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THEME 8

Mechanical Connections

Assemblages

Mechanische Verbindungen

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Fatigue Strength of Screwed Fastenings

Résistance à la fatigue d'assemblages vissés

Ermüdungsfestigkeit geschraubter Verbindungen

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SUMMARY
The present paper is concerned with the analysis of the behaviour of screwed fastenings subjected to repeated loading that can lead to fatigue. On the basis of statistical evaluation of experimental results empirical formulae are set up that make it possible to establish the design shear strength of screwed fastenings in light gauge steel structures subjected to repeated shear fluctuating loading.

RESUME
La présente contribution traite de l'analyse du comportement à la fatigue d'assemblages vissés de constructions en tôles minces soumises à l'action de charges répétées. Il décrit les différents cas de fatigue d'assemblages de tôles minces au moyen de vis, sous chargement répété. Sur la base de résultats statistiques, des formules empiriques sont établies pour le calcul des forces de cisaillement sous l'action de sollicitations variables de tels assemblages.

ZUSAMMENFASSUNG
Der Beitrag informiert über Forschungsergebnisse auf dem Gebiet der Schraubenverbindungen bei dünnwandigen Stahlkonstruktionen. Er beschreibt das Ermüdungsverhalten solcher Verbindungen unter wiederholter Belastung. Aufgrund statistischer Ergebnisse werden empirische Berechnungsformeln für die Bemessung von Blechschraubenverbindungen aufgestellt.

1. INTRODUCTION

One of the most widely used ways of connecting light gauge steel structures nowadays is by means of screwed fastenings. They differ from bolted fastenings primarily in the fact that they need no nuts since they make their own nut thread in the connected elements.

Very early, experimental research [1], [2] established essential differences in the behaviour of screwed fastenings in light gauge steel structures and that of bolted fastenings in thick steel structures. Therefore it was not possible, with regard to safety and economy of design, to apply the design formulae that were known only for bolted fastenings of thick steel structures to screwed fastenings. Lack of knowledge about the behaviour of the highly advantageous screwed fastenings on the one hand and growing pressure on their application on the other hand, stimulated extensive research in this field. Initially, this research was focused on cases of non-repeated loading [1], [2], [3], [4], [5], [6], later it grew in scope to include cases of repeated loading which can often lead to fatigue [7], [8], [9], [10], [11], [12], [13], [14].

The purpose of this contribution is
- a brief outline of the research carried out so far;
- a description of the typical behaviour of screwed fastenings subjected to repeated loading leading to fatigue;
- information about tentative formulae for characteristic loading range in repeated cyclic loading leading ta fatigue.

2. AN OUTLINE OF PAST EXPERIMENTAL RESEARCH

The primary aim of research in this field was to establish the actual behaviour of screwed fastenings of light gauge steel structures in different conditions. The result aimed at was principles and recommendations for design including design formulae.

On the basis of the materials available to us it can be said that as early as in 1971 the results of the first detailed research were published [2] describing the behaviour of screwed fastenings, including rupture modes, and giving the design formulae for the cases of non-repeated loading. Of great importance was the coordination of research in this field by European Convention for Constructional Steelwork. First recommendations for testing of connections in light gauge steel components were worked out [5] and then attention was turned to a whole range of problems connected with the design of fastenings [13]. This work also involved some problems of repeated wind loading that may, in some case, lead to fatigue of fastenings. For the sake of simplicity of design formulae, the effects of multi-level repeated wind loading were simulated by reduction of design loading observed in non-repeated loading [11], [12], [13].

In the course of the research into screwed fastenings subjected to repeated loading [9], [10] the importance of the influence of the development of plastic deformations on the fatigue strength of the fastening was observed.

3. THE RESPONSE OF A FASTENING TO REPEATED LOADING

The behaviour of screwed fastenings subjected to repeated loading, fatigue failure and failure mode are dependent on a number of conditions which can be summed up into four basic categories
- material parameters;
- parameters of manufacturing technique;
- design parameters;
- load parameters.

The influence of these conditions on fastening fatigue is gener - ally recognised and also the experiments performed are evaluated from this point of view. However, there still exists a group of problems important for the determination of fatigue [14] : in contrast to the other elements of steel structures, screwed fasten - ings of thin steel sheets generally exhibit considerable plastic deformations from the very beginning of loading. In the process of repeated loading, considerable discrepances in the behaviour of identical fastenings can be observed which cannot always be accounted for in terms of loading data alone. They are due to the different character of the development of plastic deformations in the process of loading which determines whether the failure observed is
- high-cyclic fatigue rupture;
- low-cyclic fatigue rupture;
- an increase of plastic deformation.

High-cyclic fatigue occurs if no plastic deformations are ob - served during loading or if initial plastic deformation gives rise to such residual stresses that shakedown occurs and the fastening continues to behave elastically. High-cyclic fatigue rupture is mainly characterised by an increase of fatigue cracks at a great number of loading cycles.

Low-cyclic fatigue occurs in the case of reversed plastification which leads to continual increase in plastic deformations. Rup - ture at a small number of loading cycles is also caused by an increase of fatigue cracks.

An increase of plastic deformations occures if there is no shakedown after the initial plastic deformation or if there are slips in the plastically deformed screw hole caused by repeated re - versed loading. Plastic deformations here make the fastening useless even before contingent rupture.

4. TENTATIVE FORMULAE OF FATIGUE STRENGTH OF SCREWED FASTENINGS

Experimental establishement of fatigue for each particular variant of fastening is very time-consuming and expensive. Therefore attempts are made at setting up empirical formulae with a more general validity that could be used as a substitute for experiments and could reduce their role to a mere verification of a chosen variant.

On the basis of experimental results obtained in Czechoslovakia, a model of design formulae was set up involving, in the first stage, screwed fastenings subjected to shear fluctuating loading.

Research has shown [10] that failure is commonly caused by high fatigue rupture or by increase of plastic deformations and that fatigue strength is well characterized by the loading range. The following formulae do not hold for cases of shear of fastener and end failure which we usually try to eliminate in advance through the design parameters chosen. The formulae proposed for repeated loading follow up the earlier empirical formulae for ultimate load in the case of non-repeated loading [4] :

$$F_{max} = K \times t \times R_m \times (D + 5), \text{ where} \tag{1}$$

$$t = 0.5\left[t_1 (\varkappa - 1) + t_2(3 - \varkappa)\right] ; R_m = 0.5\left[R_m^{t_1}(\varkappa - 1) + R_m^{t_2}(3 - \varkappa)\right]$$

If $\varkappa > 2$, we substitute $\varkappa = 3$.

In order to set up a model of the formulae expressing the relation between the loading range and the number of loading cycles achieved at the moment of fatigue rupture, it has been necessary to divide this dependence into two intervals characterized by different failure modes. These intervals are evident from log-log graph in Figure 1.

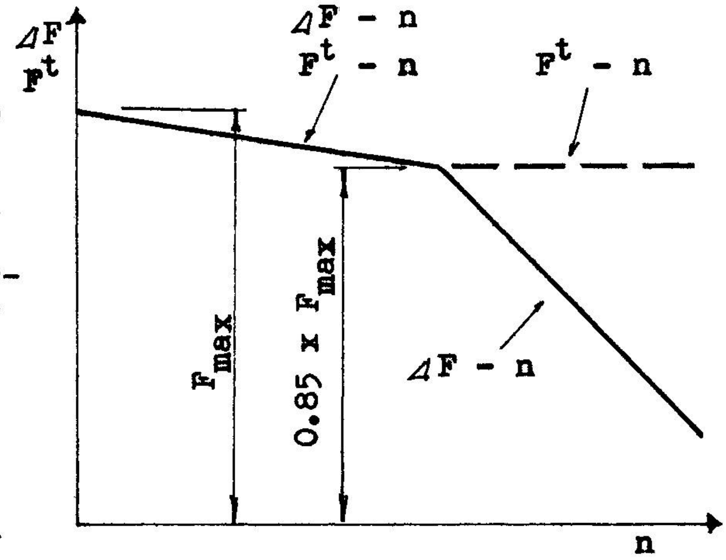

Fig. 1

In the first interval, the top value of repeated loading F^t is greater than $0.85 \times F_{max}$. In such cases plastic deformations increase considerably in the course of repeated loading. For this interval, the following dependence between F^t, ΔF and n is proposed :

$$\Delta F \leq F^t = F_{max} \frac{1}{n^C} \quad . \tag{2}$$

The practical value of this formula is rather small, for two reasons. First, the difference $F_{max} - F^t$ is relatively small compared with the possible scatter of F_{max} in actual fastenings, and thus the precision of the formula is small. Second the actual design of a fastening must, in this cases, take into account plastic deformations which impair the fastening long before rupture.

Typical of the second interval is the occurrence of high-cyclic fatigue. For the dependence of the loading range and the number of loading cycles achieved at rupture the following formula has been proposed :

$$\Delta F = 0.85 \times F_{max} \frac{1}{\left(\frac{n}{A}\right)^B} \quad . \tag{3}$$

This relation holds on condition that $F^t \leq 0.85 \times F_{max}$.

On the basis of earlier [4], [14] and recent experimental research in Czechoslovakia, the factors in (1), (2), (3) are proposed to be as follows :

$K = 0.80 + 0.35\ (\varkappa - 1)$

$A = 10^{5 - (R_m - 300) \times 0.007}$

$B = 0.08 + 0.05\ (\varkappa - 1)$

$C = 0.016$

Table 1 presents a comparison of some experimentally determined values with those calculated according to formulae (1), (2), (3). The experimental data given have been obtained by statistical evaluation of six identical samples. Owing to considerable scatter of results of identical tests found both in Czechoslovakia [14] and Sweden [9] we find advisable in future research to use more identical samples.

Formulae (1), (2), (3) relate to cases of rupture. Design values for calculations in limit states design are then determined ac - cording to Czechoslovak standards and regulations, as follows:

- In the case of non-repeated loading, design load is obtained by dividing characteristic load in (1) by material factor γ_m=2.05. Also, plastic deformations must be kept within acceptable limits.
- In the case of repeated loading leading to high-cyclic fatigue, design loading range is obtained by dividing loading range in (3) by material factor γ_m = 1.20.
- In the case of repeated loading leading to an increase of plastic deformations, formula (2) cannot be generally applied; instead, plastic deformations must be kept within allowable limits. It is advisable to choose the design loading range so that plastic deformations at a given number of loading cycles do not exceed 0.30 mm.

5. CONCLUSION

From the numerical comparison that has been carried out it can be concluded that the proposed model of formulae is in good agreement with the actual behaviour of the fastenings in which fatigue failure occurs. However, further research should bring the particular factors to greater precision and possibly include cases of cyclic repeated reversed loading which brings about a response of a fastening quite different from the response to fluctuating loading.

In fastenings subjected to repeated tensile loading, fatigue strength is influenced by a great variety of fastening para - meters. Therefore it seems that it will be better to test each case separately, rather than to set up complicated formulae.

NOTATIONS

F shear load per fastening

F_{max} ultimate shear load per fastening

n number of loadin cycles at failure

Table 1

CONNECTION					NON-FATIGUE STRENGTH		FATIGUE OF CONNECTION		
SCREW		SHEET		$\varkappa$	F_{max} [kN]		ΔF [kN] (F^t) [kN]	$n \times 10^{-6}$	
DIAMETER	TYPE	t_1 / t_2 [mm]	$R_m^{t_1}$ / $R_m^{t_2}$ [MPa]		EXPERIMENT	THEORY Formula (1)		EXPERIMENT	THEORY Formulae (2) (3)
6.3	Thread forming	0.84 / 5.00	339 / 369	>3	5.87	4.83	4.05 (4.50)	0.0888	0.0575
							3.15 (3.50)	0.1477	0.2324
							2.75 (5.00)	0.6330	0.4941
							2.52 (2.80)	1.0188	0.8028
							2.50 (5.00)	1.1593	0.8391
							2.12 (4.25)	1.8548	2.0970
4.0	Thread cutting	0.57 / 5.00	316 / 369	>3	2.35	2.43	2.00 (2.15)	0.0706	0.0924
							1.45 (1.60)	0.5843	0.5516
							1.00 (1.60)	3.0158	4.3465
6.3	Thread forming	0.84 / 0.84	339 / 339	1	3.24	2.57	2.02 (2.25)	0.2621	0.1419
							1.94 (2.75)	0.2293	0.2352
							1.80 (2.00)	0.7246	0.5998
							1.75 (2.50)	3.6226	0.8529
							1.40 (2.01)	11.8853	13.8770
4.0	Thread forming	0.63 / 0.63	325 / 325	1	1.41	1.47	1.30 (1.30)	0.0009	0.0021
							1.00 (1.10)	0.5143	1.0819
							0.81 (0.90)	12.9763	15.0708
6.3	Thread forming	0.57 / 0.82	316 / 327	1.49	2.66	2.70	2.45 (2.45)	0.0001	0.0004
							2.00 (2.25)	0.1866	0.2550
							1.75 (2.25)	0.4315	0.9208

F^t top value of repeated load

F^b bottom value of repeated load

ΔF loading range ($\Delta F = F^t - F^b$)

D nominal diameter of screw

$\varkappa$ stress-thickness ratio

$$\left(\varkappa = \frac{t_2 \times R_m^{t_2}}{t_1 \times R_m^{t_1}} \right)$$

t_1, t_2 thickness of the thinner, thicker steel sheet

$R_m^{t_1}$, $R_m^{t_2}$ ultimate stress of the thinner, thicker steel sheet

K, A, B, C experimentally determined factors

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Fatigue Behaviour of Riveted Joints

Comportement à la fatigue d'assemblages rivetés

Ermüdungsverhalten genieteter Verbindungen

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SUMMARY
Previously, most dynamically loaded steel structures, such as bridges and cranes, were designed in accordance with the specifications in force at that time. The increasing of loads has posed the question of expected reserve life. In order to assemble more information concerning fatigue life prediction, a review of data available in current literature is given in this paper with regard to the fatigue behaviour of riveted joints and the variables affecting fatigue strength.

RESUME
De nombreuses constructions métalliques actuelles, telles que ponts et ponts-roulants, soumises à des charges dynamiques, ont été dimensionnés sur la base des normes de calcul d'alors. L'augmentation des
charges dynamiques, ont été dimensionnées sur la base des normes de calcul d'alors. L'augmentation des
charges met en question la durée de vie restante de l'ouvrage. Afin de fournir une meilleure information fatigue d'assemblages rivetés et aux paramètres influençant la résistance à la fatigue.

ZUSAMMENFASSUNG
Viele bestehende, dynamisch beanspruchte Metallkonstruktionen wie Brücken und Kranbahnträger sind aufgrund älterer Bemessungsgrundlagen erbaut worden. Infolge der Belastungszunahme im Laufe der Zeit stellt sich heute die Frage bezüglich der Restlebensdauer. Um bessere Informationsgrundlagen für die Vorhersage der Lebensdauer zu erhalten wird hier ein Überblick über Angaben aus neuerer Literatur betreffend das Ermüdungsverhalten genieteter Verbindungen sowie die Einflussparameter auf die Dauerfestigkeit gegeben.

1. INTRODUCTION

Extensive fatigue tests of riveted joints were carried out in Germany in the 1930's. Well known are the testseries of O. Graf [5] and K. Klöppel [3].
In the USA there were studies conducted at the University of Illionois and Northwestern University [8]. Several investigations in the USA were reported in AREA Proceedings and Transactions ASCE [4], [7], [11].

The variables studied by the investigators were the effect of the clamping force, bearing-tension ratio (B/T) and the shear-tension ratio (S/T) on the fatigue strength of double lap and single lap riveted joints.
Also were studied the influence of the ratio R = min.stress /max.stress and the effect of paint on the contact surfaces (red lead).
The specimens were made of mild steel (A7, St37) or low alloy steel (A242, St52).

The results of the fatigue tests of riveted joints show a great scatter.
In his contribution to the AREA Seminar of 1968 [1] W.H. Munse gives a scatterband of riveted joints. In the present paper the scatterband for the ratio R = 0 of the study of W.H. Munse is used as a reference in all presented figures to establish the influences of the variables mentioned above.
In a double logarithmic network the upper bound has a slope of k = 8,3, the slope of the lower bound is k = 6,1. Fig. 1 shows these bounds, and gives also as a reference the results of fatigue tests on specimens with new drilled open holes.

