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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.

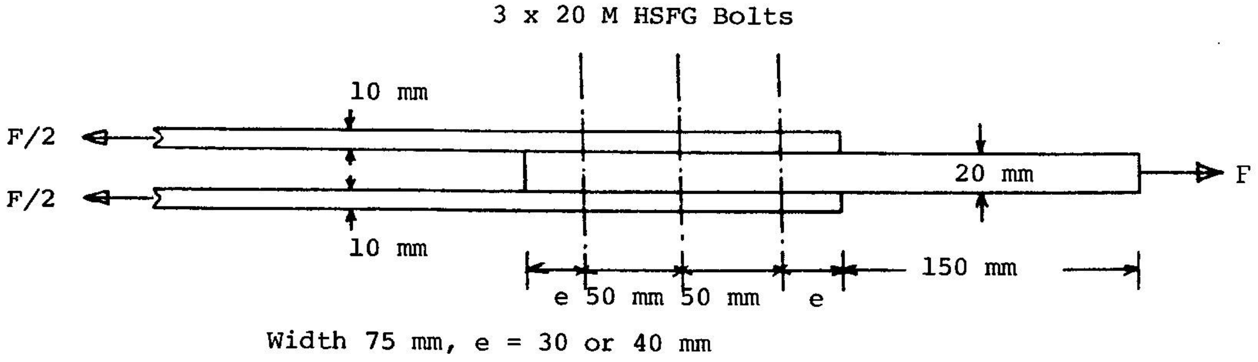

Fig. 1. Standard Fatigue Test Piece

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.

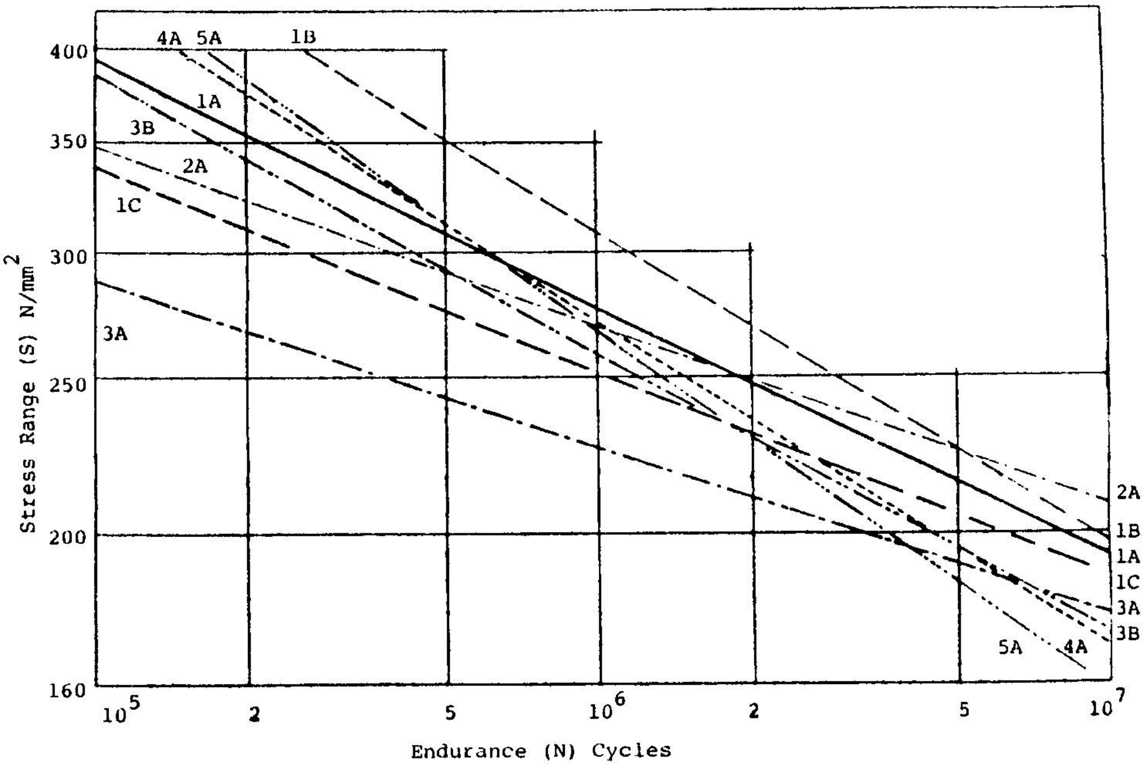

Fig. 2 Fatigue Tests Results S-N Mean Lines

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.

