Improvement of the fatigue strength of riveted joints in HSLA steel by using new high strength rivets

IMPROVEMENT OF THE FATIGUE STRENGTH OF RIVETED JOINTS IN HSLA STEEL BY USING NEW HIGH STRENGTH RIVETS.

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High strength rivets with hardnesses up to 350 HB were developed. Joints in 6mm FeE 560TM plate material made with these rivets were extensively tested and joining techniques were optimized on the base of these tests.
Endurance curves for constant- and variable amplitude loading were generated for several joints of basic configurations in order to enable the applications of these rivets in constructions.

INTRODUCTION

Riveting is one of the oldest techniques for building steel structures. Although this technique is now more or less obsolete because of the breakthrough of welding, the number of riveted constructions that are still in use is very large, e.g. railway stations, now regarded as monuments, bridges, the Eifel tower. As the development of welding into a reliable joining technique took place in the decade after 1945, these riveted structures are in use for more than fifty - often for even more than one hundred - years.
For these riveted structures when loaded in fatigue, as are bridges, there are no questions left about the endurance with regard to the original design load. The only question is now how much the allowable loads can be increased.
So riveting has proved to be a reliable joining technique for steel structures, and it must not be forgotten that it is the major joining technique in aircraft industry.

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One of the areas where riveting is still in use to build steel structures is the vehicle industry. Most manufacturers of trucks prefer riveted chassis over welded ones because of flexibility and fatigue resistance.

Now especially in the vehicle industry there is a strong tendency to use steels of higher strength because a saving of weight leads directly into an increase of the payload and into a higher efficiency in service.
However, riveting technology has had a standstill for decades and no high strength rivets were available in order to utilize the better properties of high strength structural steels.

Therefore a dutch research group in which participated:

Eindhoven University of Technology, Eindhoven
DAF- Leyland Trucks, Eindhoven
Hoogovens IJmuiden, IJmuiden
NedSchroef, Helmond
AKZO Coatings Nederland, Sassenheim

has taken this problem as their subject.
High strength, cold heading rivets with hardnesses up to 350 HB have been developed. Joints made with these rivets from HSLA steel plate were extensively tested in fatigue and joining techniques were optimized on the base of the test results.
After that, endurance curves for constant amplitude and for variable amplitude loading were generated for several basic joints, in order to enable a designer to utilize the results of this development.

RESEARCH PROGRAM.

The research program consisted of two parts, viz.

I. An evaluation program, containing
- development of high strength rivets
- reference tests on joints riveted with mild steel rivets
- optimisation of simple riveted joints on the base of fatigue tests
- stress corrosion tests
- determination of the minimum dimensions for rivet patterns

II. The generation of S-N and S_{rms}-N data for the following basic joint configurations:
- single shear lap joint with: 1 rivet
  3 rivets in series
  3 rivets parallel
- double shear lap joint with: 1 rivet
  4 rivets in a square

All fatigue tests were carried out at $F_{min} / F_{max} = R = -1$

PLATE MATERIAL.

The plate material used throughout in this investigation was a hot rolled LD steel that complied with FeE 560TM according to Euronorm 149-2. It was supplied by Hoogovens IJmuiden in two heats, both with a plate thickness of 6 mm.
This HSLA steel was micro-alloyed with Nb and V, while for inclusion control Ce or Ca was used.
More details about these materials are given in the paper by Overbeeke and Alting (1) at this conference.

The mechanical properties of both heats are given in table 1 and it follows that the differences in R_e and R_m are less than 5% and negligible.
However heat I, which was used for the evaluation program, was an ingot cast steel, while heat II, which was used for fatigue-data generation, was a concast steel.

In concast steels the segregations are more concentrated in the mid-plane region than in ingot cast steels. Now for punched holes, the transition from shear to tear is also at the mid-plane region of the plate. It follows that sub-macro lamellar tearing, which could impair the fatigue resistance, could occur due to punching.
From observations of the fracture surfaces however, no crack initiations emanating from this midplane were observed.

TABLE 1 - Mechanical Properties of the 6mm FeE560TM Steel Plates.

FeE 560TM	Heat I		Heat II	
direction	∥	⊥	∥	⊥
Re, N/mm²	628	658	611	626
Rm, N/mm²	716	727	694	709
A (1=80)%	25	21	30	25
Hardness, HB	240		230	
Fatigue limit, S_f, N/mm², R=-1	360	n.d.	304	n.d.

EVALUATION, PART I.

Development of H.S.rivets.

Out of alloy steels suitable for cold heading and in use for the fabrication of H.S. bolts, the heat-treatable micro-alloyed steel 18MnB4 was selected by NedSchroef for the production of rivets.

This steel complies with ISO 4954 class E2. The measured mechanical properties and the strain hardening exponent of the Nadai relation $\sigma = \sigma_o e^n$ in the Q + T condition are given in table 2 for 3 tempering temperatures.

TABLE 2 - Mechnical Properties of the 18MnB4 Steel.

Temper, °C	400	500	600
Re, N/mm²	1145	858	804
Rm, N/mm²	1210	879	827
HRC	33.8	22.0	19.9
HB *)	354	280	233
Z %	62	71	69
$e_{fracture}$	1.00	1.19	1.20
n	0.05	0.08	0.09

*) after forming and heat treatment.

From this material roundhead rivets complying with DIN 124 of diameter 12 mm were produced by standard industrial practice. After Q and T, all rivets were electroplated with 5-8 µm zinc and yellow passivated.

Rivetability tests with rivets of hardness 170 < HB < 350 and punched holes in the 6mm FeE560TM material have shown, see also fig.1, that
- rivet hardnesses lower than 230 HB show insufficient filling of the hole.
- rivet hardnesses in excess of 300 HB show macro plastic deformation of the plate material. This can result in an undesired bulgeing of the plate.

This left the rivets having 230 < HB < 300 to be investigated.

The riveting force necessary to produce rivets with a conical counterhead in this material with low strainhardening is $F \approx 2R_mA_o$, where A_o is the original cross section area. At $F \approx R_mA_o$ the hole is filled but not the hole irregularities. At $F \approx 1{,}75R_mA_o$ the conical head is formed for the greater part, but the hole irregularities are not yet filled sufficiently.
Between $F \approx 1{,}75$ and $2{,}0\ R_mA_o$ the filling of the hole is completed and the counterhead gets its proper size, see fig.2.

Static tests on lapjoints with one rivet, see fig.4, yielded the results given in table 3.
Failure was by shear of the rivet, but the double shear lap joints with a 280 HB rivet also showed 2 mm hole elongation.