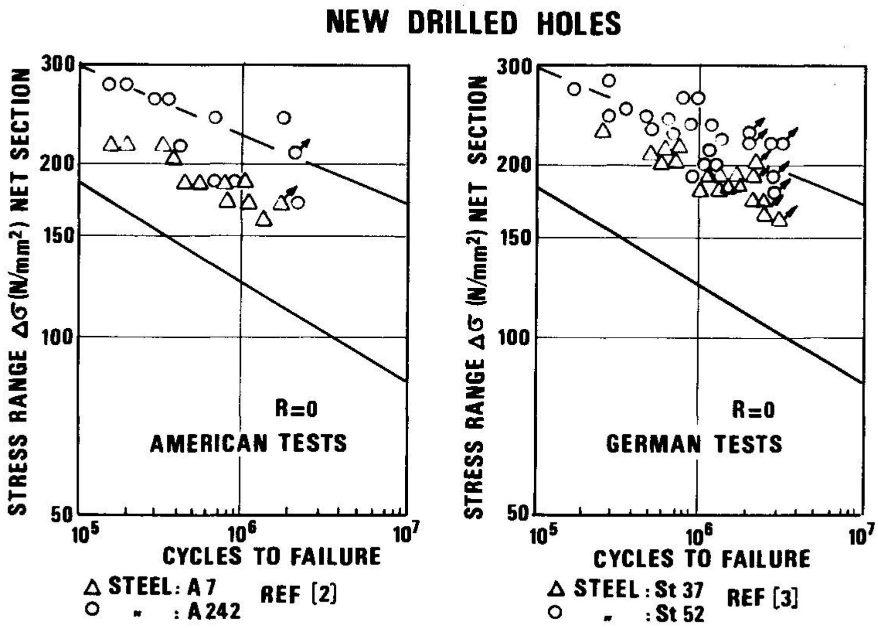


Fig. 1 Comparison new drilled holes

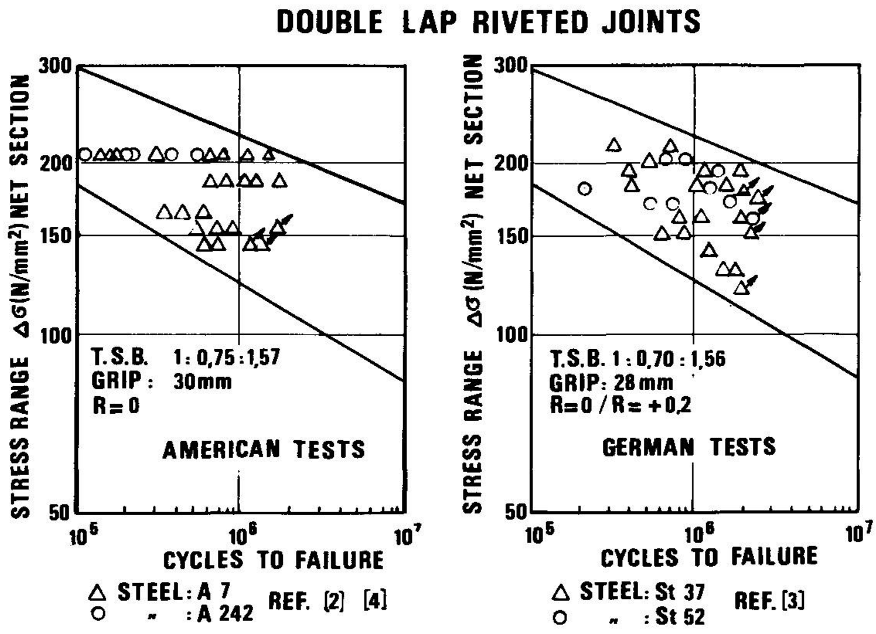


Fig. 2 Comparison riveted joints

The data of the fatigue behaviour of riveted joints presented in this paper concern connections with hot driven rivets.
The experimental data obtained from American and German double lap fatigue tests having a tension : shear : bearing ratio (T : S : B) of about 1,00 : 0,75 : 1,60, according to the standard specification for design of riveted structures, are given in fig. 2.
These data are lying within the scatterband.

2. EFFECT OF VARIABLES

2.1 Clamping force

One of the most important factors affecting the fatigue strength of a riveted joint is the clamping force. When the clamping force is great the main part of the load is transferred by friction between the plates and the rivets are less in bearing. The resulting stress concentrations near the holes are in that case much less severe.
An increase in the clamping force of the rivets results in an increase in the fatigue strength of the joint.
Theoretically the clamping stress in the rivet is independent of the length of grip. However shrinkage after driving causes some deformation of the rivet heads through which the clamping stress decreases. For a longer grip this deformation is a smaller part of the total length shrinkage of the rivet than for a shorter grip.
That is why the clamping force of hot driven rivets increases with the length of grip.

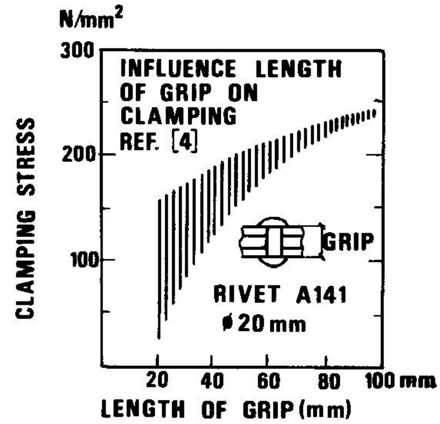


Fig. 3 Clamping stress

For a grip of about 100 mm the clamping stress approaches the yield stress (fig. 3). The shorter grips show a wide spread with lower clamping stresses. There is no assurance that a long grip will always develop a high clamping force in the whole joint.
The clamping stresses given in fig. 3 concern rivets of low carbon steel (A141) which has more or less the same properties as steel St.34.
Rivets of alloy steel may develop in some cases a very low clamping force.

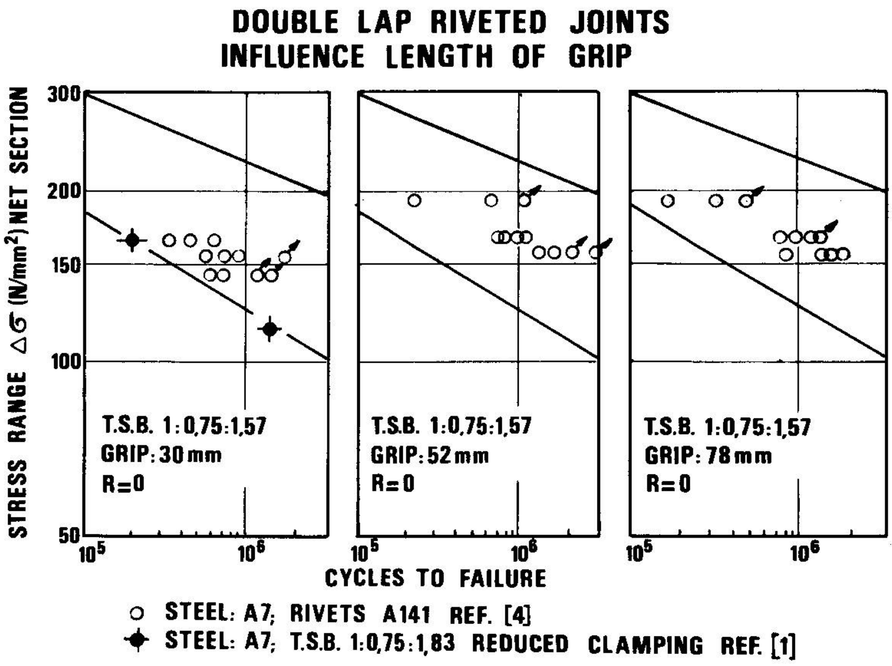


Fig. 4 Influence length of grip

Fig. 4 shows the influence of variable grip length on fatigue. The results of the tests with reduced clamping are lying at the lower bound.

2.2 Tension : Shear : Bearing ratio (T : S : B)

For a proper design the American specifications require a tension-shear-

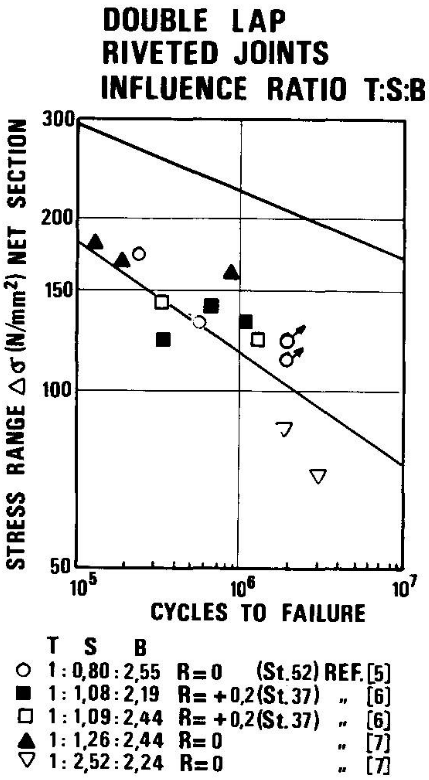


Fig. 5 Influence ratio T:S:B

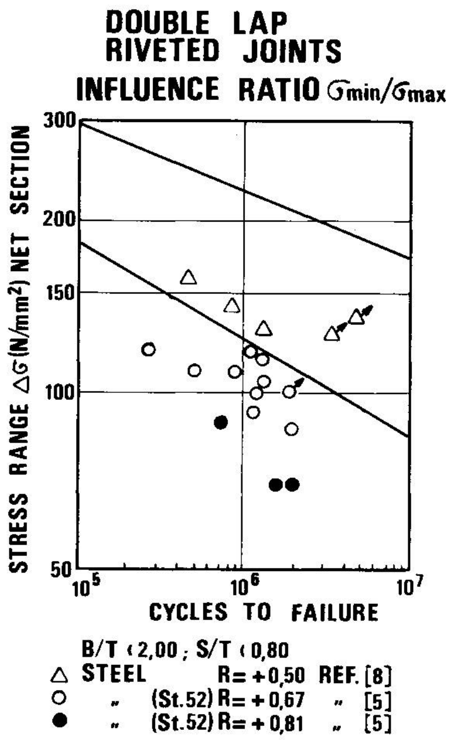


Fig. 6 Influence ratio R

bearing relationship of 1 : 0,75 : 1,50.
The German specifications allow for this ratio 1 : 0,8 : 2,00.
The results of fatigue tests on double lap joints with these ratios are concentrated within the mentioned scatterband.
Having a ratio of S/T = 0,8, the fatigue strength will decrease byond ratios of about B/T = 2,0. This is much severe in proportion to less clamping. Combined high bearing and high shear stress will further reduce the fatigue strength.
Fig. 5 shows some examples.

2.3 Ratio R = σ min/σ max

The adopted scatterband of Munse [1] for zero to tension (R = 0) represents the scatterband of the stress range for this ratio.
A comparison of the testdata shows that when the ratio R increases the stress range decreases.
This behaviour can be explained by the absence of residual stresses.
The largest stress range is found for R = -1,0.
Fig. 6 shows that the plotted data of the example for R = +0,5 with ratios B/T < 2,0 and S/T < 0,8 are within the scatterband of the stress range for R = 0.
Byond the ratio R = +0,5 the stress ranges decreases rapidly.

2.4 Painting of the contact surfaces

Most of the tested riveted specimens were assembled without painting of the contact surfaces and had the mill scale intact.
There are some experiments with riveted joints of which the joined parts were painted with red lead prior to assembly.
The coefficient of friction of surfaces with mill scale varies from about 0,30 to 0,40. The friction coefficient of surfaces with red lead is about 0,10.
Low frictional resistance brings the rivets in more bearing and causes a decrease of the fatigue strength.
Results of fatigue tests on specimens with painted contact surfaces are shown in fig. 7.

2.5 Drifting of holes

When holes for connection do not coincide and are drifted by a pin, there is an elongation at one side of the holes that may develop initial cracks.
Drifting of holes during manufacturing and construction greatly reduces the fatigue strength.
Fig. 8 shows the results of fatigue tests on specimens with drifted open holes, coming from removed parts of an existing bridge [9].
One result is given of a fatigue test on a specimen with drifted holes containing bolts in bearing with no clamping [11].
Punching of holes has a similar effect as drifting.

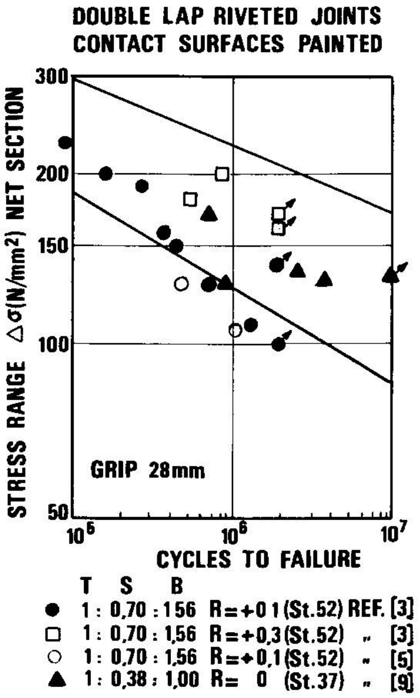


Fig. 7 Influence paint

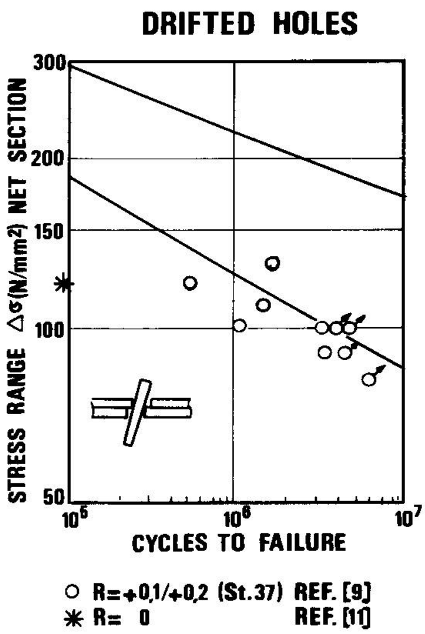


Fig. 8 Influence drifting

2.6 Single lap joints

In the middle of the 1940's fatigue failures were found in floorbeam hangers of railway bridges in the USA. These failures all occured in riveted single lap joints.
An extensive investigation was started in 1947 and continued to 1954.
The failures were explained by the fact of eccentric bearing, causing high stress concentrations at the edge of the holes, coupled with low clamping. This was proved by fatigue tests of Wyly and Carter with single lap connections having bolts in bearing with no clamping [11]. The results of these tests are shown in fig. 9b.
Single lap connections as beams with riveted cover plates and connections of beams to gusset plates always have some eccentricity. Even in the case of sufficient clamping the effect of the addition of bending will reduce the fatigue strength. Fig. 9a presents some examples.

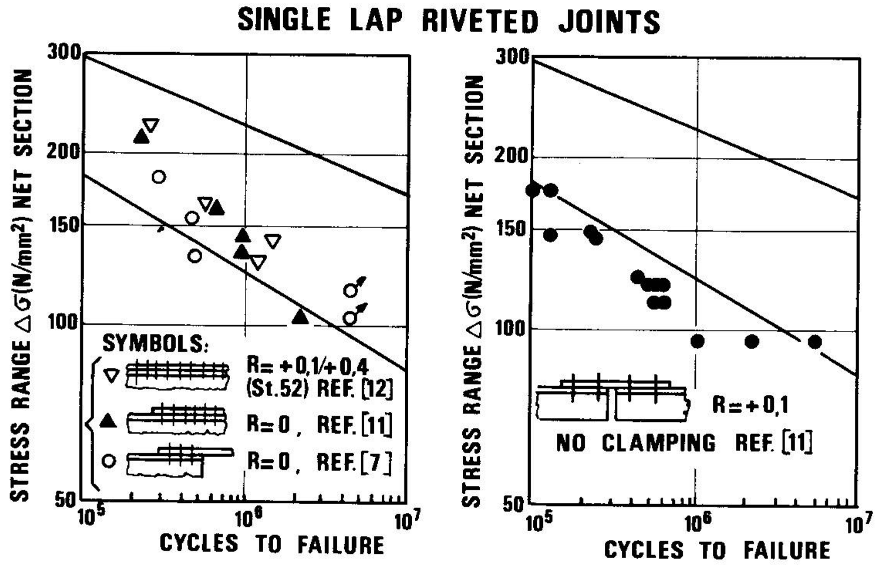


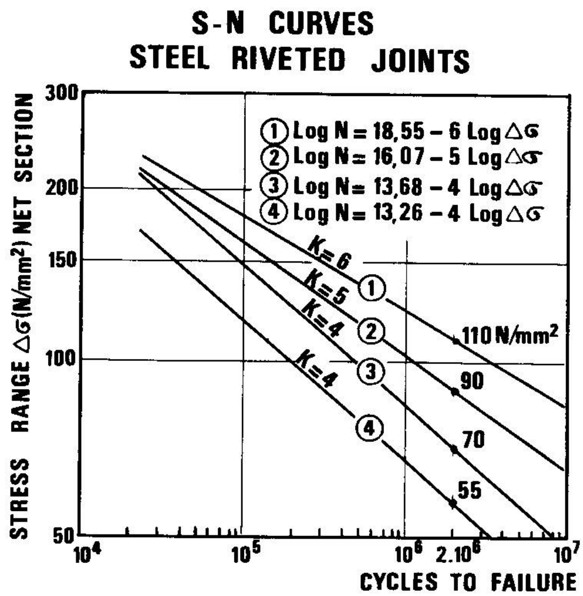
Fig. 9a - Fig. 9b Single lap riveted joints

2.7 Grade of steel

There is no significant difference between the fatigue strength of riveted joints of steel A7 and A242, and St.37 and St.52 respectively.

