivets were of a pale orange colour along their whole length. Riveting time (duration of hammering) was 15 seconds.

The testing of the riveted connections was carried out in the same way as formerly[3]).

In the case of the alternating tension and compression fatigue tests, the number of loading repetitions per minute (change between tension and compression) was as a rule between 6 and 10; and for fatigue tension testo (surge load strength) 9 to 21 loading repetitions per minute; with a lower load limit of $\sigma_{uz} = 0.5$ kg/mm^2.

The alterations in length of the riveted connections were determined for all the experiments; the measured length selected for was 2.6 cm longer than the straps.

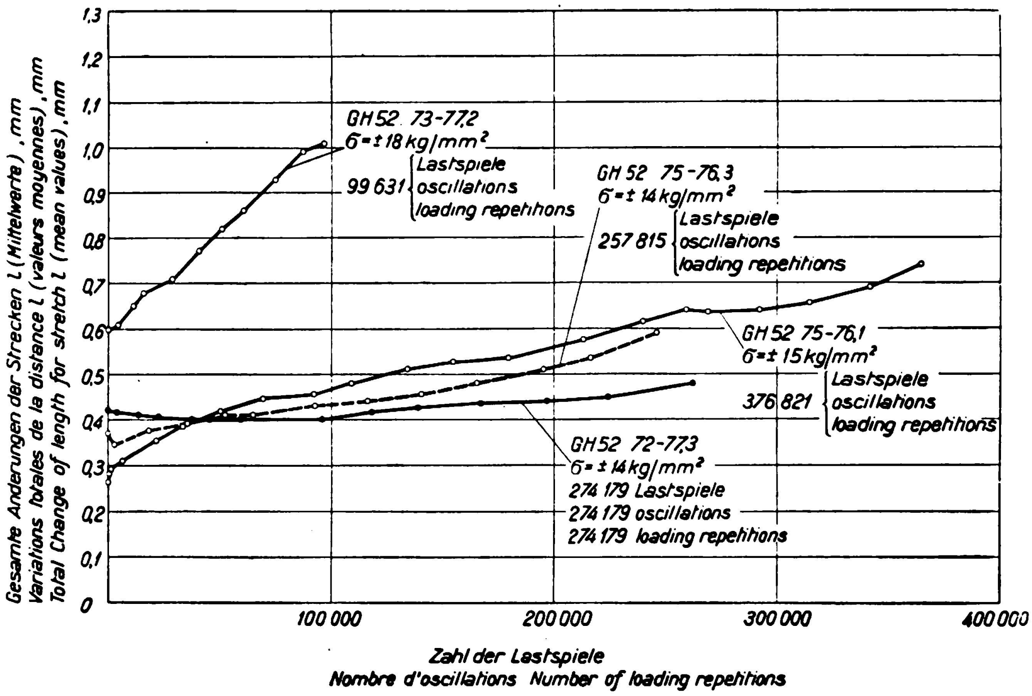


Fig. 8.

Fatigue tension-compression tests connections ef St 52 with two rivet lines
$\sigma : \sigma_l : \tau = 1{,}0 : 1{,}5 : 0{,}8$

We shall now take up the question of the

A) Deformations

resulting from these tests.

1) *Riveted connections shown in Fig. 5* (Row 3, $\sigma : \sigma_l : \tau = 1:1.5:0.8$). Fig. 7 shows the alterations in length of the riveted joints of Row 3 for alternating tensile and compressive loads. The course followed by the lines in the upper part of Fig. 7 indicates the elongations observed due to tensile stress; the course followed by the lines in the lower part of Fig. 7 shows the contractions due to be measured when compressive stress. The curve followed by these lines shows that deformation diminished considerably when the load of $\pm$ 18 kg/mm^2 was lowered to $\pm$ 15 kg/mm^2 and it diminished still further when the stress was reduced to $\pm$ 14 kg/mm^2.

The changes in length indicated in Fig. 7 as elongations and contractions have

[3] Compare Part B 5 of the Reports of the German Committee for Experimental Research on Steel Structures, 1935, Page 44.

been added together for each individual change of loading and finally plotted in Fig. 8 as inclusive alterations.