TABLE 3 - Static Strength, kN, of Riveted Lapjoints.

Rivet Hole	280 HB Punched	233 HB Bored	A.5-Al Punched
single shear	81	63	45
double shear	150	119	81

Fatigue tests on single shear lapjoints (plate surface with millscale, holes bored), fig.4, made with 233 HB and 280 HB rivets were carried out as a first step.
From the results given in table 4 it follows that at $N \approx 1.5 * 10^6$ the load carrying capacity increases with increasing rivet hardness.

TABLE 4 - Endurance at R = -1 for Single Shear Lapjoints. Failure mode: shear of the Rivet.

Rivet	Primer	Fa, kN	$N.10^{-6}$	σ(log N)	Number of spec.
A.5-Al	-	20	1.21	0.40	6
233 HB	-	30	1.92	0.46	10
233 HB	B	30	1.20	0.20	5
280 HB	-	35	1.75	0.53	5
280 HB	B	35	1.42	0.29	5

Reference tests on A.5-Al (≈ grade Fe360) rivets.

As a base for comparision, tests were carried out on joints made with class A.5-Al rivets (ISO 4954). The strength of this rivet material compares with Fe 360.
The results of static tests are given in table 3. Fatigue tests were carried out on single shear lapjoints, fig.4, made from plates with millscale and bored holes.
These results are also given in table 4, and it follows that the load carrying capacity is increased by a factor 1.5 to 2 by using the harder rivets.
Additional tests did show the following:
- deburring the hole surfaces with ½ mm x 45° bevel reduces the endurance by a factor 3.
- coating plate- and hole surfaces with red washprimer (after shot blasting) leads often to rivets that work loose and reduces the endurance by a factor 4.

- combining these two treatments reduces the endurances with a factor 4.5.

Surface condition of the plate.

Primer. In view of the adverse influence on the endurances of the primer used in the reference tests, 4 different primers were evaluated.
Plates with bored holes were shot blasted to SIS-SA 2½ to 3 before priming. Primer thickness was 35 to 45 µm. The single shear lapjoints were made with 233 HB or with 280 HB rivets.
Fatigue tests did confirm this adverse effect for 3 of the 4 primers used. The exception was primer B, which is a qualified high friction primer, $\mu > 0.55$, used for friction-grip bolted joints.

The reductions in endurance for joints with primer B and 280 HB rivets are not more than 20% as compared with joints from "bare" plates, as shown in table 4.

Blasting. From further fatigue tests it also appeared that shotblasting ($Ra \approx 5$ µm) before priming yields somewhat higher endurances than blasting with corund grit ($Ra \approx 15$ µm).

Stress corrosion.

It is known that high strength steels are sensitive to stress corrosion cracking in brine and to hydrogen embrittlement when R_e exceeds 1000 N/mm² (Wanhill(2),Kloos et.al.(3)). Therefore the grade of bolts used in the vehicle industry is usually restricted to grade 10.9.

In view of the above, sustained load tests in brine were carried on formed rivets of hardness 320 HB ($R_m \approx 1100$ N/mm²). These rivets, 60 mm long, were riveted in a divisable hard die having a hole of 13 mm. Because of that, the radius between the shaft and the conical counterhead was $r \approx 0.1$ mm.
The surface of the rivets was as heat-treated.
5 rivets were tested for more than 1000 hours in an aerated solution of 3.5% NaCl in distilled water, with an axial load of 50 kN
S = 380 N/mm²).
Not any indication of stress corrosion was observed after these tests.

So it appears that rivets from 18 MnB4 steel with hardnesses up to 320 HB are not sensitive to stress corrosion.

Punched holes.

The evaluation tests described above were on joints with drilled

holes. Now in the truck industry extensive use is made of the much cheaper punched holes.
Therefore all further tests were carried out on joints with punched holes.

Now a punched hole has 2 types of surface. A smooth cylindrical shear surface made by the punch and a somewhat rugged conical surface caused by shear-rupture. The transition between the two is at about the mid-plane region of the plate.
Therefore the stapling of the plates for all joints was as scetched in fig.3. This type of stapling yields, especially below the fixed head, a lesser filling of the hole (see fig. 1) and also lower endurances.

Endurance data I (Heat I material).

Endurance data for single- and double shear riveted joints, fig.4, with punched holes, primer B and the above mentioned stapling, riveted with rivets 280 HB were obtained for constant amplitude and variable amplitude loading (spectrum GAUSS, I = 0.99 and 0.7, $F_{max} = 5.26\ F_{rms}$).
A short description of the standard spectrum GAUSS (Haibach et.al (4), Schütz (5)) is given in (1).
Results of C.A. tests are plotted in fig. 5 and 6. The F-N curves, represented by a Basquin type equation and determined by linear regression read:

single shear : $7.43 \log F_a + \log N = 16.982$ [1] (1)

double shear : $5.80 \log F_a + \log N = 15.709$ (2)

Results of V.A. tests (GAUSS, I = 0.99 and 0.7) are plotted in fig. 7 and 8. In these figures the Miner summations for I = 0.99 and $S_f = 0$ derived from eq. 1 and 2, are given too and it appears that these are rather unconservative.
The Basquin type equations for I = 0.99 and 0.7 together are:

single shear : $9.71 \log F_{rms} + \log N = 16.633$ (3)

double shear : $8.01 \log F_{rms} + \log N = 16.291$ (4)

Note that the endurances for I = 0.99 and I = 0.7 are essentially the same.

All but two of the single shear specimens failed from cracks that started just under the fixed head of the rivet. Comparison with the results for bored holes, table 4, shows a loss in load capacity of ≈20% at an equal endurance.

The failure mode for the double shear specimens was in shear for the C.A. loading and the same holds for V.A. loading when $F_{rms} \leq$ 15 kN.

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[1] In all equations F is expressed in kN and S in N/mm²

For values of $F_{rms} \geq 17$ kN failure was by hole elongation. Note that as $F_{max} = 5.26\ F_{rms}$ this equals a maximum nominal bearing pressure on the hole of the centre plate of 1150 N/mm², which is about 1.8 Re of the plate material.

EVALUATION PART II.

Conical pressed fixed heads.

In an attempt to suppress failures from below the fixed head, as were encountered with the single shear joints, the roundhead rivets were riveted with 2 conical headers. This increases the filling of the hole below this fixed head and also seems to increase the filling in the centre part of the hole. Additional fatigue tests demonstrated that this procedure eliminated rivet head failures. Therefore all further joints were produced with 2 conical headers.

High friction primers.