3. CHOISE OF S-N CURVES

In order to get a more reasonable prediction of fatigue life the various types of riveted steel joints are distinguished.
Fig. 11 shows four S-N curves. The S-N curve for double lap joints (1) is similar to the lower confidence limit of the study of Munse [1] and has a slope k = 6.
The S-N curves (2), (3) and (4) also represent more or less lower confidence limits and have with respect to higher stress concentration steeper slopes with values assumed k = 5 and k = 4 respectively.
To take in account the influence of the ratio R, a difference is made between R = 0 and R = +0,5
The choice between the two S-N curves for the single lap joints depends on the rate of stiffness of the sustaining parts. Not all cases are covered by these S-N curves. When there are severe secondary stresses due from



CHOISE S-N CURVES STEEL RIVETED JOINTS S/T‹0,8; B/T‹2,0		
TYPE OF JOINT	R=0	R=~+0,5
DOUBLE LAP	(1)	(2)
DOUBLE LAP (PAINTED)	(2)	(3)
SINGLE LAP	(2) (3)	(3) (4)

Fig. 10 S-N curves steel riveted joints

eccentricity, these stresses have to be taken in account.

4. WROUGHT IRON RIVETED JOINTS

Most of the bridges built in the 19th century have been made of wrought iron.
During the last decennia in various countries fatigue tests were carried out on specimens of wrought iron. Fig. 12 shows the results of testseries in the Netherlands [10].
For comparison the scatterband of the steel riveted joints as used previously is plotted in this figure.
As one can see the results illustrate in comparison to steel a lower fatigue strength for the wrought iron specimens with new drilled open holes.
The same tendency show the results of the tests with the wrought iron riveted joints taken from old bridges.
To determine the lower confidence limit the results of the test on the riveted joints are assimilated in a modified Goodman diagram for 2.000.000 cycles (Fig. 12).
An assumption of the lower limit is obtained dividing the mean values by a factor of 1,4.
Fig. 12 also shows the corresponding equations of the S-N curves.

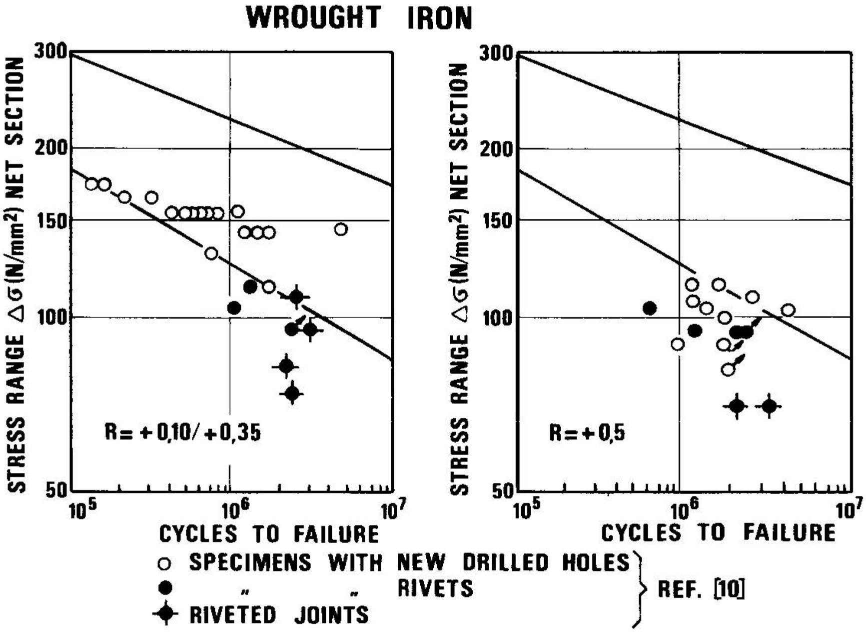
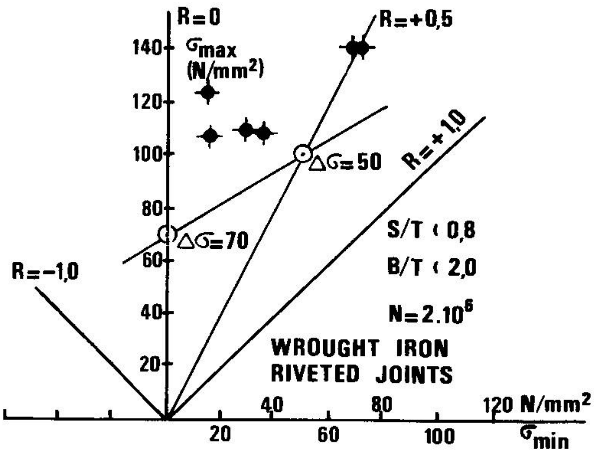


Fig. 11 Fatigue tests wrought iron

5. FINAL REMARKS

The fatigue strength of riveted joints was shown to be affected by several factors.
One of the dominant factors is the clamping force of the rivets.
Most sensitive to fatigue are the single lap connections.



WROUGHT IRON RIVETED JOINTS S/T < 0,8; B/T < 2,0 S-N CURVES	
R=0	R= +0,5
$\log N = 15{,}52 - 5\log\Delta\sigma$	$\log N = 14{,}80 - 5\log\Delta\sigma$

Fig. 12 Fatigue behaviour wrought iron riveted joints

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ASCE = American Society of Civil Engineers
AREA = American Railway Engineer Association

Fatigue Strength of Joints with Bolts in Staggered Patterns

Résistance à la fatigue des assemblages boulonnés de type échelonné

Ermüdungsfestigkeit von Verbindungen mit versetzt angeordneten Schrauben

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SUMMARY
In connections made with high-strength bolts in staggered patterns the fracture path, under fatigue loading, is frequently different from that under static loading. As a result of fatigue tests on a large number of specimens, with various stagger patterns, it was found that, irrespective of the pattern, the fatigue stress intensity calculated on the basis of the gross sectional area is almost constant. An allowable stress range for high-strength bolted connections based on the gross sectional area is recommended.

RESUME
Dans les assemblages réalisés avec des boulons à haute résistance de type échelonné, le mode de rupture sous des charges de fatigue est souvent différent de celui sous des charges statiques. Les résultats d'essais de fatigue sur un grand nombre d'éprouvettes, avec différents types d'échelonnement, ont montré que, indépendamment du type, l'intensité de la contrainte de fatigue, calculée sur la base de la surface de la section brute, est presque constante. Une contrainte admissible dans de tels assemblages basée sur la surface de la section brute, est recommandée.

ZUSAMMENFASSUNG
Bei hochfesten Schraubenverbindungen mit versetzt angeordneten Schrauben ist der Verlauf der Bruchlinie unter Ermüdungsbelastung oft verschieden gegenüber dem Bruchverlauf unter statischer Belastung. Als Ergebnis einer grossen Anzahl Versuche an Prüfkörpern mit verschiedener Schraubenanordnung wurde festgestellt, dass die Ermüdungsspannungsintensität, berechnet am Bruttoquerschnitt, unabhängig vom Verbindungstyp ist und praktisch konstant bleibt. Es wird demnach für hochfeste Schraubenverbindungen ein zulässiger Spannungsbereich, basierend auf der Bruttoquerschnittsfläche, empfohlen.

1. INTRODUCTION

According to the current design specifications, the stress intensity working in the sectional area of a tension member connected by rivets with a stagger pattern is checked on the basis of the net sectional area which is calculated by so-called V. H. Cockrane's Formula as follows; "The net width for any chain of holes extending progressively across the part shall be obtained by deducting from the gross width the sum of the diameters of all the holes in the chain and adding, for each gage space in the chain, the quality; $p^2/(4g)$ where p= pitch of any two successive holes in the chain, and g= gage of the same holes". This is currently applied also to the design of high-strength bolt joints in tension members. It has been used for a long time and may be reasonable in the case where loads are statically applied. It is, however, known that the type of fracture of a tension member connected with rivets or high-strength bolts with a stagger pattern under repeated loading is different from that under statical loading. Under the fatigue loading crack proceeds generally from the bolt or bolts in the first row straightly in the direction perpendicular to the axial tensile stress.

The authors investigated the fatigue strength of specimens which were spliced with high-strength bolts arranged in a stagger pattern in order to find a formula that can be applied to such cases. In the test specimens the pitch between bolt rows and the gage between bolt lines were varied in order to clarify their influence on the fatigue strength.

2. SPECIMENS AND APPARATUS

The dimensions, designation and number of the specimens are shown in Fig 1. All of them are connected with a double splice. The specimens of Series A are provided with three bolt lines and the pitch between the first bolt row and the second one varies from 10 to 30 mm, while the gage between bolt lines is kept invariable, 35 mm. The specimens of Series B are provided with five bolt lines and the other conditions are identical with those of Series A. The specimens of Series S are similar to those of Series A, except that the gage is changed; 30 mm in S-1 and 40 mm in S-3, while the pitch between the first row and the second row is kept invariable, 20mm. Together with A-3 the test results of this series were expected to reveal the influence of the gage length.

All the base plates and splice plates are 6 mm thick and their physical and chemical properties conform to the requirements of JIS-SS 41. According to the static test on the coupon specimens the yield point and the ultimate strength are about 34 kg/mm^2 and 46 kg/mm^2, respectively. Plates of 108 mm in width and 16 mm in thickness were attached to the base plates by welding so as to fit the grip of the testing machine. The surface of the base plates and the splice plates were shot-blasted in a roughness of 50μ on average. High-strength bolts of F 10 T and 12 mm in nominal diameter were used. They were tightened by a torque wrench with an axial tension up to 6.3 tons.

In the fatigue test, the specimens were tested by a 100 ton-fatigue machine in a tension range from 2 kg/mm^2 to a maximum at a rate of 600 cycles per minute. Prior to the fatigue test, the static test was conducted on two specimens from each kind.

3. TEST RESULTS

3.1 Static Test

Because the main purpose of the investigation conducted this time is the fatigue behavior, the results of the static test will be briefly presented only for comparison to the fatigue test results. There are roughly two kinds of fracture type according to the difference of geometric pattern of bolt arrangement; straight type and zigzag type. Fig 2 shows the classification of all the specimens into the two frature types. Figs 3, 4 and 5 give the ultimate stress intensity on the basis of the net sectional area calculated by Cockrane's Formula, the one on the basis of the fracture sectional area and the one based on the gross sectional area, respectively. (Photos 1 and 2)

3.2 Fatigue Test

Crack started from the bolt hole or holes on the first row in the direction perpendicular to the applied force, that is, at right angles with the plate surface and the side edge. In some of the specimens the crack passed throughout across the whole section. (Photos 3 and 4)

According to some fatigue tests conducted by other investigators, however, the crack did not started from the hole edge, but from the portion of the base plate just under the front edge of a bolt-washer.

Figs 6, 7 and 8 show the relations of all the specimens between the number of loading cycles of fracture formation and the stress intensity. In Fig 6 the stress is expressed on the basis of the net area calculated by Cockrane's Formula, in Fig 7 on the basis of the fracture area (the net area across the first row of holes)and in Fig 8 based on the gross sectional area. The correlation coefficients in reference to the straight line drawn by means of the least squares method are 0.565 in Fig 6, 0.886 in Fig 7 and 0.867 in Fig 8.

Figs 9, 10 and 11 give the relations between the stagger angle Θ (See Fig 1) and the fatigue strength in two million cycles of loading repetition. The areas referred to for the stress calculation in Figs 9, 10 and 11 are the same as those in Figs 6, 7 and 8, respectively. In Figs 9, 10 and 11 the results of test series previouly conducted by the authors on the specimens provided with only one bolt line, designated as TA, and those with four bolts in each row, designated as TB, are added for comparrison.

4. DISCUSSION

4.1 Static Test

In the static test the ultimate stress intensity shown in Fig 3 decreases as the stagger angle Θ increases. It means that the Cockrane's Formula is not quite adequate, but at least up to about 45 degrees the values are considerably higher than the ultimate strength obtained from the coupon test specimens, 46 kg/mm^2, thus giving conservative values.

Fig 4 shows a similar tendency to Fig 3, but there is a great discrepancy between the result of Series A and that of Series B. Moreover, this method can not be applied to an actual design, because the fracture path can not be determined before the test is done.

Fig 5 show that the values are not constant with variation of Θ and, moreover, considerably lower than 46 kg/mm^2. Therefore, the stress calculation disregarding the deduction of the sectional area due to bolt holes is not adequate.

In conclusion, it will be better to develop a new calculation method for the static strength of the connection with high-strength bolts with a stagger pattern. But in order to formulate a new one, much more test should be conducted, varying the conditions such as bolt patterns, plate width, plate thickness and stress.

4.2 Fatigue Test

In the fatigue test, while the values in Fig 6 have a considerable scattering (c= 0.565), those in Figs 7 and 8 both have a small scattering (c= 0.886 and 0.867, respectively). In Fig 9 the fatigue strength is not constant, but decreases as the stagger angle Θ increases. It may be concluded from both Figs 6 and 9 that Cockrane's Formula is not adequate to predict the fatigue strength of bolt connection with a stagger pattern.

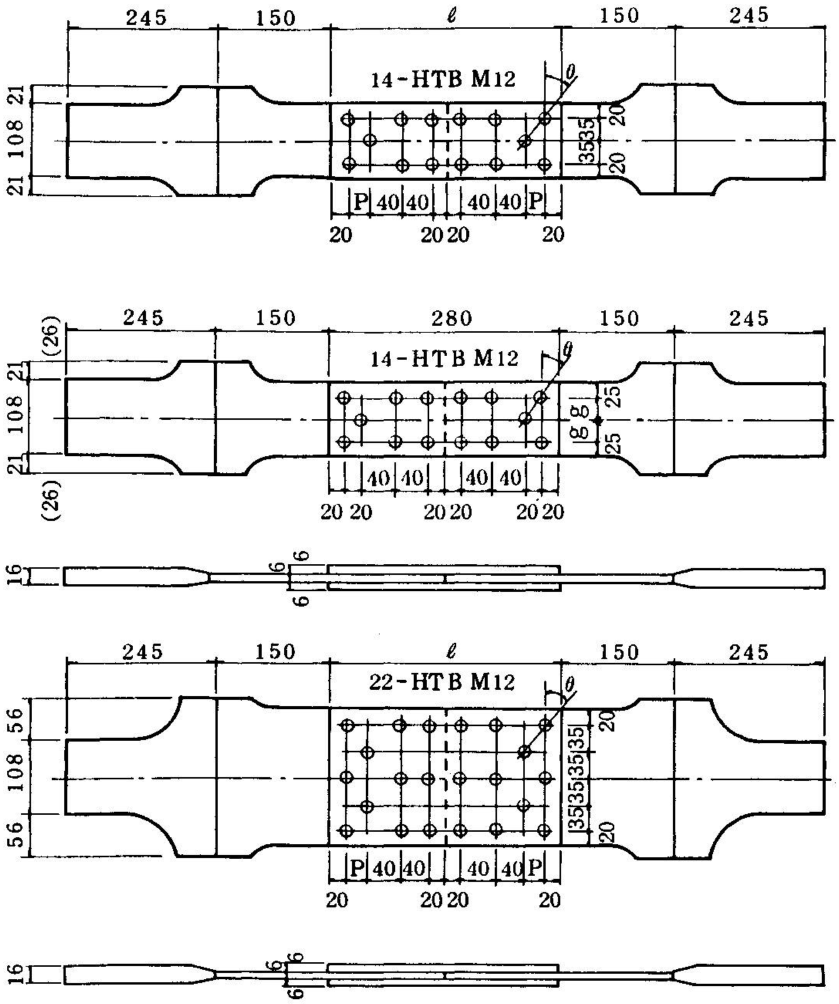
Although the values in Fig 7 (based on the fracture area) scatter to almost as small an extent as those in Fig 8 (based on the gross area), the values in Fig 11 (based on the gross area) are more constant than those in Fig 10 (based on the fracture area), only 2 kg/mm^2(17.5 to 19.5 kg/mm^2) in variation, irrespective of the stagger angle Θ, including the values obtained from the test specimens with a square pattern. It is, however, about two thirds of the fatigue strength of a plain plate. It reveals that the stress is raised in the neighbourhood of the bolts.