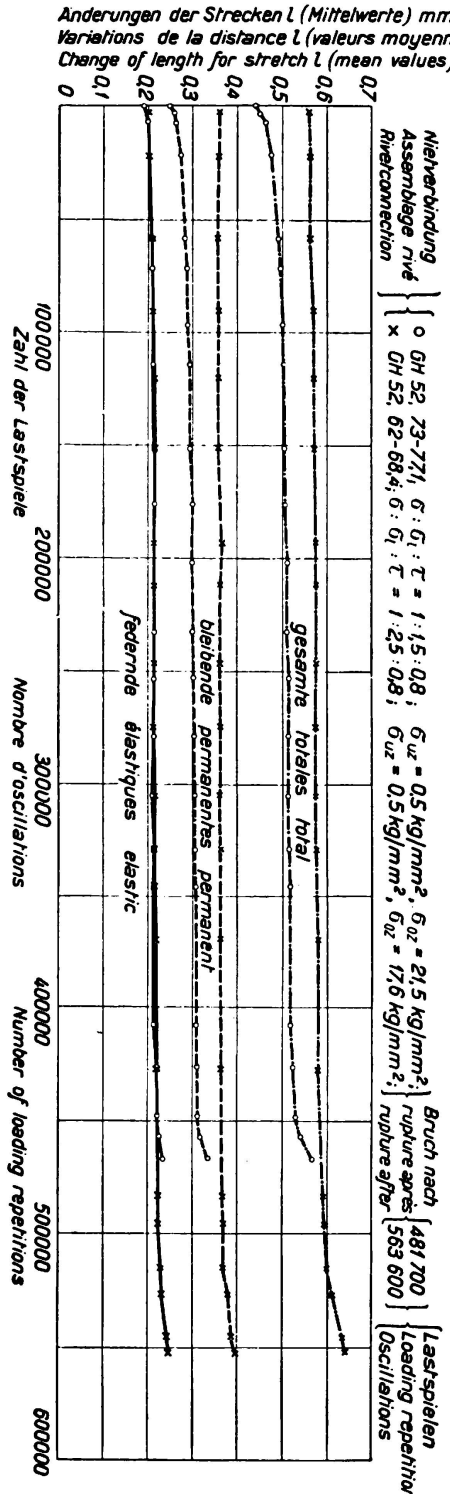


Fig. 9.

Fatigue tests with rivet connections of St 52 with two rivet lines.

For comparison we refer to Fig. 9. In this figure, the lines enclosed in circles represent the alterations in length observed for the surge loads of $\sigma_u = 0.5\,\mathrm{kg/mm^2}$ and $\sigma_o = 21.5\,\mathrm{kg/mm^2}$, that is, those having a stress amplitude of a $21.0\,\mathrm{kg/mm^2}$.

The aggregate alterations of length reached an average figure of about 0.5 mm, which is higher than that for the tension-compression tests with stress amplitude of 28 kg/mm^2. Compare the lower course of line in Fig. 8.

2) *Riveted connections shown in Fig. 6.* (Row 5, $\sigma:\sigma_l:\tau = 1:2.5:0.8$). The results of the measurements made are given in Fig. 10 (these refer to tests with alternating tensile ans compressive loads) and in Fig. 9 (lines marked with crosses refer to a test made with tensile surge loads).

3) The examination of the results given in paragraph 1) and 2) will show that the alterations in length of the connections subjected to alternating tensile and compressive loads are very great and the consequence is that when these joints are "knocking" when put in commission. Attempts should be made to manufacture joints such that these movements remain small. The alterations in length of riveted joints depend

a) on the amount of the friction between the contact surfaces of the riveted joint, that is, on the coefficient of friction of the surfaces of the metal and of the clamping force of the rivets,

b) on the margin of play of the rivet shank within the rivet hole.

Recent tests made with large graups of rivets and the experiments described in Part B 5 drawn up by the Committee for Experimental Research on Steel Structures produced the following information:

The friction of the contact surfaces of the plates was greater after sand blast cleaning than after cleaning with benzine, and naturally, the friction was far less for surfaces having a coat of red lead than for those without a coat of paint.

The clamping force was greatest when the rivet had been heated to a light colour for its whole length and when the end of the shank reached a white incandescent heat. The rivet was then hammered for 10 seconds with powerful compressed air hammers. The clamping force was lower and less regular in the rivets having a lower temperature.