The qualified (6) high friction primer B as used in the first evaluation tests is not suitable for series production as takes place in the truck industry, because of potlife and drying time. Therefore a high friction, corrosion resisting primer, called G, was developed by AKZO Coatings. Its coefficient of friction is in excess of 0.55, its potlife is more than 8 hours while its drying time can be reduced to a couple of hours by curing at a higher temperature.

Endurance data II (Heat II material).

The effect of this primer on the fatigue endurance was evaluated by tests on the "standard" specimens, fig.4, with punched holes, primer G, rivets 280 HB and 2 conical heads.

The results for C.A. loading are plotted in fig. 9 and 10, and the equations for the endurances are:

single shear : $8.06 \log F_a + \log N = 17.895$ (5)
$F_f \approx 23$ kN
double shear : $5.53 \log F_a + \log N = 14.887$ (6)
$F_f \approx 31$ kN

Note that the lower bound of the scatterband in fig.10. differs only a factor 2 in endurance with regard to eq.6.

The results for V.A. loading (Gauss, I = 0.99) are plotted in fig. 11 and 12 and the equations for the endurances are:

single shear : $8.68 \log F_{rms} + \log N = 15.352$ (7)
double shear : $8.13 \log F_{rms} + \log N = 16.519$ (8)

All fractures where in shear planes except for the double shear lapjoint when $F_{rms} \geq 17$ kN. These specimens failed again from hole

elongation.
Comparing the above mentioned results with those given in the previous paragraph, eq.1 through 4, yields the following results:
single shear joints: the endurance for C.A. and V.A. are about equal.
double shear joints: the endurances for V.A. loading are about equal, but for C.A. loading the joints with primer G show a reduction in endurance of a factor 2½ with regard to joints with primer B. However the fatigue limits are equal.
The reason for this reduction in endurance for C.A. loading is not known, but it was observed that for the joints with 2 conical heads and primer G more than one crack were formed in both shear planes, while for joints with one standard roundhead (primer B) there usually was only one dominating crack.
So this difference in endurance is attributed to the effect of riveting with 2 conical headers and not to the effect of a different high friction primer.

Note: From fractographic observations it appears that a number of different crack-initiations in the rivet are possible in riveted joints:

- Cracks in joints with bored holes emanated from fretting in the hole and then grew in the shear plane.
- Cracks in joints with punched holes and rivets with one round fixed head emanated from the sharp neck below this head, most probably due to a lesser degree of filling just below this fixed head.
- The multiple cracks in joints with punched holes and 2 conical rivet heads emanated from the ridges on the rivet stem at the separation planes of the plates (remember the stappling sequence!).
- All cracks emanated at sites on the centre line (load line) of the specimens. No mode III cracks were observed.

Apparently a further increase in endurance of the rivet can only be obtained by using bored holes that are reamed after fixing the position of the plates with regard to one another. This technique was used formerly for pressure vessels, but is not feasible for the truck industry today.

JOINTS WITH MORE THAN ONE RIVET

General

The experiments described in the preceeding paragraphs were to optimize the quality and the economy of a joint with a single rivet.

Investigated were the influence of the hardness of the rivet, the type of primer, the hole quality and the method of riveting. Failures were rivet failures or were due to hole elongation.

In general however, joints consist of a pattern of rivets, and cracks in the plates are to occur when the net section stresses in the plates are increased.
Therefore the following joints (plates from Heat II material) were tested, see fig.13:
- single shear joints with 3 rivets in series.
- ,, ,, ,, with 3 rivets parallel.
- double shear joints with 4 rivets in a square.

The single shear joints are typical for truck chassis, while the double shear one is typical for steel constructions.

The dimensions of specimens were minimized, see the next paragraph, in order to promote plate failure and so to determine a lower bound of the endurances.

Rivet pattern dimensions.

For rivet patterns in steel constructions the following dimensions are recommended (DIN 15018 T2 and DIN 1050):
pitch : $a \geq 3d$
edge distance in loading direction : $e_1 \geq 2d$
edge distance in transverse direction : $e_2 \geq 1.5d$

Because here the rivet is harder than the plate, bulgeing of the plate may occur more easily than with soft rivets. Therefore the edge distance necessary to prevent bulgeing for the FeE 560 TM plate material (Heat II) was determined experimentally for rivets of different hardnesses.
The specimen used is given in fig. 14. Criterion was $(f1 + f2) \leq 0.4$ mm and the results are given in table 5.

TABLE 5 - Minimum Edge Distance, e, to prevent Bulgeing.

Plate HB	Rivet HB	Riveting Force, kN	e mm
240	230	350	26 = 2d
240	280	400	26 = 2d

From table 5 it appears that the minimum edge distance, e, has to be increased from 1.5d to 2d.
So for the joints with more than one rivet parallel, the following minimum dimensions were used:
$d = 12 + 1 = 13$ mm $a = 4d = 52$ mm
$e_2 = 2d = 26$ mm $e_1 = 2.67\ d = 35$ mm

Note that the ratio's e_1/e_2 and a/e_2 are equal to those in the DIN standards.

3 rivets in series, SS joint, fig.13a.

The results are plotted in fig.15 for CA loading and in fig.16 for VA loading, GAUSS, I=0,99.
In these figures the load F and also the net section stress, S (N/mm²)=2.16F(kN), are given.
All fractures except 3 were plate failures. The cracks were initiated near the outer rivets by fretting between the plate surfaces. The initiation sites were a few mm away from the hole at an angle of 10º to 70º to the tension direction, see fig. 17a.
The Basquin type equations are as follows:

C.A. loading : $7.80 \log F_a + \log N = 20.392$ (9)
or $7.80 \log S_a + \log N = 23.002$ (9a)

The fatigue limit for plate failure is estimated at $F_f = 65$ kN or $S_f = 140$ N/mm²

V.A. loading : $7.06 \log F_{rms} + \log N = 16.038$ (10)
or $7.06 \log S_{rms} + \log N = 18.407$ (10a)

Under CA loading and very high endurances also 3 rivet failures were observed, so that two S-N lines are to be distinguished, see fig.15.
The relation between these failures and those for the single rivets, eq.5, is as follows:
The loads, L, on the outer rivets are bounded between L=F/2 for rigid riveted connections and elastic plates and L=F/3 for rigid plates and elastic riveted connections.

Therefore in fig. 15 are also drawn the endurance lines which would apply when this joint would have 2 or 3 times the load carrying capacity of the joint with one rivet, eq.5. It follows that the load on the (outer) rivets was close to F/3.
So the rivet acts as a "soft spring".
In fig.16 the lines for 2 and 3 x eq.7 are plotted too, to allow further comparison with the single shear joint.