5. CONCLUSION

- In the bolt connections with a stagger pattern that can be applied to a practical design, the fatigue fracture type is different from the static one. Even in the case where a specimen fractures in a zigzag type under statical loading, it fractures across the bolt holes (or the portion under the washer edge) in the direction perpendicular to the axial stress.

- Irrespective of the stagger pattern that can be applied to practical design of connection, the difference of fatigue strength of two million cycles is found to be as small as 2 kg/mm^2 (17.5 to 19.5 kg/mm^2), if it is expressed as a stress on the gross sectional area. In conclusion it is recommended that the stress intensity should be checked based on the gross sectional area in reference to a suitable fatigue allowable unit stress, say, 15 kg/mm^2.

- According to the results of static test conducted by the authors, Cockrane's Formula which have been currently used is found to be conservative but not sufficiently adequate. However, in order to establish any new better formula that can be more universally applicable, much more tests will be required.



SERIES A

	p	θ	No. of Test S	F
A-1	30	40.6	4	5
A-2	25	35.5	3	5
A-3	20	29.7	2	5
A-4	15	23.2	2	5
A-5	10	15.9	2	5

g = 35mm, constant

SERIES S

	g	θ	No. of Test S	F
S-1	30	33.7	2	5
S-2*	35	29.7	2	5
S-3	40	26.7	2	5

p = 20mm, constant
* S-2 is the same as A-3

SERIES B

	p	θ	No. of Test S	F
B-1	30	40.6	2	5
B-2	20	29.7	2	5
B-3	10	15.9	2	5

g = 35, constant

S ; Static Test
F ; Fatigue Test

Fig 1 Designation, Configuration and Number of Test Specimens

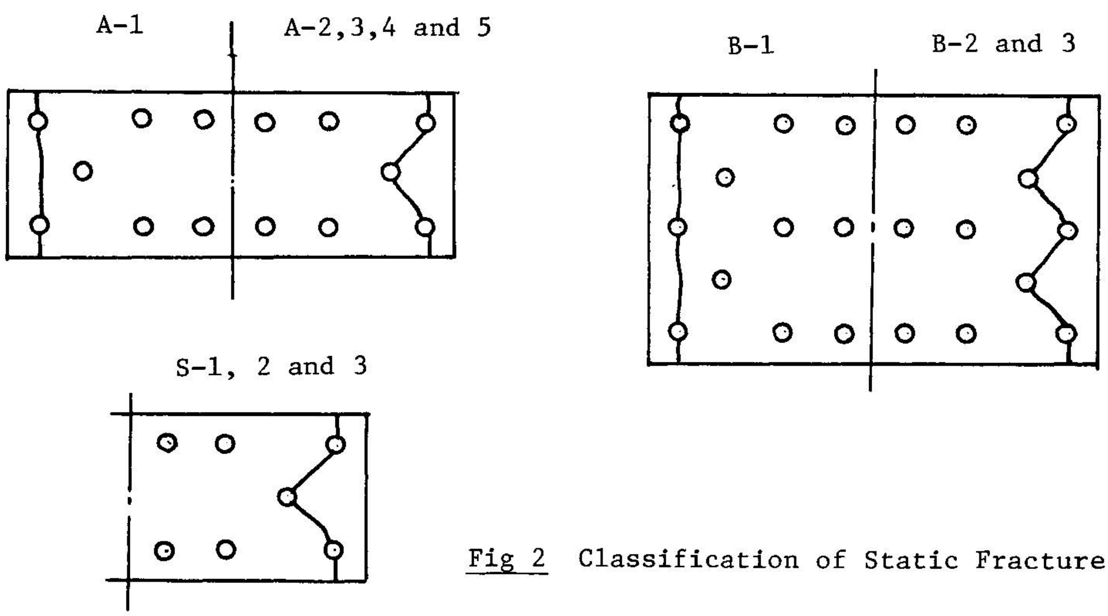


Fig 2 Classification of Static Fracture Types

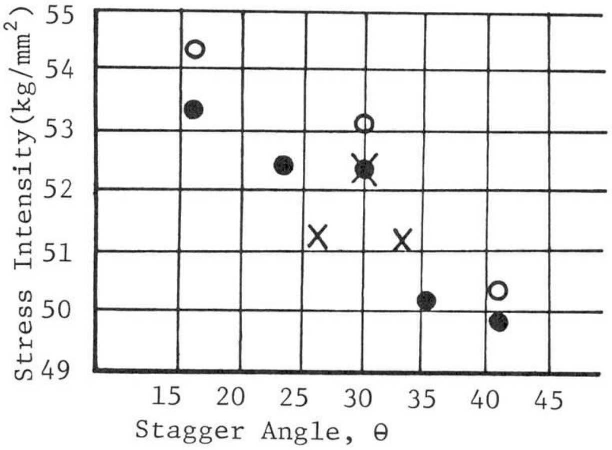


Fig 3 Relation between Stagger Angle and Statical Stress based on Cockrane's Formula

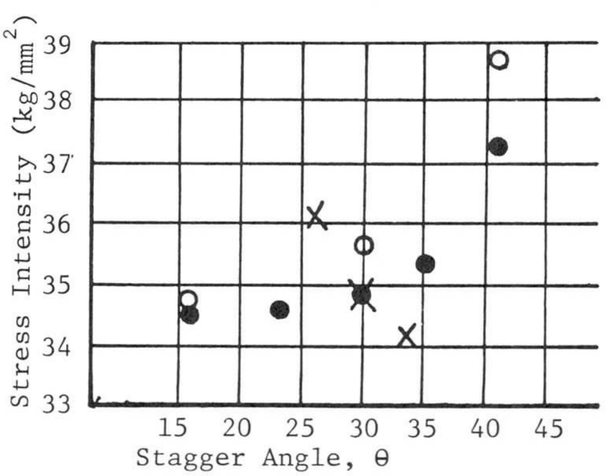


Fig 5 Relation between Stagger Angle and Statical Stress based on Gross Sectional Area

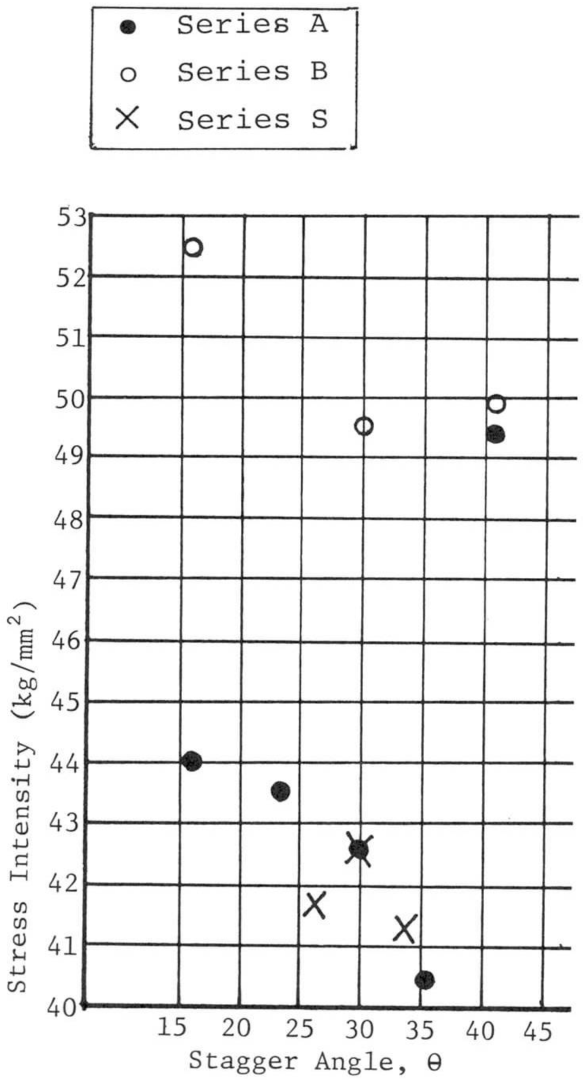


Fig 4 Relation between Stagger Angle and Statical Stress based on Fracture Sectional Area

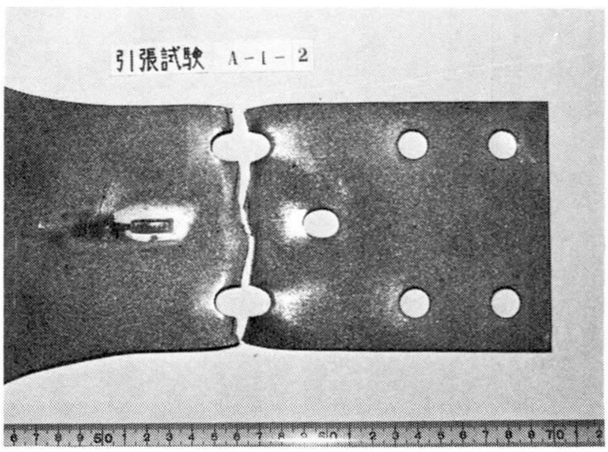


Photo 1 Statical Fracture Example 1

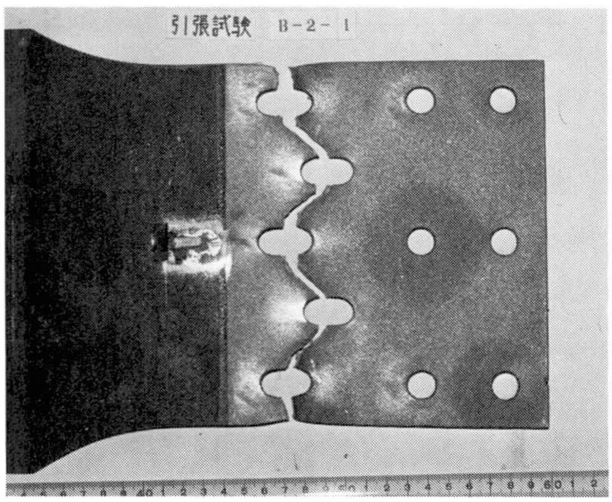


Photo 2 Statical Fracture Example 2

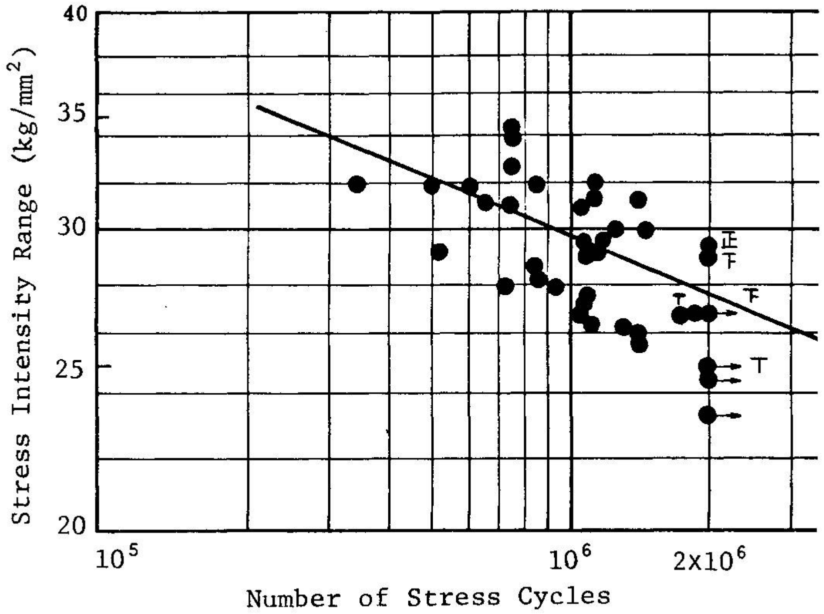


Fig 6

Relation between Number of Loading Cycles and Fatigue Stress based on Cockrane's Formula

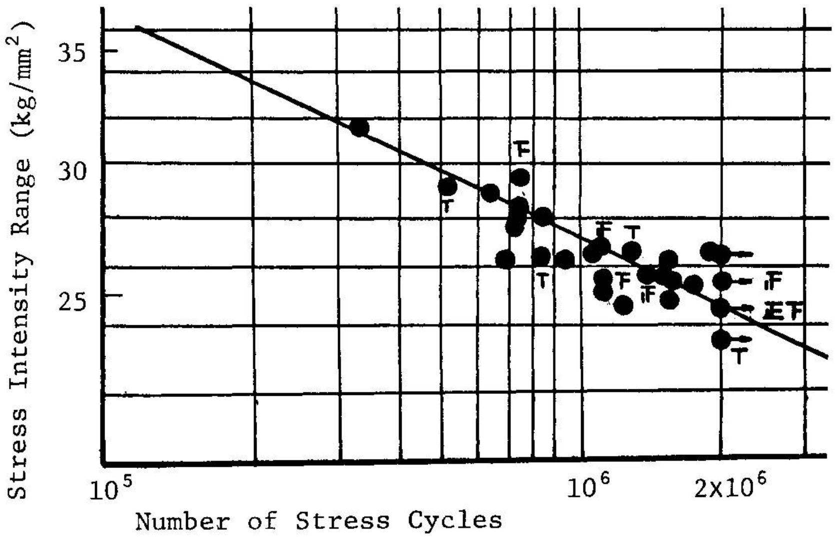


Fig 7

Relation between Number of Loading Cycles and Fatigue Stress based on Fracture Sectional Area

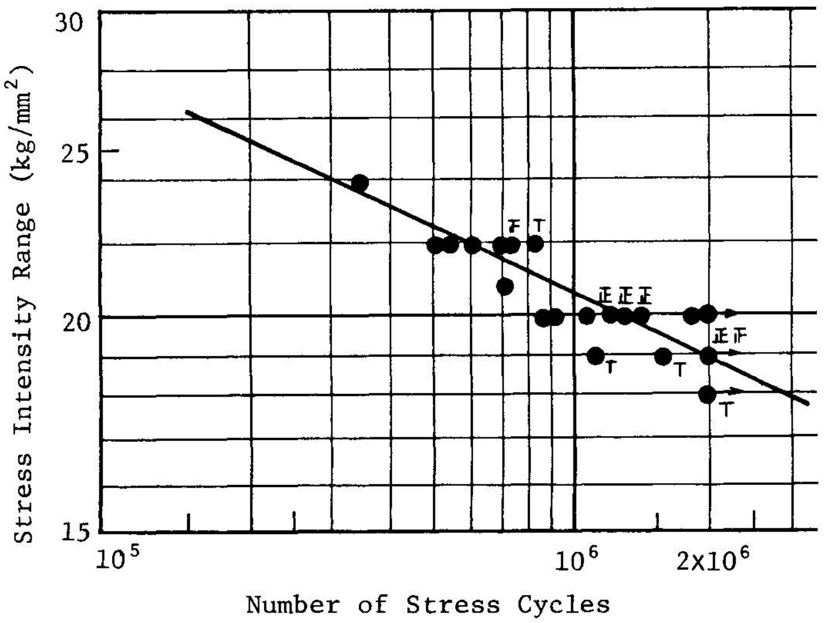


Fig 8

Relation between Number of Loading Cycles and Fatigue Stress based on Gross Sectional Area

●	Series A	Stagger Pattern
○	Series B	Stagger Pattern
X	Series S	Stagger Pattern
▼	Series TA	Square Pattern
▽	Series TB	Square Pattern