The play space between the shank of the rivet and the wall of the rivet hole was less than 0.15 mm for rivets having a diameter of 23 mm, provided the diameters of the rivets were kept from the start just slightly below the diameter of the rivet hole. This was accomplished by turning the rivets on a lathe. Similar results were attained when the unfinished rivets selected were thicker than those mentioned in the Regulations. The process of "upsetting" the rivets before making the closing head resulted in the space between the rived shank and the plate wall being less than 0.15 mm.

An important point to be considered is

B) *The carrying capacity of the connections.*

In the following the tests results for connections of the various tests are here given according to fig. 5 and 6 are given separately.

1) *Rivet connections as shown in Fig. 5* (Row 3, $\sigma:\sigma_l:\tau = 1:1.5:0.8$).

Four joints were tested on alternating equal tensile and compressive loads. The results were

for joints	73—77.2	75—76.1	73—77.3	75—76.3
with tensile and compressive stresses σ	18	15	14	14 kg/mm²,
i.e. amplitude of stress from $+\sigma$ bis $-\sigma$	36	30	28	28 „ ,
the bearing valne σ_l	26.4	22.1	20.5	20.7 „ ,
the shearing stress of the rivet τ	14.4	12.0	11.2	11.2 „ ,
the ratio $\sigma:\sigma_l:\tau$	1 : 1.47 : 0.80		1 : 1.46 : 0.80	1 : 1.48 : 0.80,
the number of loading repetition till fracture occurs	99 631	376 821	274 179	257 815.

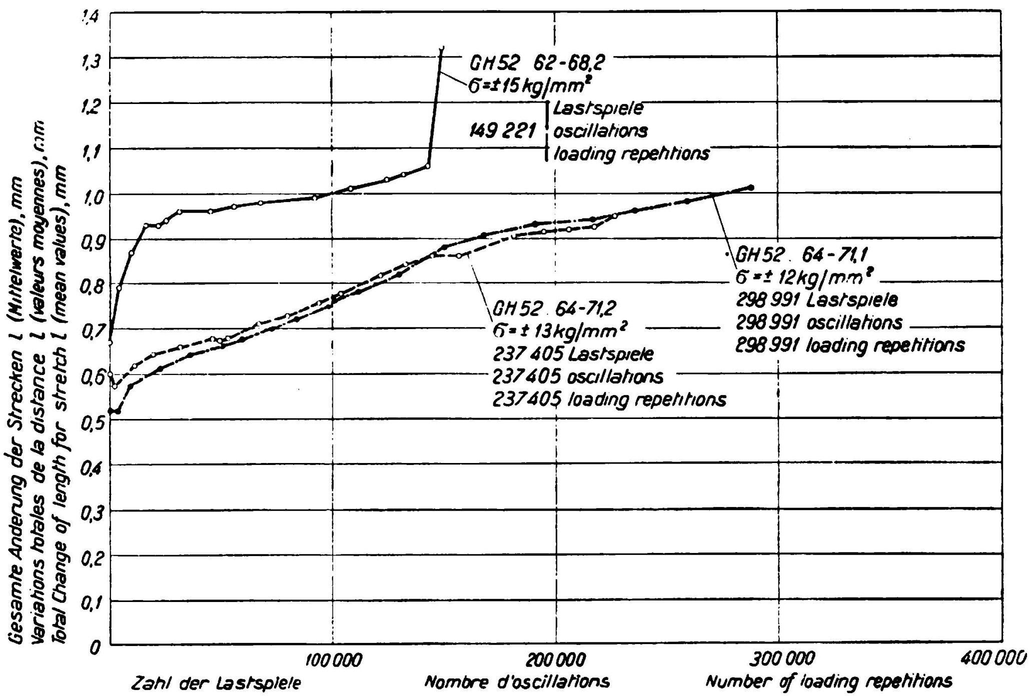


Fig. 10.

Fatigue tension-compression tests connections of St 52 with two rivet lines

$\sigma : \sigma_l : \tau = 1{,}0 : 2{,}5 : 0{,}8$

From this it will be seen that the amplitude of stress which may occur 250 000 times without fracture taking place is 28 kg/mm²; if the extent or stress amplitude is to occur 500 000 times without fracture taking place, it must not exceed 26 kg/mm².