3 rivets parallel, SS joint, fig.13b.

The results are plotted in fig. 18 for CA loading and fig.19 for VA loading, GAUSS, I=0.99.
All speciments showed plate failure and the cracks were again initiated by fretting.
For CA loading the initiation sites were as sketched in fig.17a. For VA loading however, the crack in the centre initiated in front of the hole, apparently from plate bending, see fig.17b.
The Basquin type equations are

CA loading : $4{,}50 \log S_a + \log N = 14.761$ (11)
$S_f \leq 71$ N/mm²
VA loading : $8.15 \log S_{rms} + \log N = 19.823$ (12)

A plot in fig 19 of 3*(eq.7) shows that for VA loading the loadcarrying capacity of this joint is almost 3 times that of the joint with one rivet (however no rivet failures did occur).
In view of the above and the of low scatter for VA loading where

$S_{max}=5.26S_{rms}$, it is thought that the scatter for CA loading is caused by differences in load transfer between the rivets. Therefore the S_a-N curve, eq.11 is based on the lower endurances measured and is ment as a base for a design curve.
Note that the fatigue limit $S_f \leq 71$ N/mm² is extremely low as compared to the joints with 3 rivets in series, S_f=140N/mm², or to the joints with 4 rivets in a square, S_f=171 N/mm², described in the next paragraph.

4 rivets in a square, fig 13c.

The results are plotted in fig.20 for C.A. loading and in fig.21 for V.A. loading, GAUSS, J=0,99. All cracks initiated again from fretting between the plates near the holes, fig.17a, except the one specimen having an endurance of 2.4 * 10^6 cycles at S_{rms} = 34 N/mm². The cracks in this specimen initiated from the edges of the holes in the plate.

The Basquin type equation are
C.A. loading : 4,31 log Sa + log N= 15,727 (13)
Note that eq.13 is based , just as eq.11, on the lower endurances in the scatterband.
The fatigue limit is estimated at Sf = 171 N/mm² which means that, based as usual on the net section stress, $K_f \approx 2$ and very low indeed.
V.A. loading : 5,72 log S_{rms} + log N= 17,580 (14)
Note that eq. 14 follows from linear regression based on all specimens.
From fig.12 it follows that hole elongation was not to occur.

CONCLUSIONS

In order to improve the fatigue strength of riveted joints in high strength steels, high strength rivets were developed.
Joints made with these rivets in 6 mm FeE 560TM steel plate were extensively tested.
From optimizing the joining techniques on the base of fatigue- and other tests it follows that
- Rivets from 18 Mn B4 steel, Q and T to 350 HB or less, are rivetable by cold pressing.
- No stress corrosion was observed for 320 HB rivets under sustained load tests in brine at S= 380 N/mm².
- For FeE 560TM plate material rivets having a hardness of 280 HB are the most suitable.
- The use of a conical header for the round head of the rivet
- prevents fatigue failures from below the head.
- The edge distance of the rivet to avoid plate bulgeing is $e \geq 2d$
- Surface blasting resulting in a low surface roughness has positive effect on the endurances.

- Common corrosion resisting primers have a detrimental effect on the endurance. High friction primers are to be used.
- Punched holes decrease the fatigue strength of the rivet by 20% with reference to bored holes, however
- when plate failures occur, as in joints with more than one rivet, cracks initiate from fretting between the plates.

Furthermore endurance curves were obtained for constant amplitude loading and variable amplitude loading with the standard spectrum GAUSS for the following joints:
- single shear joints with 1 rivet
  3 rivets in series
  3 rivets parallel
- double shear joints with 1 rivet
  4 rivets in a square

From these endurance curves, preliminary design curves could be deduced.

ACKNOWLEDGEMENT

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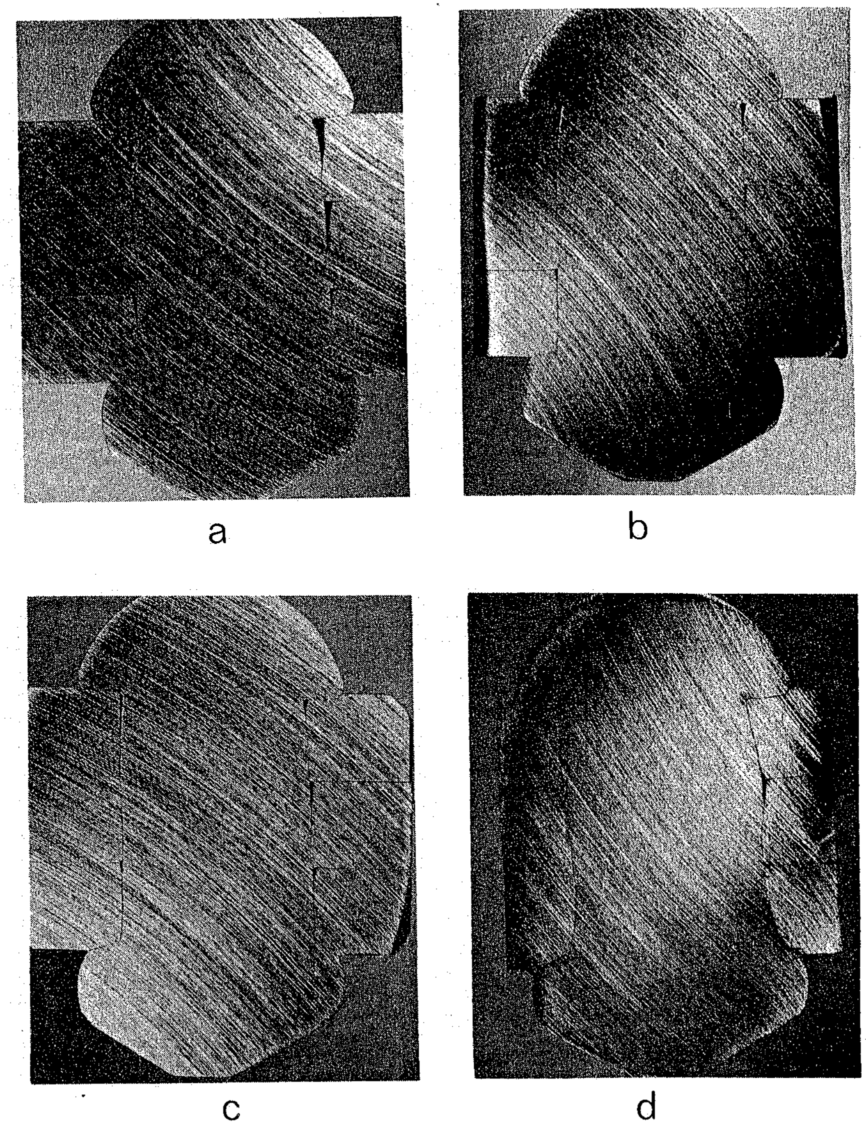