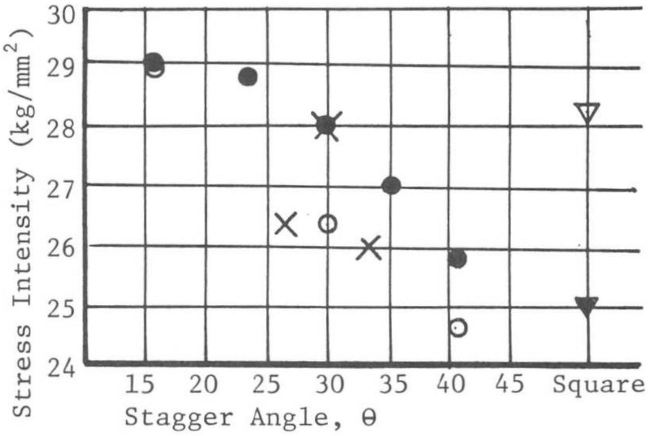


Fig 9 Relation between Stagger Angle and 2-Million Fatigue Stress based on Cockrane's Formula

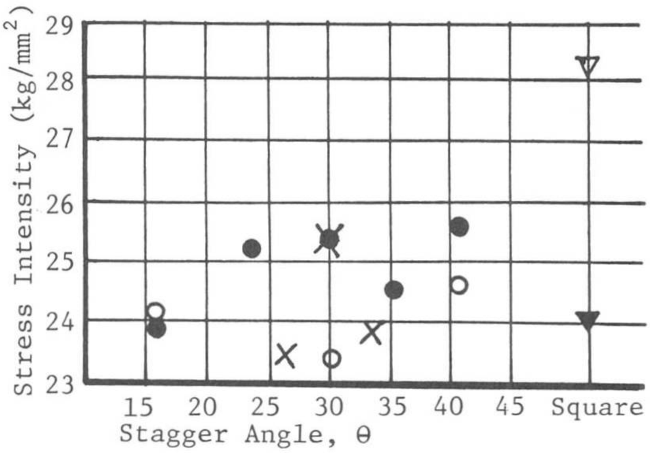


Fig 10 Relation between Stagger Angle and 2-Million Fatigue Stress based on Fracture Sectional Area

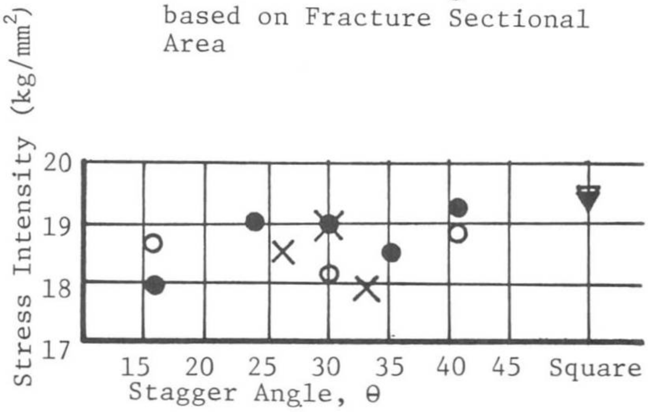


Fig 11 Relation between Stagger Angle and 2-Million Fatigue Stress based on Gross Sectional Area

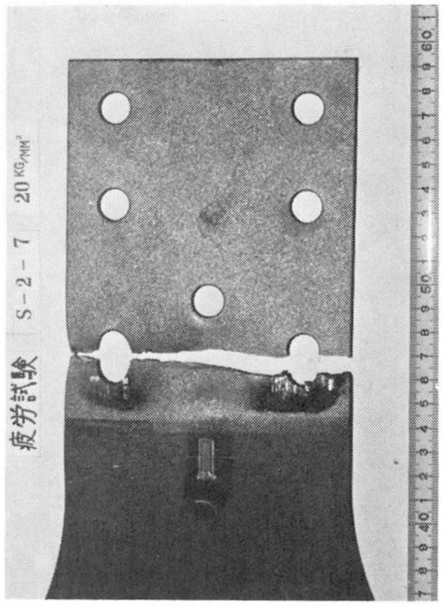


Photo 3 Fatigue Fracture Example 1

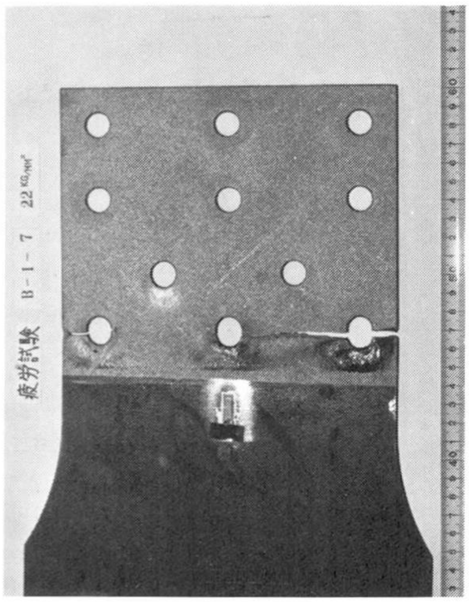


Photo 4 Fatigue Fracture Example 2

Fatigue Strength of High Strength Bolted Joints

Résistance à la fatigue des assemblages avec boulons à haute résistance

Ermüdungsfestigkeit von Anschlüssen mit hochfesten Schrauben

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SUMMARY
Testing results showed that increasing the number of fasteners along the line of force decreased the fatigue strength of a bolted joint but increased that of a riveted joint. In both cases this tended to the fatigue strength of the plate with holes. Based on the test results different allowable fatigue stresses are proposed depending on the number of bolts in the line.

RESUME
Les résultats d'essais ont montré que l'accroissement du nombre de boulons le long d'une ligne de force diminue la résistance à la fatigue dans le cas d'assemblage au moyen de boulons à haute résistance, tandis qu'elle augmente dans le cas d'assemblage au moyen de rivets. Dans les deux cas, la résistance à la fatigue d'un tel assemblage tend vers celle d'une plaque percée de trous. Sur la base des résultats d'essais, différentes contraintes admissibles de fatigue sont proposées en fonction du nombre de boulons sur une ligne.

ZUSAMMENFASSUNG
Versuchsergebnisse zeigen, dass im Gegensatz zu Nietverbindungen die Ermüdungsfestigkeit von Schraubenanschlüssen mit zunehmender Anzahl Verbindungseinheiten in der Linie der Kraftrichtung rasch abnimmt. In beiden Fällen nähert sich die Ermüdungsfestigkeit derjenigen der gelochten Platte. Aufgrund einer Analyse von Versuchsergebnissen werden in Funktion der Anzahl Schrauben pro Reihe unterschiedliche zulässige Spannungen für die Berechnung der Ermüdungsfestigkeit von Schraubenverbindungen angegeben.

1. INTRODUCTION

The first adoption of high-strength bolts in connections of steel structures dated back to 1949, and they have been widely used in China for about two decades. In recent years, riveted connection has been essentially replaced by high-strength friction-grip bolted (HSFGB) connection. The main reason why such connection has been developed so rapidly lies in its three prominent advantages, viz., higher rigidity, higher fatigue strength, and convenience in installation and maintenance. However, the above conception about higher fatigue strength is not exact. In fact, it is true only when there are not too many bolts in a line of a joint. For example, when there are 2-4 bolts in a line, fatigue strength of bolted joints is usually 25% higher than that of riveted joints. But, in the case of joints with a great number of bolts in a line, say 6 bolts, it will decrease sharply. Although, this phenomenon has been noticed by some researchers and mentioned in their works as early as 1960, yet till now, perhaps owing to the limited capacity of test machines, the tendency of decreasing unit fatigue strength along with increasing the number of bolts in a line has not been profoundly investigated and appropriate rules formulated. In case of long-span steel bridges, the internal forces in main members are large and there are usually many bolts in the joints. Therefore, it becomes necessary to study the effect of the number of bolts in a line on fatigue strength of HSFGB joints. Based on our test data, the object of this paper is to express our view on fatigue strength of HSFGB joints, some suggestions about modification of the design codes are also presented.

All test specimens are made of normalized 15MnVN high-strength alloy steel with an ultimate tensile strength of 60kgf/mm^2. The high strength bolts are made of 40B alloy steel, its ultimate tensile strength is around 115kgf/mm^2.

2. THE EFFECT OF THICKNESS OF PLATES ON THEIR FATIGUE STRENGTH

Since in HSFGB joints, once prestressing force in each bolt, the frictional coefficient, and the number of lines in a joint are predetermined, the number of bolts in each line varies directly with the thickness of the plate, therefore the fatigue behavior of HSFGB joints is always concurrent with the problem of plate thickness, known as the thick-plate effect, which means the variation in static and fatigue strength of the plates on account of their difference in thickness. Consequently, before we go deep into the question of effect on the fatigue strength with respect to the number of bolts in a line, we have to find out the effect of thickness of plate first.

The chemical composition of the test specimens is listed in Tab.1, and their yield and ultimate strength are given in Tab.2. From Tab.2, we can see that there is no evident difference in their yield/ultimate strength.

In order to reduce the influence of these complicate factors,such as quality of workmanship, coefficient of stress concentration, position of final failure, and etc. to a minimum, we used the specimens with a hole drilled at their center. Tab.3 gives the results of fatigue tests. It is evident that the fatigue strength of 15MnVN steel, just as its static strength, is almost independent on its thickness.

Tab.1 Chemical composition of test specimens (%)

thickness(mm)	C	Si	Mn	V	N	P	S
20	0.140	0.290	1.570	0.140		0.014	0.027
24	0.170	0.340	1.450	0.130	0.016	0.016	0.021
50	0.150	0.440	1.680	0.165	0.016	0.020	0.024

Tab.2 Static test data

thickness (mm)	yield strength (kgf/mm^2)	ultimate strength (kgf/mm^2)
20	45.2	58.8
24	45.0	58.5
50	44.5	61.5

Tab.3 Fatigue strength of plates with an empty hole (R=0, $2x10^6$ cycles)

thickness (mm)	fatigue strength (kgf/mm^2)	loading frequency (Hz)
20	14.0	32
50	14.4	4.2

3. THE RELATIONSHIP BETWEEN THE NUMBER OF BOLTS/RIVETS IN A LINE AND THE FATIGUE STRENGTH OF JOINTS

The results of fatigue strength tests of joints with different number of bolts/rivets, are shown in Figs.1 & 2, and Tab.4. From these, we can deduce:

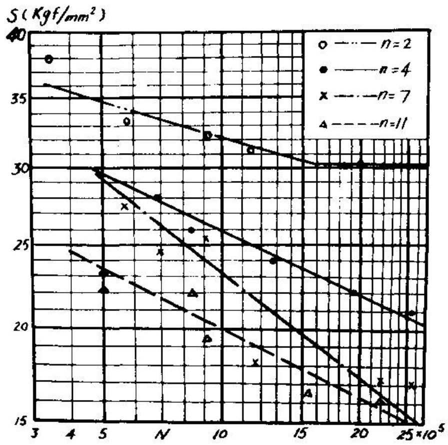


Fig.1 S-N curves of bolted joints

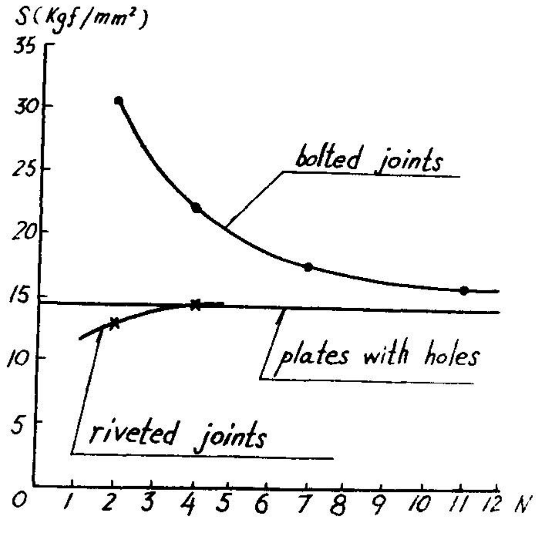


Fig.2 Relationships between fatigue strength of joints and number of fasteners in a line (R=0, $2x10^6$ cycles)

(1) The unit fatigue strength of bolted joints calculated either according to net or gross cross-section decreases as the number

Tab.4 Fatigue strength of bolted/riveted joints ($R=0$, $2x10^6$ cycles)

number of fasteners in a line		dimension of core plates	fatigue loading net cross-section	fatigue loading gross cross-section
bolts	rivets	(mm)	(kgf/mm^2)	(kgf/mm^2)
2		74x16	30.10	20.70
4		90x20	21.92	16.31
7		150x24	17.24	14.60
11		90x50	16.29	12.13
	2x2	160x16	12.90	
	4	90x20	14.50	

of bolts increases. When there are only a very few bolts in a line, say 2 bolts, the unit fatigue strength calculated on net cross-section basis is much greater than that of plates with an empty hole. With the number of bolts increasing, the decrease in fatigue strength is very rapid at the beginning, but gradually slows down and finally approaches the fatigue strength of plates with an empty hole.

(2) Just on the contrary, the fatigue strength as calculated according to net cross-section of riveted joints with only 2 rivets in a line is slightly smaller that of plates with an empty hole. When the number of rivets increases to 4, these two are almost approaching the same value.

4. THE MECHANISM OF FATIGUE STRENGTH VARIATIONS IN BOLTED/RIVETED JOINTS

Since the fatigue strength of a joint is closely related with its stress concentration factor, so the analysis of fatigue behavior may proceed from the study of stress concentration.

4.1 Riveted joints

In riveted joints, forces in constituent parts are transmitted from one to another both thru the frictional resistance on the surfaces of contact and by the bearing of rivet shanks on the walls of holes (Fig.3), among them, the former takes only a minor part of the whole, and the latter plays the main role. Furthermore, it is known to all that when the diameter of the empty hole in a plate is large enough, the stress concentration factor k_o is around 3, i.e. $k_o=3$. And, also the stress concentration factor k_{r1} of a riveted joint with only one rivet is usually greater than 5 Fig.4), or $k_{r1}=5$.

Now, let us suppose, a two-rivet joint is subjecting to an external force P, assuming that each rivet sustains equal share of force, thus P/2 goes to the first rivet, and another P/2 passes around it and goes to the second. As a result, at a section cut thru the first hole, we obtain the equivalent stress concentration factor of the whole section $k_{r2}=k_o/2+k_{r1}/2=4$.

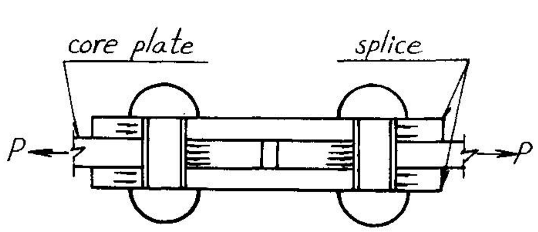
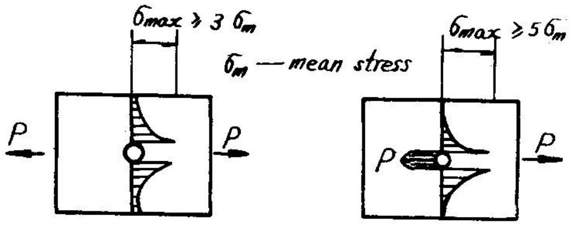


Fig.3 Manner of force transmission of riveted joint



(a) Plate with a hole (b) Joint with a rivet

Fig.4 Stress distribution in the cross-section

In the same manner, for joints with multiple rivets, we can establish: $k_{T3}=2k_o/3+k_{r1}/3=11/3$; $k_{T4}=3k_o/4+k_{r1}/4=14/4$;......; $k_{r10}=9k_o/10+k_{r1}/10=32/10\approx3=k_o$. That is to say the stress concentration factor at the section passing thru the first rivet decreases with the increasing of number of rivets in the joint and finally approaches that of a plate with an empty hole. It seems to us that the fatigue strength will follow the same law.

4.2 HSFGB joints

So far as the fatigue behavior is concerned, HSFGB joints have two merits as compared with plates with empty holes:

(1) In HSFGB joints, forces are transmitted by the frictional resistances on the surfaces of contact. During transmission,a part of the force is invariably delivered in front of the first hole in the line, because there exists frictional resistance in this region too. Thus the actual force reached the cross-section of the first hole is lessened.

(2) The prestressing of the high strength bolt will produce deformations in the plates in the direction normal to their contact surfaces, this will create a compressive stress around the periphery of the hole, and in turn, cut down the tensile stress peak at that cross-section.