For purposes of comparison a riveted joint, such as that shown in Fig. 5, was tested with a frequently applied tensile load. The test was carried out

$$\begin{aligned}
\text{with } \sigma_{uz} &= 0.5 \text{ kg/mm}^2\\
\sigma_{oz} &= 21.5 \text{ kg/mm}^2\\
\text{stress amplitude } \sigma_o - \sigma_u &= S = 21 \text{ kg/mm}^2\\
\sigma_l &= 31.6 \text{ kg/mm}^2\\
\tau &= 17.3 \text{ kg/mm}^2\\
\sigma : \sigma_l : \tau &= 1 : 1.47 : 0.80.
\end{aligned}$$

The rupture occurred after 481 700 applications of the load.

It may be deduced from this test that the stress amplitude imposed 500 000 times was approximately 20 kg/mm². According to other tests made on narrower joints having, however, the same ratio[4], it can be estimated that the stress amplitude is about 22 kg/mm² for 250 000 loading repetitions.

The ratio of the stress amplitude for tension-compression loads to those of surge loads is:

$$\text{for } 250\,000 \text{ loading repetitions } 28:22 = 1.27:1$$
$$\text{for } 500\,000 \text{ loading repetitions } 26:20 = 1.30:1$$

The figures which are in agreement with the results attained with the joints shown in Figs. 3 and 4, indicate that the stress amplitude was considerably less with the primary tensile surge loads than with the alternating tension and compression loading.

2) *Riveted joints shown in Fig. 6* (Row 5, $\sigma:\sigma_l:\tau = 1:2.5:0.8$).

Three joints were tested for alternating tensile and compressive loads. The connections tests gave:

Specimen number	62—68.2	64—71.2	64 - 71.1
with tensile and compressive stresses	15	13	12 kg/mm²,
i. e. stress amplitude from $+\sigma$ bis $-\sigma$	30	26	24 „ ,
the bearing valne σ_l	36.4	32.1	29.7 „ ,
the shearing stress of the rivet τ	11.9	10.4	9.6 „ ,
the ratio $\sigma:\sigma_l:\tau$	1 : 2.43 : 0.79	1 : 2.47 : 0.80,	
the number of loading repetitions till fracture occurs . . .	149 221	237 405	298 991.

From this it will be seen that the stress amplitude which may occur 250 000 times without causing fracture is approximately 25 kg/mm²; the stress amplitude which is imposed 500 000 times, estimated according to the graphs, would be 21 kg/mm.

A riveted joint of the kind shown in Fig. 6 was tested with tensile surge load, and the results were:

$$\sigma_{uz} = 0.5 \text{ kg/mm}^2$$
$$\sigma_{oz} = 17.6 \text{ kg/mm}^2$$
$$\sigma_o - \sigma_u = 17.1 \text{ kg/mm}^2$$
$$\sigma_{lo} = 42.8 \text{ kg/mm}^2$$
$$\tau_o = 14{,}1 \text{ kg/mm}^2 \text{ and}$$
$$\sigma:\sigma_l:\tau = 1:2.43:0.80.$$

The joint broke after 563 000 applications of load.

By reference to earlier observations made, the stress amplitude for tensile surge load can be estimated at:

$$\text{for } 250\,000 \text{ load applications at } 20 \text{ kg/mm}^2$$
$$\text{for } 500\,000 \text{ load applications at } 17 \text{ kg/mm}^2.$$

[4] Part B 5 of the Reports drawn up by the Committee for Experimental Research on Steel Structures, Page 40.

The ratio of stress amplitudes with tensile compressive loads to the stress amplitudes with tensile surge load was:

for 250 000 repetitions of loading $25 : 20 = 1.25 : 1$
for 500 000 repetitions of loading $21 : 17 - 1.24 : 1.$

3) Speaking generally, the observations made on the carrying capacity of riveted joints would seem to point to the following:

a) The amplitude of stress which the material could resist without a fracture ocurring was considerably greater with the alternating tensile to compressive loads than where the tensile surge loads alone came into play; the increase in the case of Fig. 5 was 27 and 30%, in that of Fig. 6 it was 19 and 23%.

b) The fatigue strength of the riveted joints was seen to be greater with $\sigma:\sigma_l:\tau = 1:1.5:0.8$ than with $\sigma:\sigma_l:\tau = 1:2.5:0.8$[5]; when the rivets withstood 500 000 load applications, the stress amplitude S was:

with alternating tensile-compressive loads

with $\sigma : \sigma_1 : \tau = 1 : 1.5 : 0.8$ $S = 26$ kg/mm^2
with $\sigma : \sigma_1 : \tau = 1 : 2.5 : 0.8$ $S = 21$ kg/mm^2.

with tensile surge load

with $\sigma : \sigma_1 : \tau = 1 : 1.5 : 0.8$ $S = 20$ kg/mm^2
with $\sigma : \sigma_1 : \tau = 1 : 2.5 : 0.8$ $S = 17$ kg/mm^2.