Figure 1. Cross section of joints with rivets of different hardness
a. 167HB b. 233HB c. 280HB d. 354HB

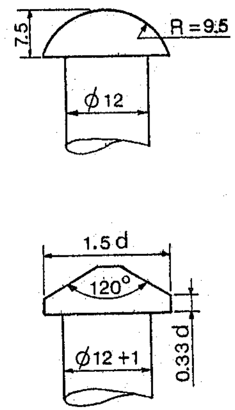


Figure 2. Dimensions of the rivet

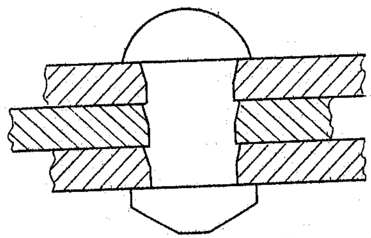


Figure 3. Stapling of the plates

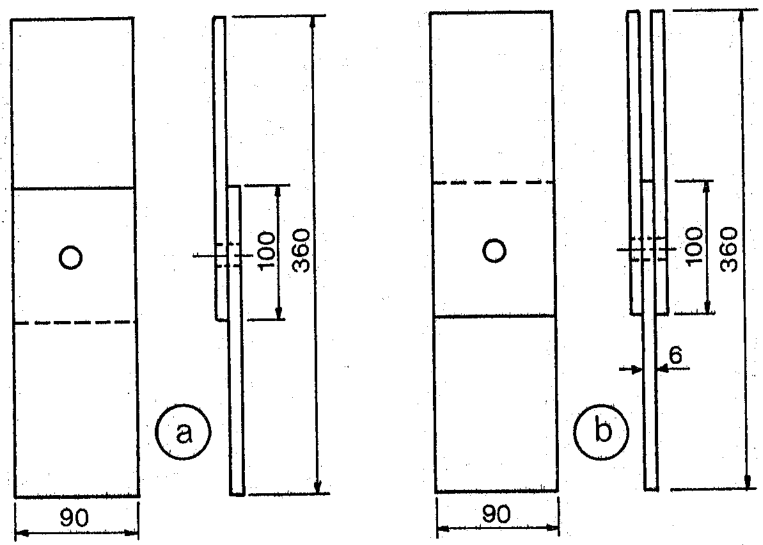


Figure 4. Specimens with one rivet
a. single shear (S.S.)   b. double shear (D.S.)