However, these merits are evident only when the number of bolts in the line is comparatively fewer, and diminish greatly as the number of bolts increases.

Fig.5 shows a HSFGB joint with a single bolt, it subjects to an axial load P. The frictional resistance developed in front of the hole is f=P/2. Therefore, only the remainder P-P/2=P/2 passes around the hole. That means, the actual stress in the main plate at this cross-section is P/2. Furthermore, in one-bolt joint, the plates are very thin, thru them, the prestressing force in the bolt can only spread over a relative small area. This tends to produce relatively high compressive stress around the periphery of the hole, and the tensile stress peak will be cut down by the same amount. These are probably the reasons why the fatigue strength of joints with one bolt is much higher than that of plates with an empty hole.

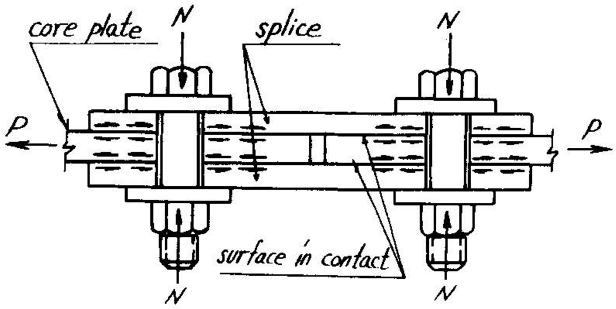


Fig.5 Manner of force transmission of a bolted joint

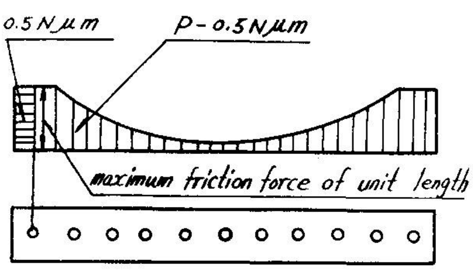


Fig.6 Friction force distribution in the direction of force

In cace of 2-bolt joints, following the same line of thought, we will find: The frictional resistance developed in front of first hole is P/4, the actual stress existed in main plate is 3P/4, and the reduction in tensile stress peak due to the presence of peripheral compression around the hole becomes smaller. As a result, the fatigue strength of a 2-bolt joint will drop sharply. Consequently, when the number of bolts in a line increases further, the fatigue strength of the joint will drop further.

Besides, it also deserves to mention that the frictional resistance is usually not evenly distributed among bolts of large joints (Fig.6), yet it cannot exceed $N\mu m/2$ in front of each hole, (in which, N—the axial stress of the bolt, μ—the coefficient of friction between contact surfaces, m—the number of contact surfaces in action). Thus all the remaining force $F=P-N\mu m/2$ will pass thru the cross-section at the first hole. Due to back and forth slipping in extreme bolts caused by repeated action of internal stress, the value μ at these places is usually smaller. Eventually, in joints with a great number of bolts in a line, the value F approaches P. This explains why the fatigue strength of these joints approaches that of plates with an empty hole.

5. CONCLUSION AND SUGGESTIONS

From above discussion, now we can conclude: When the number of bolts in a line is small, the fatigue strength of a joint is much higher than that of a riveted joint and that of a plate with an empty hole; but when the number of bolts in a line is large, then the fatigue strength of the joint is only slightly higher than or neerly the same as that of a riveted joint and that of a plate with an empty hole.

Nevertheless, current bridge design specifications of some countries, as we understand, ignore completely this variations in the fatigue strength of HSFGB joints. Allowable fatigue stress is stipulated at a same value disregarding the number of bolts in the joint.(Tab.5) The consequence will be either one of the following, yet both are undesirable:

—If the allowable fatigue stress is formulated according to test data made on joints with comparatively fewer bolts, some part of the structure may act at deficient factor of safety;

—If the allowable fatigue stress is formulated according to test data made on joints with comparatively more bolts, then, another part of the structure may not be economical.

Tab.5 Allowable fatigue stresses or stress ranges (kgf/cm^2)

country	bolted joints (1)	riveted joints or plates with holes (2)	k=(1)/(2)
Japan(1977)	1530/(1-0.7R)	1275/(1-0.7R)	1.20
USA(1979)	1270	700	1.81
UK(1980)	1750	1250	1.40

It may be seen from Fig.3 that only if the number of bolts in a line is less than five, the variation in fatigue strength becomes prominent.

With a desire not to introduce too cumbersome work into design practice, also at the same time, with a hope to take into consideration both the economy and the safety of a structure, we therefore suggest:

In bridge design specifications, the value of allowable fatigue stresses of HSFGB joints may be classified into two categories, viz.:

(1) Category A—For joints of 1-4 bolts in a line, derived from test data of HSFGB joints with four bolts in a line;

(2) Category B—For joints of 5 and more bolts in a line, derived from test data of plates each with an empty hole at center.

In box girder construction, relatively thinner plates with joints of fewer bolts are often used, while in long-span truss bridges, relatively thicker plates with joints of more bolts are frequently needed. In short, under different conditions, we use different value of allowable fatigue stress. We believe that this way of treatment will not bring the designers much inconvenience. Doubtless, an understanding of the effect of the number of bolts in a line on the fatigue behavior of HSFGB joints will urge designers to choose details which provide the best fatigue resistance.

Finally, for improving HSFGB joints subjected to fatigue loading, we recommend the following measures in addition:

—Use double splice plates instead of single splice plate wherever feasible;

—Avoid the staggering arrangement of the bolts if possible;

—Use high strength bolts with larger diameter rather than smaller diameter whenever practicable;

—Increase the coefficient of friction between the surfaces in contact by all the technical means.

Fatigue of HSFG Bolted Joints — Effects of Design Parameters

Fatigue des assemblages au moyen de boulons précontraints — effets des paramètres de dimensionnement

Ermüdung von hochfesten Schraubenverbindungen — Einfluss der Bemessungsparameter

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SUMMARY
The effects of variation in steel strength, surface finish, bolt tension, and mean stress on the fatigue strength of friction grip bolted connections are described. Although the magnitude of the stress range was the dominant factor, reducing the mean stress increased the fatigue strength, as did an increase in the bolt tension. It was shown that the fatigue strength was not likely to be increased by increasing the number of rows of bolts beyond three. There was no tendency for the joints to creep.

RESUME
Cet article traite des effets de la variation de la résistance de l'acier, du traitement des surfaces, de la tension des boulons et de la contrainte moyenne sur la résistance à la fatigue d'assemblages par friction au moyen de boulons précontraints. Bien que l'amplitude de la différence de contraintes soit le facteur dominant, on a constaté que la résistance à la fatigue augmente avec une diminution de la contrainte moyenne, ainsi qu'avec une augmentation de la tension dans les boulons. On a montré que la résistance à la fatigue n'augmente pratiquement plus lorsque l'on augmente le nombre de rangées de boulons au-delà de trois. Les assemblages ne manifestent aucune tendance à se déformer dans le temps.

ZUSAMMENFASSUNG
Es wird der Einfluss der Stahlqualität, der Oberflächenbehandlung und der Spannung auf den Ermüdungswiderstand von reibungsschlüssigen, vorgespannten Schraubenverbindungen beschrieben. Obwohl die Grösse der Spannungsdifferenz der dominierende Faktor war, erhöhte sich die Ermüdungsfestigkeit bei kleinerer Mittelspannung als auch bei einer höheren Schraubenspannung. Es wurde festgestellt, dass sich die Ermüdungsfestigkeit bei mehr als drei Reihen Schrauben kaum mehr erhöhte. Es wurde keine Tendenz zu Kriechverformungen in den Verbindungen bemerkt.

1. INTRODUCTION

1.1 This project, commissioned by the UK Transport and Road Research Laboratory, in the context of the drafting of a new Code of Practice for the Design of Steel Bridges (BS5400) [1], examined the effects on the fatigue strength of friction grip bolted connections of variations of the design parameters : steel plate strength, surface finish, bolt tension, and mean stress. The displacement stability of the joint and the effects of the number of bolts in the line of the load were also investigated.

1.2 Design of the joint for fatigue testing

Ideally, the basic fatigue properties should be determined for a joint with a single bolt (a 1-bolt joint)*. However, with joints of normal proportions, slip limits the maximum upper stress obtainable to a value that is unlikely to cause fatigue failure. For the same centre plate width (w) and thickness (t) the slip load is doubled by using a 2-bolt joint and a more useful range of stress is available for testing. Failure, if due to fretting, will start around the edge of the contact pressure area in front of the leading bolt [2] so the fact that the in-plane plate stress at the rear edge of the pressure area is not zero, as it is in the 1-bolt joint, will not of itself affect the fatigue strength of the joint.

A 3-bolt configuration was chosen for the fatigue tests as the further increase in slip load so obtained not only increased the available stress range, but also allowed slip conditions at the outer bolts to be approached with the joint still stable against overall slip. This condition can occur in practice at the end bolts of long joints.

The test piece for the basic test, shown in Fig. 1, was made of BS.4360 Grade 50 steel with three M20 bolts, tightened to 190 kN, the tension specified in BS.4395 Pt. 2. The bolts were a special load indicating type which enabled the bolt tension to be monitored continuously throughout the test. The contact surfaces of the joints were grit-blasted with chilled iron grit G34.

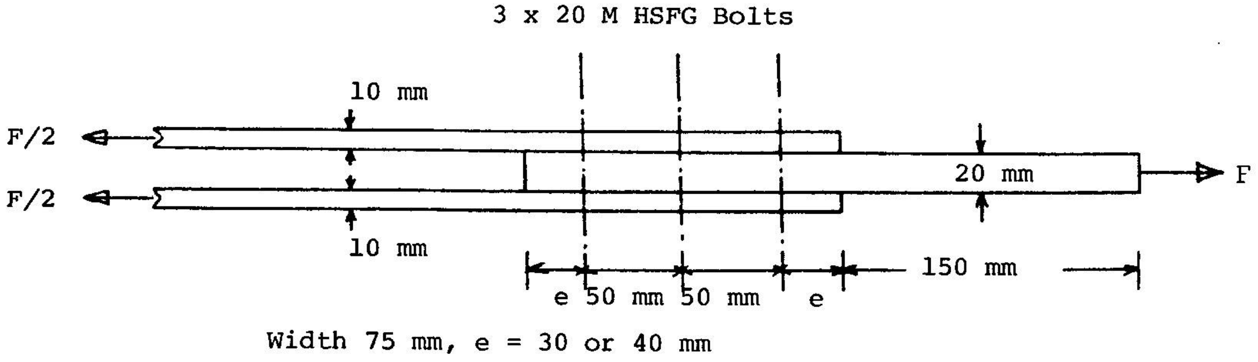

Fig. 1. Standard Fatigue Test Piece

A mean stress of 50 N/mm^2 was chosen as typical and three stress ranges were selected with the aim of obtaining endurances between about one and five million cycles. Sufficient tests were done to obtain three failures at each stress range; unbroken specimen results were not included in the regression line analysis. Reference stresses in all cases were calculated on the gross cross-sectional area of the centre plate. The tension in the bolt was monitored

* This description, used throughout, refers to the number of bolts in the direction of the load.

during assembly of the joint, setting up and throughout the test. Displacements between the centre and cover plates, on both sides, were also measured. After grit-blasting the plates were exposed to the air for 24 hours before assembly to allow a mild degree of corrosion. Testing was commenced 24 hours after assembly to allow the initial bolt relaxation to take place. Details of the variants for the various series of tests are given in Table 1.

Table 1.

Series	Material Steel BS4360 Grade	Surface	Bolt Tension kN	Edge Dist. mm	Mean Stress N/mm^2	Steel Plate* strength N/mm^2	
						Yield	Ult.
1A Basic	50B	Grit blasted	190	30	50	347	548
1B	50B	Mill scale	190	"	0	"	"
1C	50B	Painted zinc silicate primer	190	"	50	"	"
2A	50B	Grit blasted	190	"	0	"	"
3A	43A	Grit blasted	144	"	50	326	511
3B	55C	Grit blasted	190	"	50	485	626
4A	50B	Grit blasted	144	"	50	347	548
5A	50B	Grit blasted	190	40	50	"	"

* Averages of the results of tension tests on coupons taken from each bar of material used.

1.3 Static Test Results

The results of static loading tests made to determine the slip factor for the basic test piece and its variants are shown in Table 2.

Table 2.

Series No.	Variation	Slip Load kN	Slip Factor	Standard Deviation
1A	Basic test	419	0.367	0.020
1B	Mill scale surfaces	278	0.243	0.056
1C	Painted - zinc silicate primer	427	0.373	0.025
2A	Mean stress zero	419	0.367	0.020
3A	Steel Grade 43 Part 1 bolt tension	362	0.418	0.005
3B	Steel Grade 55	506	0.441	0.016
4A	Part 1 Bolt tension	387	0.446	0.022
5A	Edge distance 40 mm	416	0.365	0.015

2. FATIGUE TESTS

2.1 Description of Fatigue Failures for each Series of Tests

2.1.1 Series 1A - Basic test joint

Failure at the highest stress range was by cracking starting from the inside of the bolt hole (minimum section). In other cases failure was in the section away from the bolt hole. Cracks occurred either in the centre plate from origins in the fretting area in front of the leading bolt or, frequently, in the cover plate. The latter originated on the outer surface at, or near, the edge of the indentation made by the washer face of the bolt head of the last bolt and led to fracture of the bolt head in some cases. In subsequent tests this indentation was prevented by using a washer under the bolt head as well as under the nut. But, although there were no more bolt failures, similar cracks appeared in the cover plate on the nut side which sometimes resulted in cracks through the washer.

2.1.2 Series 1B : Variant - Surface. As received with Mill-scale (zero mean stress)

As the static slip load for this joint was only 278 kN, the originally proposed mean stress of 50 N/mm^2 would have restricted the maximum stress range to about 170 N/mm^2. Earlier experience having shown that fatigue failure was unlikely to occur at values below this, it was decided to test with zero mean stress to permit larger stress ranges to be used.

Failure in all cases was by fretting of the centre plate. In one instance, at a stress range of 284 N/mm^2, a fretting initiated failure was observed in the cover plate also.

2.1.3 Series 1C - Variant : Surface. Grit-blasted and painted with zinc silicate primer

The self-curing alkyl inorganic zinc silicate primer was applied by brushing, the thickness varying from 0.08 to 0.13 mm.

Fretting and minimum section failures were obtained in both cover plates and centre plates at all stress ranges. In one case at the lowest stress range fracture occurred at the line of the centre bolt, but this was thought to have been preceded by a failure of that bolt.

2.1.4 Series 2A - Variant : Mean stress - zero

Failure at the lowest stress range was from crack origins in the fretting area of the centre plate. At the highest stress range cracks originated in this area and also from the inside of the first bolt hole in all cases.

In the intermediate range of stress one specimen failed by fretting of the centre plate, another by fretting and minimum section cracking which, in the third, was accompanied by fretting cracks in the cover plate. A joint tested at a stress range of 234 N/mm^2 survived 6.04×10^6 cycles unbroken.

2.1.5 Series 3A - Variant : Plate strength, BS.4360 Steel Grade 43A

There were two distinct types of failure. At the lower two stress ranges fatigue cracks in the centre plate originated in the fretting zone of the contact area of the first bolt. At the higher stress range when the upper stress of the cycle was a high proportion of the yield stress of the material, the origin of failure was at the inside of the first bolt hole.

2.1.6 Series 3B - Variant : Plate strength BS4360 Steel Grade 55C

Minimum section failures in the cover plates were obtained at the lowest stress range. Fretting failures of cover and centre plates were obtained at the other two stress ranges with, in two cases, minimum section failures of the cover plates.

2.1.7 Series 4A - Variant : Bolt tension, BS.4395 Pt. 1 (144 kN)

The first specimen, tested at a range of 200 N/mm^2 survived 14.67×10^6 cycles unbroken, the lowest range was therefore increased to 215 N/mm^2. At the stress range of 234 N/mm^2 fatigue cracks originated from the inside of the bolt hole in the cover plate (minimum section). In all three cases the washer also cracked and, in the case of the longest life, the nut also cracked. Three different failures were observed at the higher stress range : fretting of the centre plate, minimum section cracking of the centre plate, and minimum section failure of the cover plate, accompanied by cracking of the washer.

2.1.8 Series 5A - Variant : Edge distance (40 mm)

In all but two cases failure was initiated by fretting. In one case at the lowest stress range a minimum section failure of the cover plate was obtained and in the other, at the highest range, a minimum section failure of the centre plate occurred.