Finally, something should be said concerning:

C) *The failure of the riveted connections.*

All the connections broke in the plates at an outer row of rivets, for instance, at c in Fig. 11. The fracture started at the edge of the rivet hole, as had already been noted in many earlier experiments. Furthermore, in the case of the joint

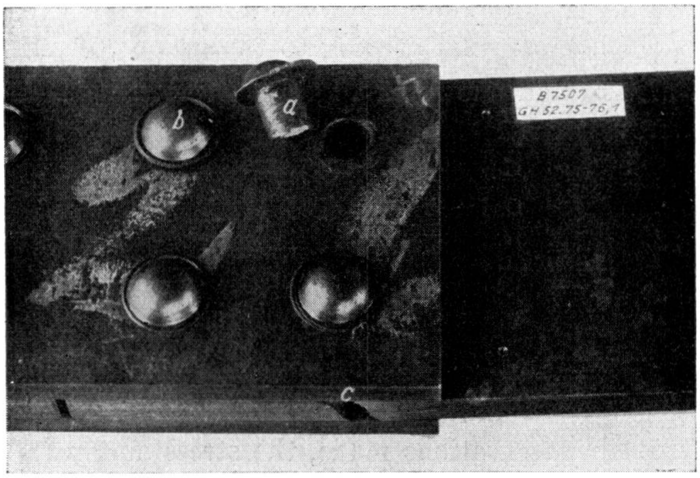


Fig. 11.

Rivet connection 75—76,1. $\sigma : \sigma_1 : \tau = 1 : 1,5 : 0,8$.

Fracture in plate at c, starting from the edges of rivet holes. Rivets a and b fractured.

[5] It is not possible to make a direct comparison between the joints of Fig. 3 and 4, because the steel used was supplied in different lots.

shown in Fig. 11, the rivet broke at a and b, that is to say, the bending strength of the rivet was exceeded as a result of frequently alternating loads[6].

A riveted joint in the same row which showed no outward signs of fracture was cut open after the test as shown in Fig. 12. It was then found that minute cracks r_z (due to tensile load) and r_d (due to compressive load) had occurred at each die head of the rivet and in one case also for the closing head. These tests show the limits of strength of the rivets.

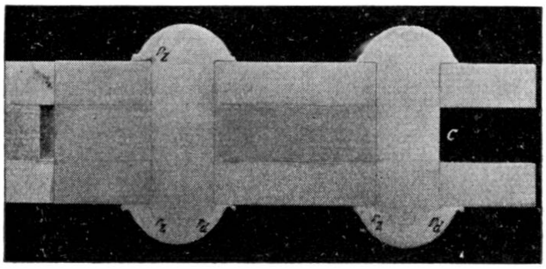


Fig. 12.

Longitudinal section through rivet connection 75—76,3.
$\sigma = \pm 14$ kg/mm²; $\sigma : \sigma_1 : \tau = 1 : 1{,}5 : 0{,}8$; 257815 loading repetitions, until fracture; rupture at c startet at the edge of the rivet hole.

Summary.

The experiments showed that the stress amplitude of frequently repeated loads is considerably greater with alternating tensile and compressive loads than with tensile loads alone. (Cp. Paragraph B, 3a). Furthermore, it was found that the stress amplitude for joints with

$\sigma : \sigma_1 : \tau = 1 : 1.5 : 0.8$ is greater than with
$\sigma : \sigma_1 : \tau = 1 : 2.5 : 0.8$. (Cp. Paragraph B, 3b).

The observations made with regard to the magnitude of the longitudinal deformations of riveted joints are of particular interest. Several tests are mentioned in Paragraph A 3 which were carried out in order to attain higher clamping forces and less play for the rivet.

The tests made with the joints seen in Fig. 5 show us once again that when rivets are subjected to frequently repeated loads, fracture may result from bending stresses.

[6] Cp. Part B 5 of the Report of the Committee for Experimental Research on Steel Structures, Page 31.