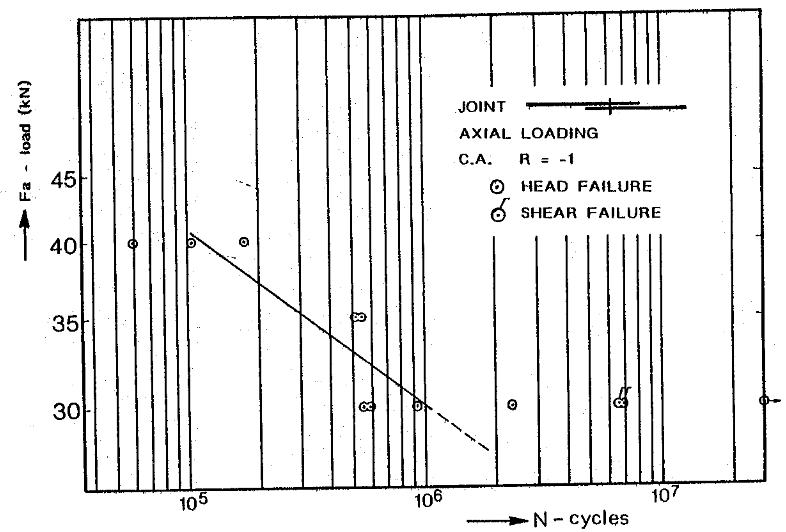


Figure 5. Results of C.A. tests, S.S. lap joint, round rivet head

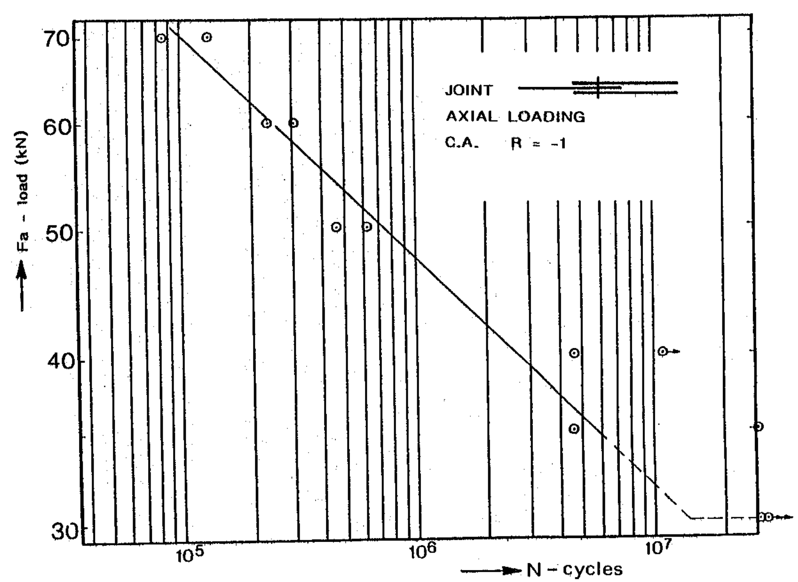


Figure 6. Results of C.A. tests, D.S. lap joint, round rivet head

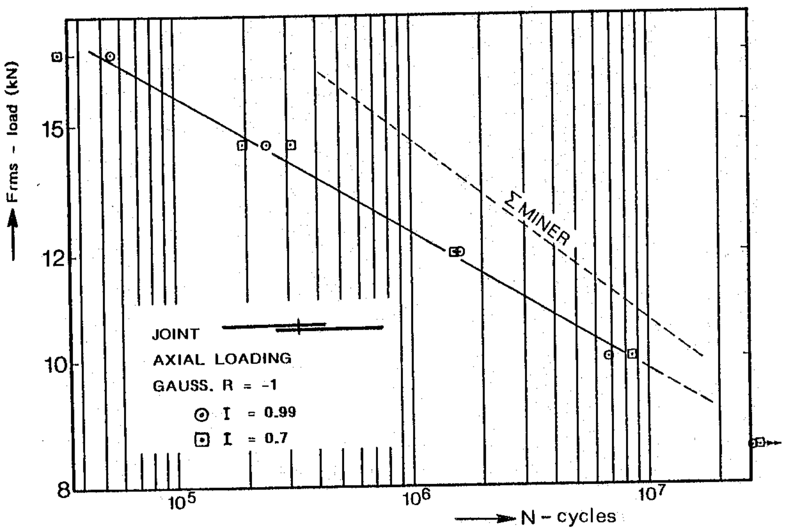


Figure 7. Results of V.A. tests, S.S. lap joint, round rivet head

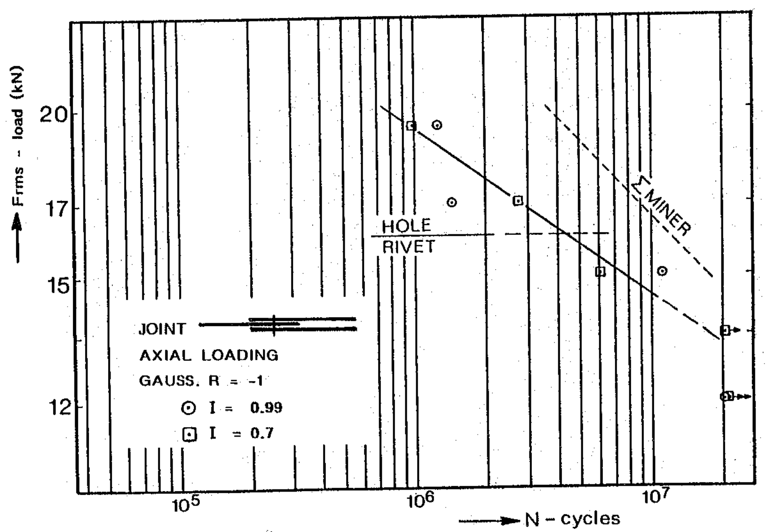


Figure 8. Results of V.A. tests, D.S. lap joint, round rivet head

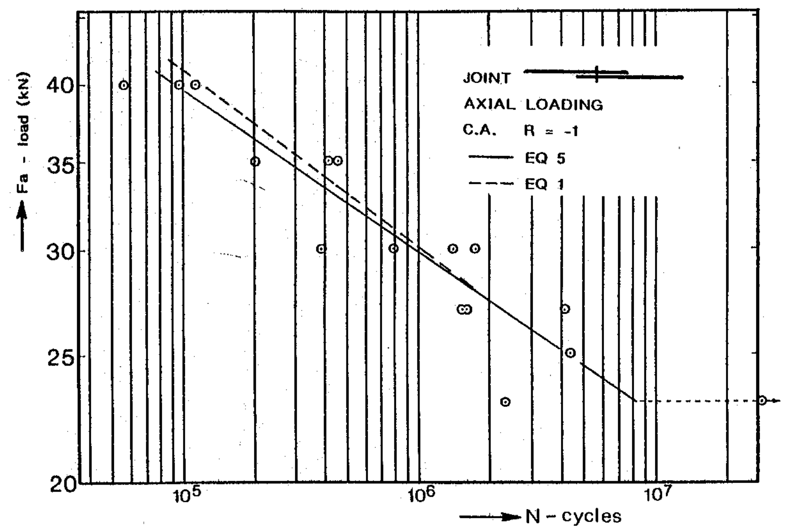


Figure 9. Results of C.A. tests, S.S. lap joint

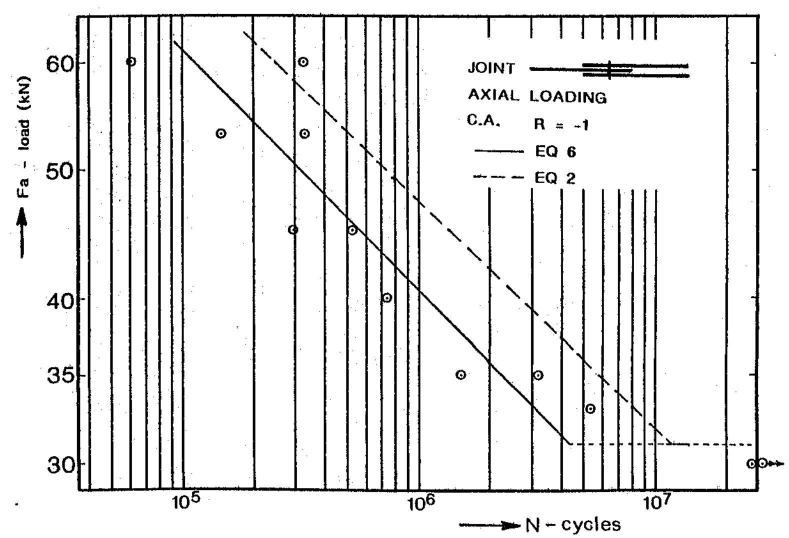