2.2 Summary of Results of Fatigue Tests

These results are summarised graphically in Fig. 2. The values of the coefficients m and K in the equation :-

$$\log N = K - m \log S$$

obtained from the regression analysis for each series of tests are presented in Table 3.

Table 3

Series	Variant	No. of Tests	m	K	Std. Dev. (N)
1A	Standard	16	-6.46	21.77	0.097
1B	Mill scale surfaces	9	-9.07	28.03	0.113
1C	Painted surfaces	10	-7.88	24.92	0.187
2A	Zero mean stress	10	-5.23	19.01	0.128
3A	Grade 43A plate	9	-9.56	28.50	0.285
3B	Grade 55C plate	9	-5.78	19.95	0.158
4A	Pt. 1 Bolt tension	11	-4.93	17.78	0.309
5A	Edge distance 40 mm	9	-4.38	16.64	0.221

2.3 Comments on the Effects of the Variants

2.3.1 Mean stress - A reduction in mean stress gives a marked improvement in the life for a given stress range, especially at the higher stress range.

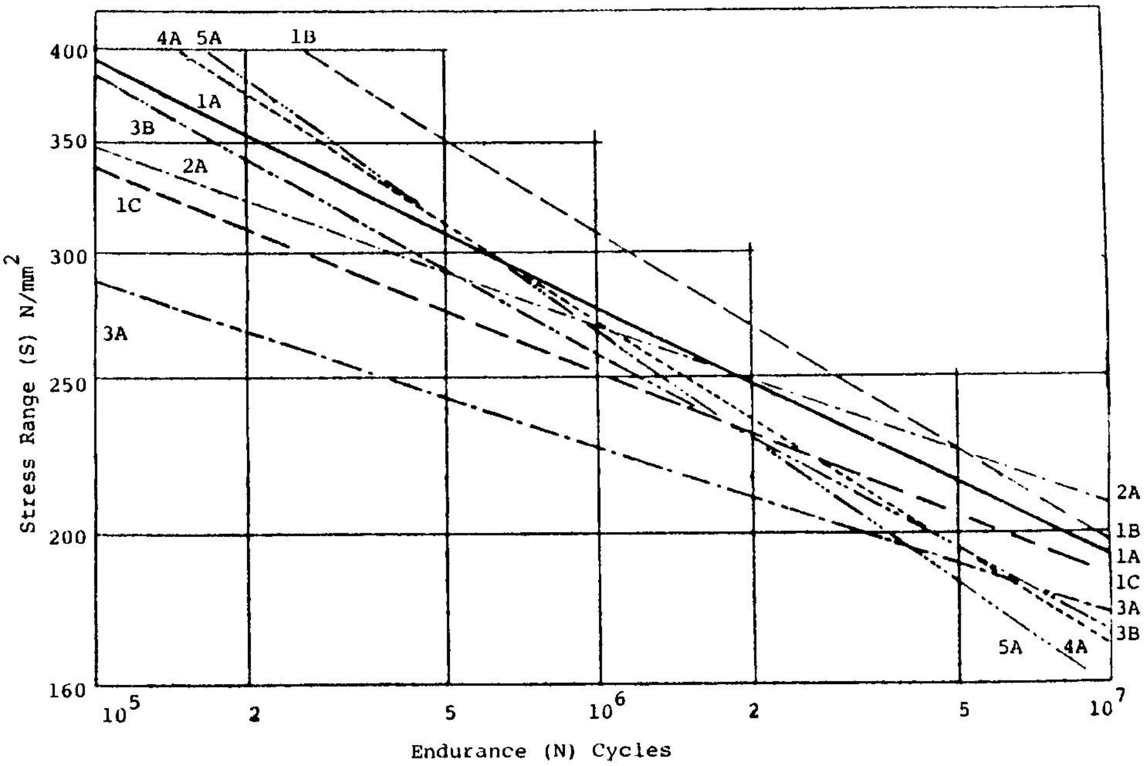

Fig. 2 Fatigue Tests Results S-N Mean Lines

2.3.2 Surface finish - The mill scale surface joints had a very much lower life at the higher stress ranges than the shot blasted ones. The effect, however, appears to be reversed at stress ranges below about 220 N/mm^2. The effect of the zinc epoxy primer was to reduce the fatigue life for all the stress ranges used.

2.3.3 Plate strength - The higher strength Grade 55 steel gave a consistently inferior fatigue performance to the Grade 50 steel. The fatigue strength of the lower strength Grade 43 steel joints was poorer than either. In the latter case, the maximum stresses in the area of the first bolt were approaching the yield strength of the material.

2.3.4 Bolt tension - For lives above one million cycles joints with the higher bolt tension had a better fatigue strength than those with the lower tension.

2.3.5 Edge distance - Increasing the edge distance did not produce the expected improvement in performance. The consistency of these results was, however, poorer than for the standard test so that it could be that the increase from 30-40 mm is insufficient to cause a significant change.

2.3.6 Bolt and washer failures - The load indicating bolts which failed from cracks at the radius under the head had not only been used many times, but were re-used after having been in joints which had failed by cracking in the washer area. Bolts would not be used in this way in practice.

Fatigue failures of the washers only occurred when there were fatigue cracks in the cover plate under the washer and may reasonably be assumed to have followed from them.

3. FATIGUE STRENGTH OF HSFG BOLTED JOINTS WITH ANY NUMBER OF BOLTS

3.1 It is necessary to consider how the results obtained in the previous section for joints with three bolts may be applied to those with a different number of bolts. In an earlier investigation [3] it was demonstrated that the fatigue life of a joint was increased by reducing the traction stress at the bolt at the critical section. As the material and test piece sizes used in that investigation were different from the present one, it was decided to verify the findings and to design a test piece for this purpose.

A suitable 1-bolt specimen could not be made from 20 mm plate as, even with the minimum width, the maximum stress (at the slip load) was too low to cause fatigue failure. It was necessary to use another combination of plate thicknesses which would allow an adequate stress range and give approximately the same stress situation in the contact pressure area. An adequate stress range was obtained by reducing the centre plate to 10 mm x 50 mm. The radius of the contact pressure area (R) between the cover and centre plates and the ratio (Pa/Pb) of the maximum pressure there to the pressure on the bolt head annulus were calculated [4] for the standard (75 mm wide) 3-bolt test piece as 22.4 mm and 0.90 respectively. The desired conditions would be obtained almost exactly by using 11 mm thick cover plates with the 10 mm thick centre plate. However, as 11 mm is not a standard thickness, 10 mm cover plates were used, giving R = 21.9 mm and Pa/Pb = 0.95, which were considered to be close enough to the values for the standard test piece for practical purposes. The remaining details were the same as those of the standard test piece.

The loads transmitted by the first bolt in 50 mm wide joints with 10 mm thick cover and centre plates for various numbers of bolts in the joints are :- 1-bolt - F (F), 2-bolt - 0.62F (0.50F), 3-bolt - 0.53F (0.30F), 4-bolt - 0.52F (0.34F). The figures in parentheses are the corresponding values for the fatigue test piece used in the investigation. The traction ratios (load transmitted by the bolt/slip load of the bolt) for the 3 and 4-bolt joints were so nearly equal that it was decided to test 1, 2 and 3-bolt joints only. Fatigue failure occurred in three of the 1-bolt joints, but because of slipping in the higher stress ranges insufficient results were obtained to draw a mean line.

3.2 Comparison of Fatigue Test Results for 2 and 3-bolt Joints

The endurances for the three series have been compared for a gross area stress range of 300 N/mm^2, which gives an upper load of 300 kN in the case of the 1A series and 100 kN for the other two. A slip value for one bolt of 140 kN is assumed.

Table 4

Series	Endurance x 10^{-6}	Load transmitted by 1st bolt kN	Traction Ratio
1A	0.600	0.38F = 114	0.911
6B	1.63	0.62F = 62	0.646
6A	2.05	0.53F = 53	0.578

This, limited, evidence supports the concept that endurance increases with decrease in traction ratio.

4. JOINT DISPLACEMENT STABILITY IN FATIGUE LOADING

4.1 No evidence of fatigue failure having been accompanied by slipping was noted, except in the case of the highest loads used in the Grade 43 steel tests (and in the 1-bolt tests), where the upper load was a high proportion of the slip load and the stresses at the first bolt were approaching yield.

The results of measurements of bolt tension and displacement monitored continuously throughout a typical test are shown in Fig. 3. The load displacement loop was not closed on the first cycle, giving a small irrecoverable displacement. This got smaller with each succeeding load cycle until complete stabilisation (loops of constant size) was obtained after about 50,000 to 70,000 cycles. The bolt tensions show the expected relaxation with time [5]. Failure in this case was by cracking of the cover plate and washer, which probably accounts for the loss of bolt tension in the bolt there (lower of three curves) after about 58 hours. After the initial increase, the displacements show very little change.

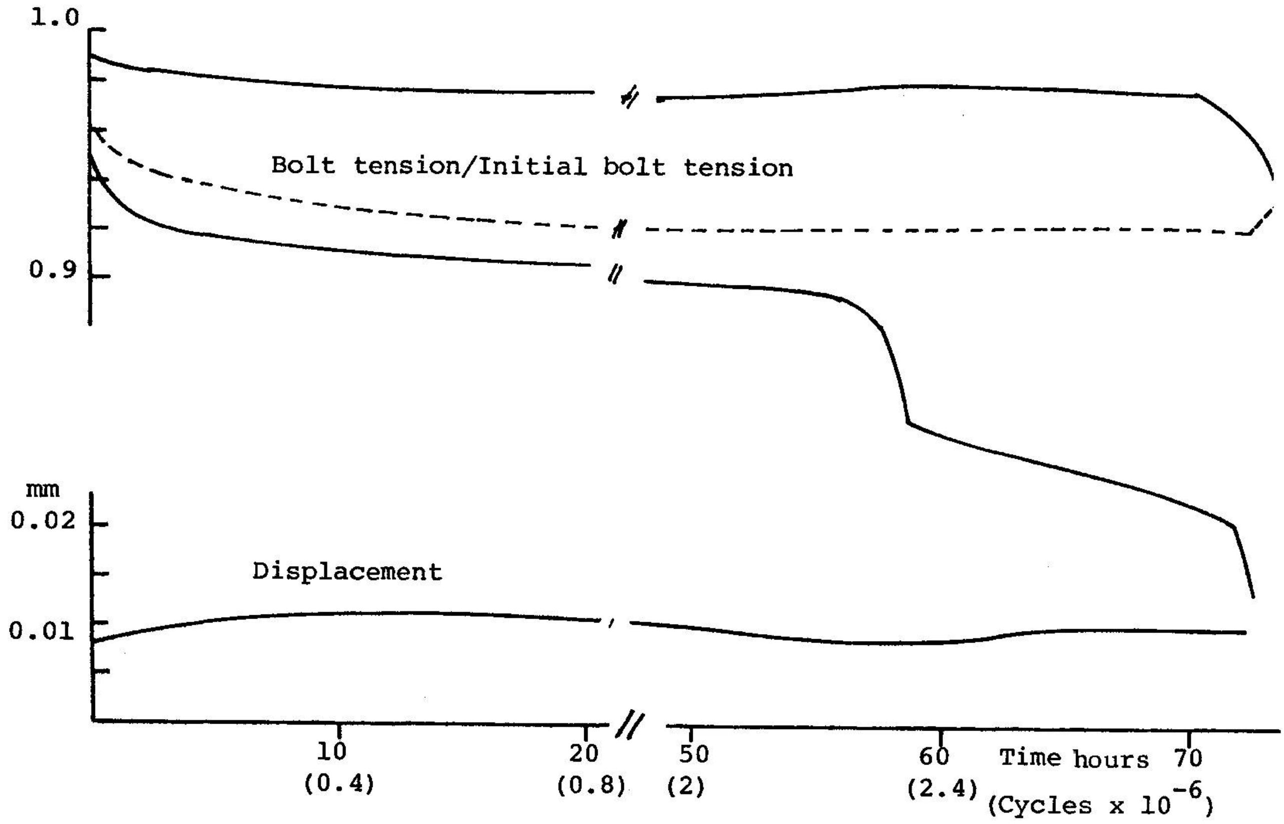

Fig. 3 Fatigue Test - Joint Stability

5. CONCLUSIONS

The fatigue strength of the best test joints was better than that of the standard average for good butt welds. All the joints tested were better than BS.5400 Class C for endurances exceeding 0.5 million cycles. Although the predominant factor is the range of applied stress, reducing the mean stress improves the fatigue strength, as does an increase in bolt tension. The strength of the steel has only a marginal effect, except in the case of the lower strength material when its yield strength is approached at the upper stress of the load cycle. The performance of joints with shot blasted surfaces was superior to that of joints with "as-received" or zinc-silicate painted surfaces.

There was no evidence of joints suffering progressive slip as the number of load cycles became large. The initiation of cracks in the cover plate caused by indentations will be reduced by using washers under both bolt head and nut.

In terms of stress range on the gross area of the centre plate, the fatigue strength is not likely to be altered by increasing the number of bolts in the line of the load beyond three.

ACKNOWLEDGEMENT

The permission of the Director of the Transport and Road Research Laboratory, Crowthorne, UK, to publish these results is gratefully acknowledged.

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Fatigue Cracks in Bolt Threads

Fissures dues à la fatigue dans le fond de filet des boulons

Riss im Gewindegrund eines Schrankenbolzens — Lebensdauerermittlung

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SUMMARY
A method is proposed which allows the prediction of the fatigue life of a notched component. A knowledge of the state of the stress field in the vicinity of the notch in an uncracked component (the stress concentration) permits the study of fatigue behaviour by integration of the crack growth law. The method is demonstated by application to the development of a crack in a bolt thread. Good agreement is achieved with experimental results.

RESUME
Une méthode est proposée qui permet de prédire la durée de vie d'une pièce entaillée. Il suffit de connaître la concentration de contrainte, calculée sur la pièce entaillée, sans fissure, pour pouvoir évaluer, au moyen de l'intégration de la loi de propagation des fissures, le comportement à la fatigue. La méthode est appliquée à l'exemple de la fissure au fond d'un filet de boulon. La durée de vie calculée concorde bien avec les résultats expérimentaux.

ZUSAMMENFASSUNG
Es wird ein Verfahren angegeben, mit dessen Hilfe die Lebensdauer gekerbter Bauteile vorausberechnet werden kann. Die Kenntnis der Spannungskonzentration, berechnet am ungerissenen, gekerbten Bauteil, reicht aus, um mittels Integration des Rissausbreitungsgesetzes das Ermüdungsverhalten zu studieren. Das Verfahren wird am Beispiel des Risses im Kerbgrund eines Schraubengewindes demonstriert. Die vorausberechnete Lebensdauer der Schraubenverbindung zeigt gute Übereinstimmung mit experimentellen Ergebnissen.

1. INTRODUCTION

Highly strengthened threaded joints are sometimes sore points in machines or steel constructions, especially in the case of cyclic loading.
In order to estimate the life time of threaded connections the behaviour of a crack in the most strengthened region of the bolt is investigated using the finite element technique.
As a prerequisite for the analysis of the local stress field the load transfer in the bolt-nut connection has to be calculated. This analysis shows the well known fact that the load is not distributed evenly along the threads. The thread at the base of the nut (the first thread) carries more load than all the subsequent threads. Furthermore, a significant stress concentration arises at the notch forming the bottom of the screw profile. It is essential to allow slip motion between the thread of the nut and the thread of the bolt in the model of analysis.

With this information the local behaviour of a crack in the bolt can be analysed. Singular crack tip elements are used to take account for the stress singularity. Because of the high stress gradient at the notch the LEFM (Linear Elastic Fracture Mechanics) geometric compliance factor, Y, [1] in the commonly used relation for the stress intensity factor is strongly dependent on the crack length, a. The crack propagates into areas with decreasing stress level.

To predict the fatigue life of structures many authors integrate the crack growth formulas (as e. g. that of Paris or Forman [1]) under simplifying assumptions. One of these assumptions is the neglect of the variation of Y(a) during crack growth. In the present paper this assumption, leading to a too short fatigue life, was not made. Y(a) is obtained calculating the Y values for several crack lengths. A correlation between the variation Y(a) and the stress distribution in the uncracked notch is recognized. Paris' law is integrated in a modified form for an estimation of the fatigue life of the threaded connection. Well agreement with experiments is found.

