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:

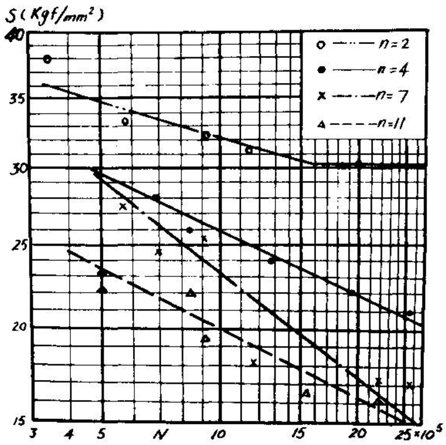


Fig.1 S-N curves of bolted joints

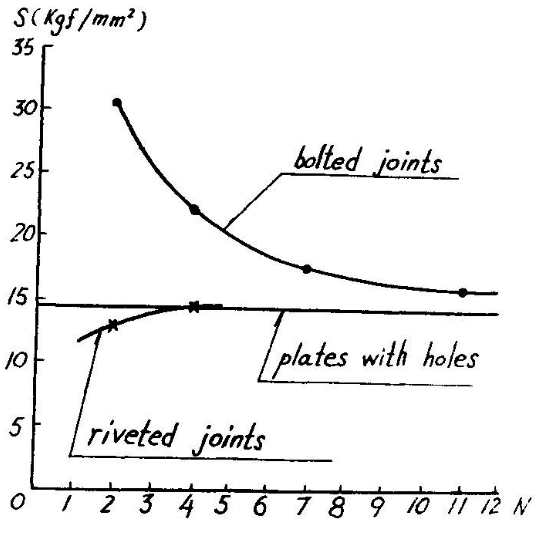


Fig.2 Relationships between fatigue strength of joints and number of fasteners in a line (R=0, $2x10^6$ cycles)

(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	fatigue loading
			net cross-section	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 $k_{r2}=k_o/2+k_{r1}/2=4$.

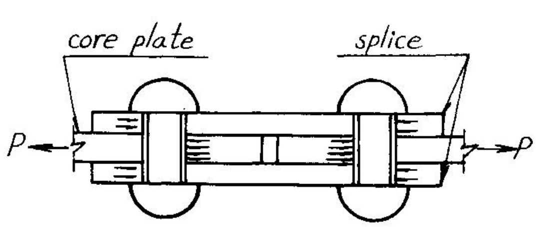
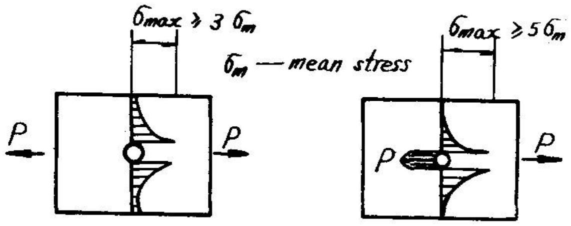


Fig.3 Manner of force transmission of riveted joint



(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: $k_{T3} = 2k_o/3 + k_{r1}/3 = 11/3$; $k_{T4} = 3k_o/4 + k_{r1}/4 = 14/4$; ......; $k_{r10} = 9k_o/10 + k_{r1}/10 = 32/10 \approx 3 = k_o$. 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.

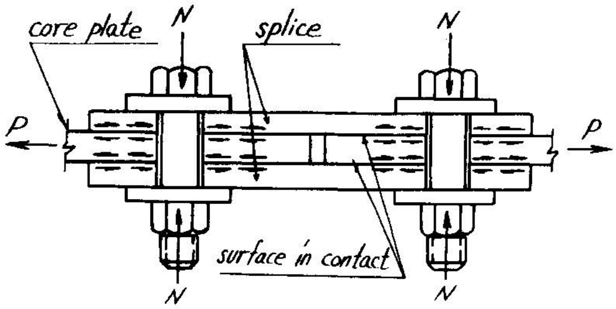


Fig.5 Manner of force transmission of a bolted joint

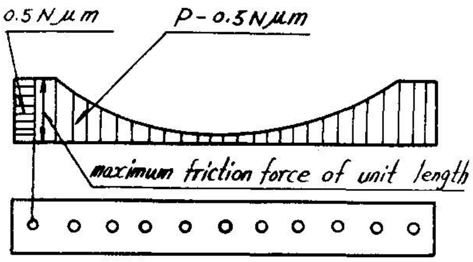


Fig.6 Friction force distribution in the direction of force

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 strèsses 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.