Figure 10. Results of C.A. tests, D.S. lap joint

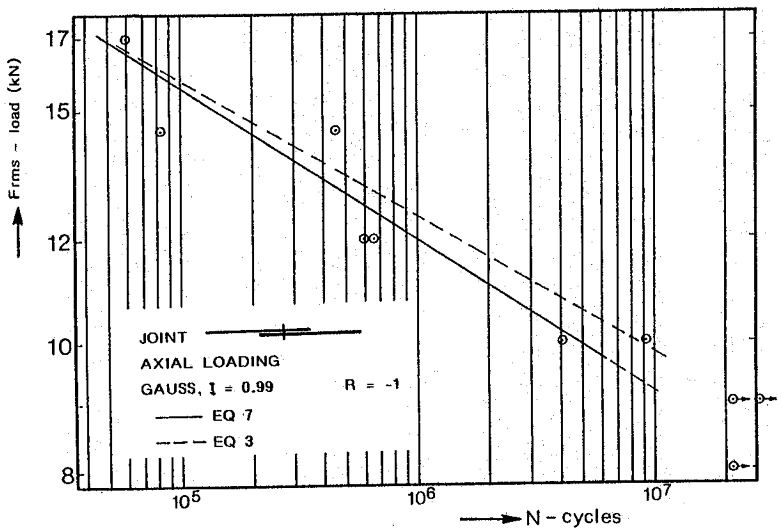


Figure 11. Results of V.A. tests, S.S. lap joint

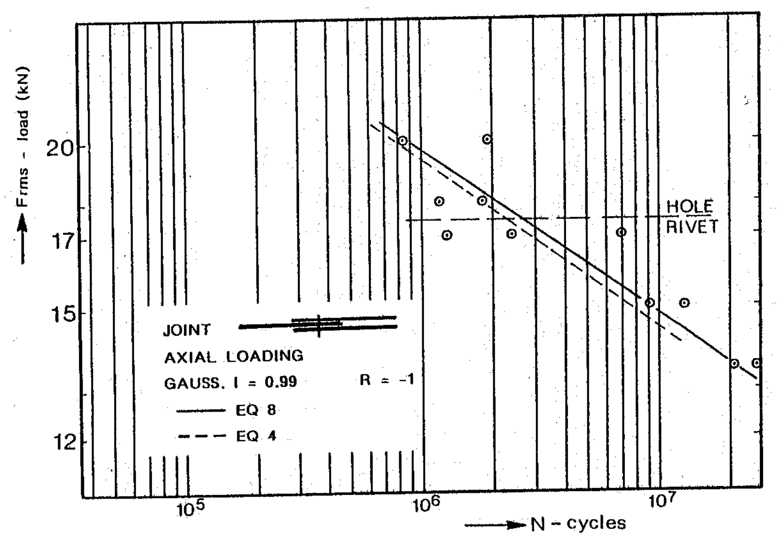


Figure 12. Results of V.A. tests, D.S. lap joint

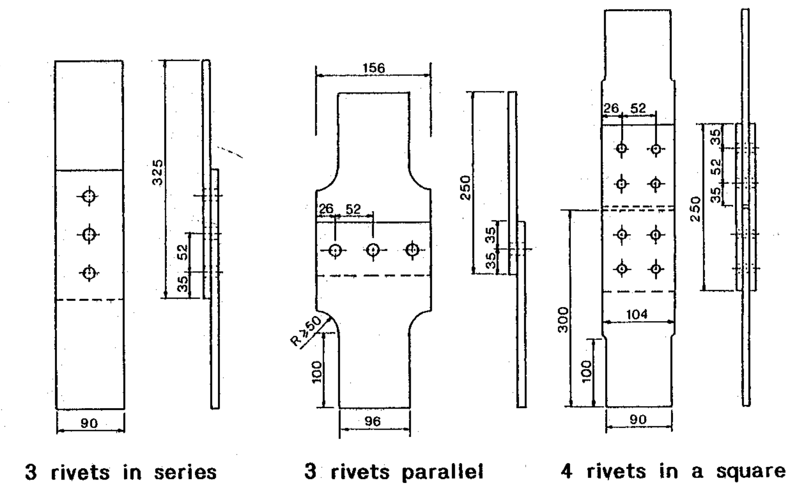


Figure 13. Specimens with 3 and 4 rivets, 6mm plate

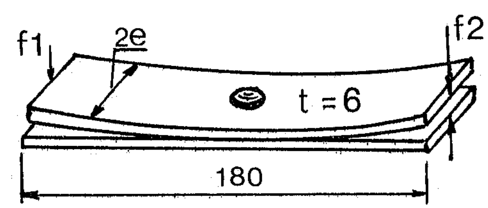


Figure 14. Specimen for bulge test

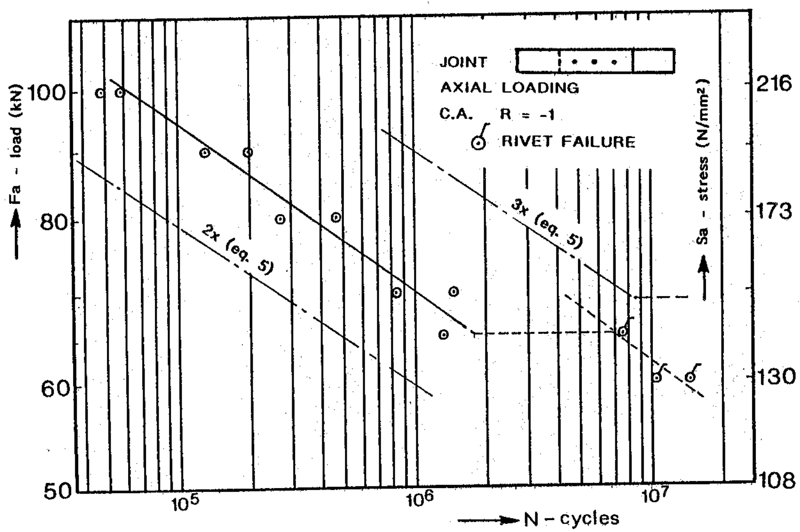


Figure 15. Results of C.A. tests, joint with 3 rivets in series

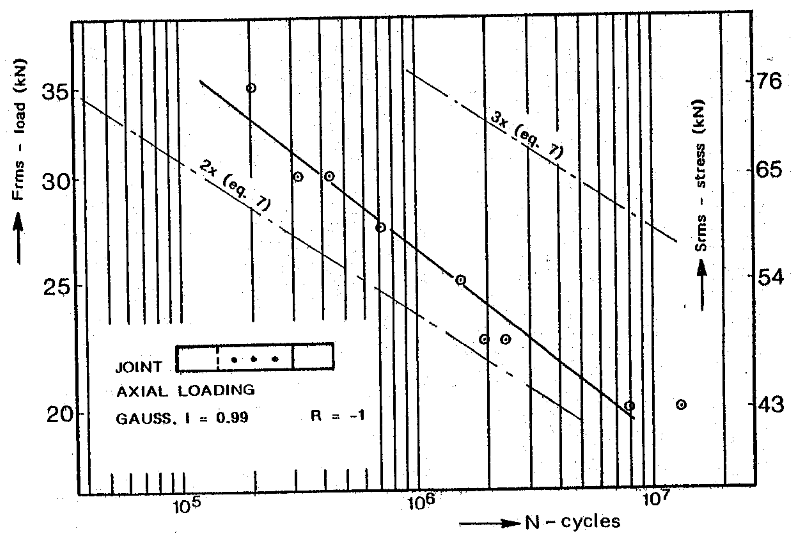
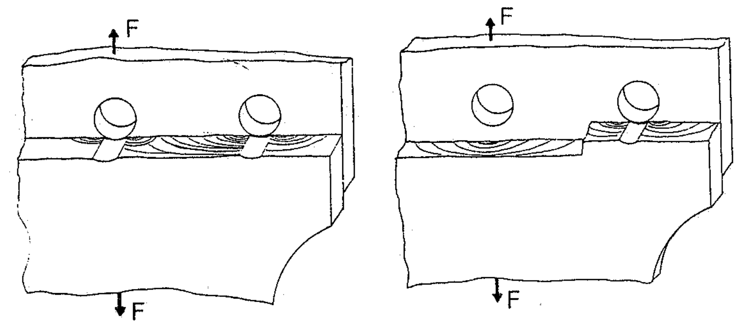