2. CALCULATION OF THE LOAD TRANSFER IN A THREADED CONNECTION

For the threaded connection M1∅, as shown in Figure 1, a stress analysis is performed using the Finite Element Method (FEM).

2.1 The FE-Model

The axisymmetric FE-model consists of substructure elements, see Figures 1 and 2. The degrees of freedom of the nodes within the boundary of those elements are condensed out [2]. Therefore the degrees of freedom of the whole structure are only those of the boundary nodes of the substructure elements.

Load-transfering nodal points between nut thread and bolt thread are allowed to slip in the direction of their surfaces, friction is neglected.
The applied reference nominal stress, σ_n, is assumed to be 100 N/mm^2. The boundary conditions are shown in Figure 1, the substructure elements in Figure 2.

2.2 Results of the Stress Analysis

The variation of the maximum principal stresses, σ_I, is displayed in Figure 3. The stress concentrations at the notches can be recognized by an increasing isostress line density. From notch to notch both the stress levels and the stress line density become less. This implies that the stress concentration and the part of the whole load transferred from bolt to nut decrease from thread to thread.

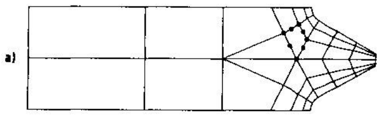


Fig. 2a Substructure element of a bolt thread

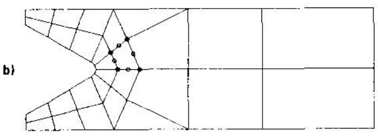


Fig. 2b Substructure element of a nut thread

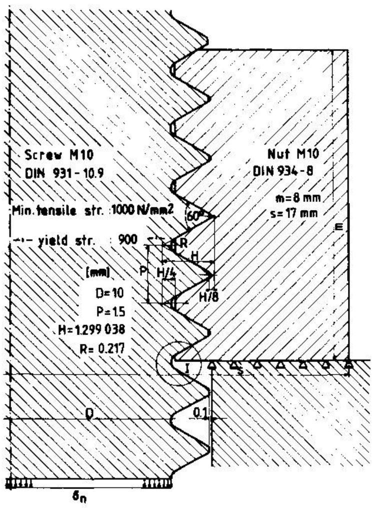
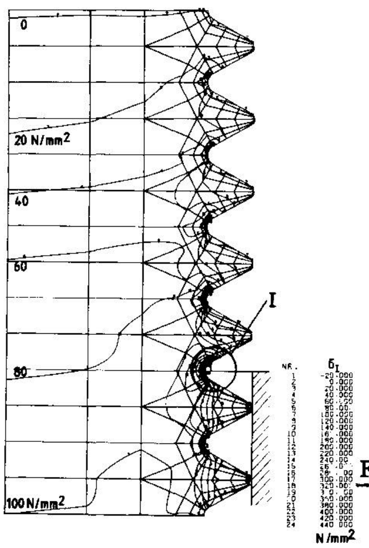


Fig. 1 Threaded conncection M10



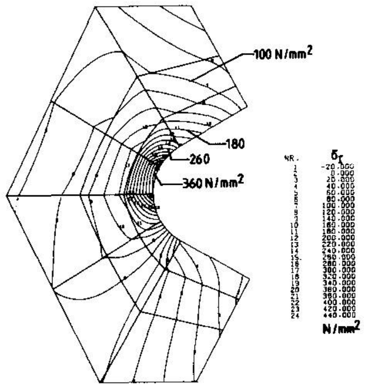


Fig. 4 Stress concentration at the notch root of the first and most stressed bolt thread (I in Fig. 1 and 3)

Fig. 3 Variation of principal tensile stresses in the bolt

Several other investigations about stress analysis of threaded connections are listed in references [3-7].

3. A CRACK IN THE THREAD OF THE BOLT

The stress distribution of the first load transmitting bolt thread is presented in detail in Figure 4.
The elastic stress concentration factor, α_K, which is defined as

$$\alpha_K = \frac{\sigma_{Imax}}{\sigma_n}, \qquad (1)$$

approaches the value of 4.0 at the notch root. σ_{Imax} is the maximum principal tensile stress.
In these domains of high stress concentration cracks may originate under cyclic loads.

3.1 Stress Intensity Factors

Investigations [8,9] have shown that failure of threaded connections is usually caused by tearing of the threaded bolts.
A number of local axisymmetric analyses of the bolt are now performed with several cracks assumed. The cracks are - in accordance with [1] - assumed to be normal to the maximum principal tensile stresses,i.e. normal to the notch surface. FE meshes for two sample crack lengths are shown in Figure 5. Singular elements

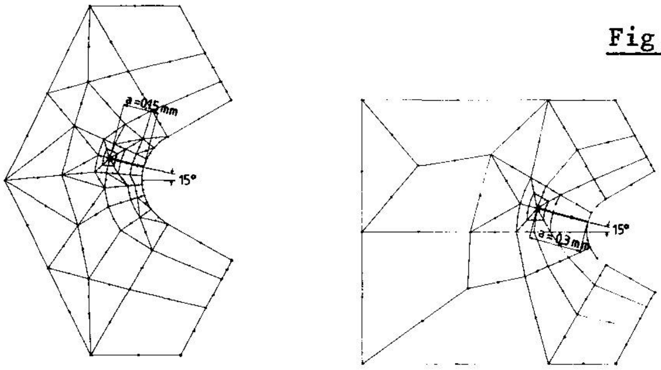


Fig. 5 Local FE models of the most stressed notch of the cracked bolt thread

[10,11] and transition elements according to Lynn [12] are used in the crack tip region.

The angle of 15^o between crack and the horizontal line as shown in Figure 5 is in good agreement with experimental results [13]. The loading condition for the local FE model is given by the displacements of the boundary nodal points which were determined in the global stress analysis.
The stress intensity factors, K_I and K_{II}, are calculated making use of the method described in [14]. The geometric compliance factor, Y(a), according to

$$K_I = Y(a)\ \sigma_n \sqrt{\pi\ a} \qquad (2)$$

is shown in Figure 6 in relation to the crack length, a.
The K_{II} values are very small even for greater crack lengths. Hence the assumption of a crack propagation in the initial crack direction is justified.
Checking the size of the plastic zone at the crack tip by Rice's formula [12]

$$\omega = \frac{1}{3\pi}\left(\frac{K_I}{\sigma_y}\right)^2 \qquad (3)$$

justifies the application of the linear elastic fracture mechanics concepts in this analysis.
ω is the plastic zone size, σ_y is the yield stress. Plane strain condition is assumed.

3.2 Crack Initiation

Differing from the procedure outlined in Ref. [14] the definition of the stress intensity factor range as proposed by El Haddad et al [16] is used:

$$\Delta K = Y(a)\ \Delta\sigma_n \sqrt{\pi(a+\ell_o)}\ . \qquad (4)$$

$\Delta\sigma_n$ is the applied nominal stress range. ℓ_o is a constant, characteristic for the material and surface conditions. It takes account for micro effects which could not be covered by continuum mechanics. In Ref. [16] the excellent ability of ℓ_o for eliminating discrepances between short and long crack results is demonstrated. The stress level at which a crack in acyclic loaded specimen will not just yet propagate is defined as the threshold stress. This threshold stress at a very short crack length is shown [16] to approach the fatigue limit stress of the material, $\Delta\sigma_e$.

ℓ_o is obtained from equation (4) by:

$$\ell_o = \left(\frac{\Delta K_{th}}{Y_o\ \Delta\sigma_e}\right)^2 \frac{1}{\pi}. \qquad (5)$$

ΔK_{th} is the threshold stress intensity factor, and Y_o is the geometric compliance factor for a very short crack. The crack length, a_o, at which a crack will propagate at a certain stress level, $\Delta\sigma_n$, is obtained by (4) and (5) as:

$$a_o = \left(\frac{\Delta K_{th}}{Y_o}\right)^2 \left[\left(\frac{1}{\Delta\sigma_n}\right)^2 - \left(\frac{1}{\Delta\sigma_e}\right)^2\right] \frac{1}{\pi} \qquad (6)$$

with the simplifying assumption: $Y(a_o) \approx Y_o$.

When the applied nominal stress range, $\Delta\sigma_n$, exceeds $\Delta\sigma_e$ cracks will initiate and propagate, because a_o would become negative, formally calculated by equ. (6). In other words, if $\Delta\sigma_n > \Delta\sigma_e$ cracks of very small size will propagate

Schwalbe [17] suggests ΔK_{th} being dependent on the Young's Modulus, E, and the stress ratio R_e, as described by:

$$\Delta K_{th} = E \times (2.75 \pm 0.75) \times 10^{-5} \times (1-R_e)^{0.31}. \qquad (7)$$

R_e is the ratio of minimum to maximum stress at fatigue limit load. The dimensions are $[MN/m^{\frac{3}{2}}]$ and $[MN/m^2]$ for ΔK_{th} and E, respectively.

In order to compare computed results with results of Illgner's fatigue tests [8] two examples are chosen:

$$(1)\ \Delta\sigma_n = 180\ N/mm^2 \text{ and } (2)\ \Delta\sigma_n = 240\ N/mm^2$$

as load in addition to the prestress $\sigma_V = 140\ N/mm^2$, of the bolt. The fatigue limit stress taken from Illgner's results is $\Delta\sigma_e = 140\ N/mm^2$ and the value of Young's modulus is $E = 2.06 \times 10^5\ N/mm^2$.

Using equ. (7) in combination with equ. (5) ΔK_{th} and the characteristic length, ℓ_o, are calculated:

$$\Delta K_{th} = 144.5\ N/mm^{\frac{3}{2}} \text{ and } \ell_o = 0.0212\ mm.$$

4. LIFE TIME ESTIMATION OF THE THREADED CONNECTION

Based on tests with cyclic loaded, cracked specimens various crack growth laws have been established [18,19]. The fatigue crack growth rate is controlled by loading, geometry of the specimen (notches etc.), mean stress, stress frequence, temperature and fracture mechanics material constants.

Here Paris' law [20] will be applied. It is formulated by:

$$\frac{da}{dN} = C(\Delta K)^m. \qquad (8)$$

$\frac{da}{dN}$ is the fatigue crack growth rate, ΔK is the stress intensity factor range and C and m are material constants.

By integration of equation (8) the number of endurable cycles of the specimen may be estimated.

ΔK is used as defined in equ. (4). At a certain crack length, a_c, failure of the component will occur if either

$$K_{Imax} = Y(a_c)\,\sigma_{nmax}\,\sqrt{\pi\, a_c} = K_{Ic} \tag{9}$$

or the nominal stress in the remaining net section approaches the tensile strength. K_{Imax} is the stress intensity factor at the maximum applied nominal stress σ_{nmax}. K_{Ic} is the critical stress intensity factor.
The variation of the geometric compliance factor, Y(a), especially for notched specimens like the threaded bolt under consideration, must not be neglected as will be seen later.

Figure 6 contains the variation of Y with crack length, a. Y decreases to unity at the end of the notch stress field. A distinct correlation of Y with the stress variation at the notch can be observed.

For cracks longer than the notch domain fatigue crack growth is governed by the bulk stress field only.
Hence, for cracks with $\frac{a}{r_K} > 0.02$ (with r_K being the half minor diameter of the bolt thread), Y(a) may be obtained from the geometric compliance factor of the unnotched specimen, Y_G.
According to Rooke and Cartwright [21] Y_G is given by

$$Y_G = \frac{\frac{a}{r_K}}{(1-\frac{a}{r_K})^2}\;\frac{1}{\sqrt{0.8+\dfrac{4\,\frac{a}{r_K}}{1-\frac{a}{r_K}}}} \tag{10}$$

r_K is the radius of the unnotched specimen and a is the crack length.
Richard [22] describes the relation of Y_G in the following way:

$$Y_G = \left(\frac{r_K}{r_K - a}\right)^2 \frac{1}{1-\frac{a}{r_K}} \sqrt{\frac{A + B\,\dfrac{a}{r_K - a}}{1 + C\,\dfrac{a}{r_K-a} + D\left(\dfrac{a}{r_K-a}\right)^2}}\;\cdot \tag{11}$$

A = 1.26; B = -0.24; C = 5.35; D = 11.6.
Two important features will be recalled. First, there exists a good correlation between the stress variation of the uncracked threaded bolt and the geometric compliance factor of the cracked threaded bolt in the notch stress field. Second, the influence of the notch may be neglected for long cracks.
Therefore, Y(a) for the threaded bolt may be well approximated by

$$Y(a) = Y_G\,\frac{\sigma_I(\ell)}{\sigma_n}\;. \tag{12}$$

Y_G is the geometric compliance factor for the unnotched specimen, $\sigma_I(\ell)$ is the principal tensile stress of the uncracked threaded bolt at $\ell = a$ (see Figure 6) and σ_n is the applied nominal stress. Similar formulas for Y(a) may also be found in Refs. [16,23].
Fig. 7 shows the variation of Y and K_{Imax} for both the unnotched specimen and the threaded bolt with crack length a.
Since Y is highly nonlinearly dependent on a, Paris' law is integrated numerically [24].

From equs. (4) and (8) the number of cycles corresponding to a certain crack length, a, is obtained by:

$$N(a) = \int_{0}^{a} \frac{da}{C.(Y(a)\ \Delta\sigma\sqrt{\pi(a+\ell_o)})^m} \qquad (13)$$

To get the number of cycles to failure, N_f, a_c must be taken as upper integration limit.

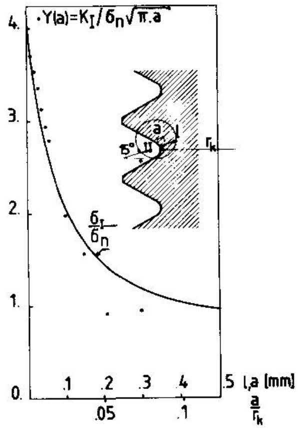


Fig. 6 Stress concentration at the notch of the uncracked bolt. Geometric compliance factors for various crack lengths.

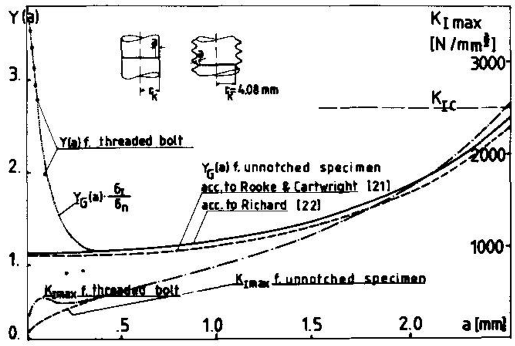


Fig. 7 Variation of the geometric compliance factor. Maximum stress intensity for the threaded bolt and the unnotched specimen ($\Delta\sigma_n$ = 180 N/mm^2)

Now two sets of material constants are taken from limiting curves of the deviation band of experimental data (see Figure 251 of Ref. [17]).

$C_1 = 8.5704\times10^{-9}$; $m_1 = 3.16$. $C_2 = 4.1706\times10^{-9}$; $m_2 = 2.94$.

Results of numerical integration of (13) for the two examples described in 3.2 are shown in Figure 8.

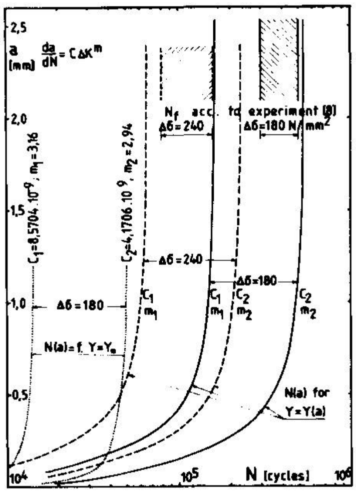


Fig. 8 Load cycles N, dependent on the actual crack length a for the threaded bolt.

Integration of the fatigue crack growth law with a constant geometric compliance factor, $Y(a) \equiv Y_o$, would render to a significant underestimation of the final fatigue life of the threaded bolt.

Taking into account the true variation of Y(a) of the cracked threaded bolt the integration of equ. (13) yields resonable agreement of the fatigue life of the threaded connection compared with results of Illgner's experiments, as shown in Figure 8.

CONCLUSIONS

The variation of the geometric compliance factor for a threaded bolt is given by equ. (12).

$\sigma_I(\ell)$ is calculated by a stress analysis of the uncracked threaded connection. Y_G is the geometric compliance factor of the unnotched specimen. By numerical integration of the appropriate crack growth law the fatigue life of a threaded connection may be predicted.

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