Figure 16. Results of V.A. tests, joint with 3 rivets in series

EIS 90 - ENGINEERING INTEGRITY THROUGH TESTING



a. near the hole b. in front of the hole

Figure 17. Crack initiations from fretting

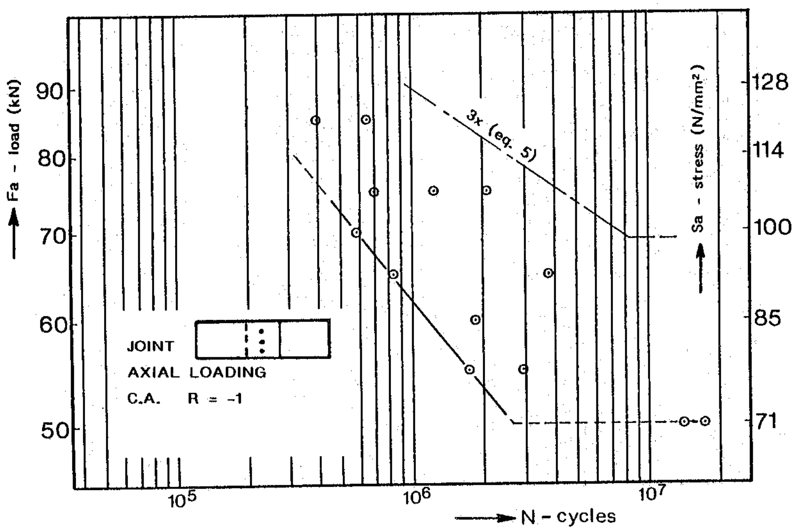


Figure 18. Results of C.A. tests, joint with 3 rivets parallel

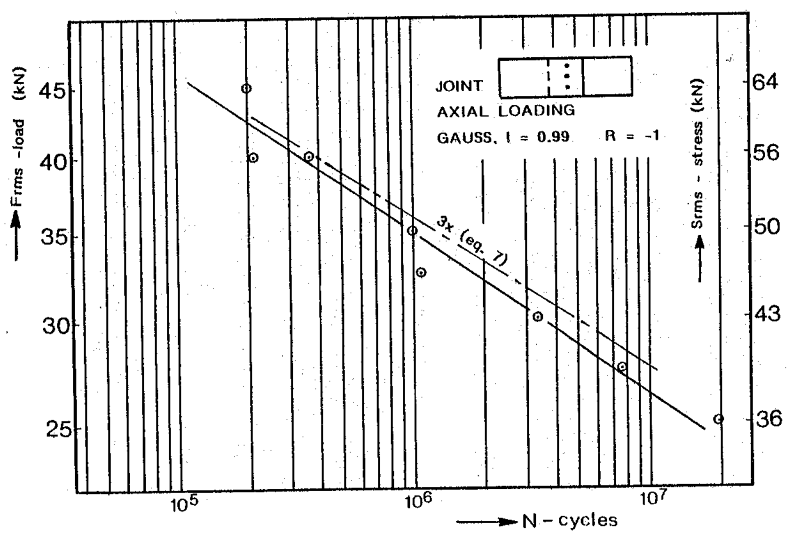


Figure 19. Results of V.A. tests, joint with 3 rivets parallel

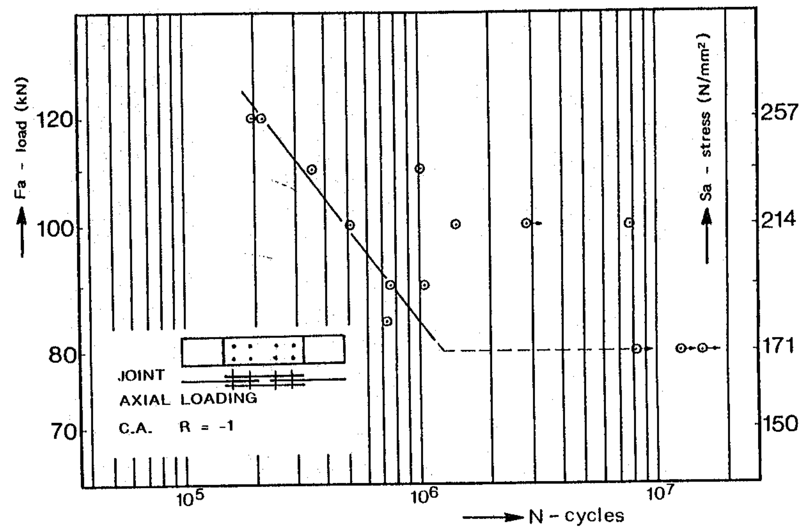


Figure 20. Results of C.A. tests, joint with 4 rivets in a square

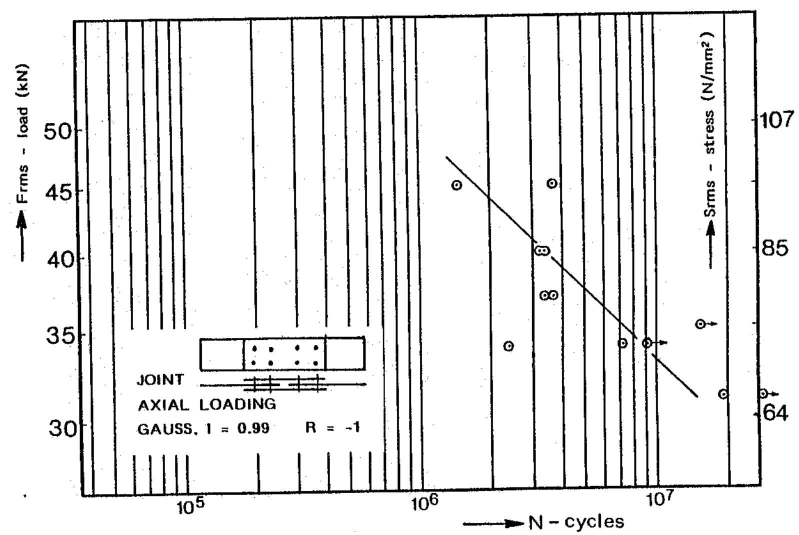


Figure 21. Results of V.A. tests, joint with 4 rivets in a square