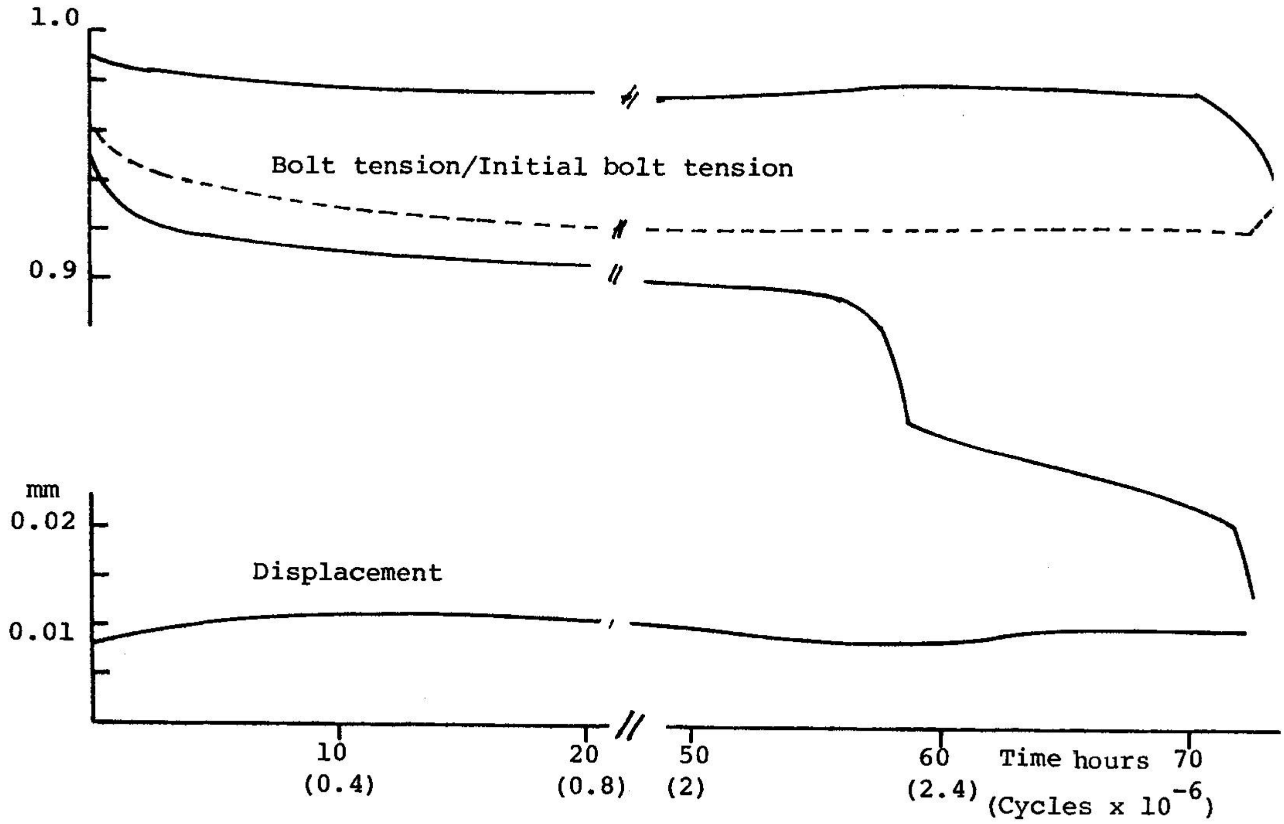

Fig. 3 Fatigue Test - Joint Stability

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

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REFERENCES

1. British Standards Institution : "Code of Practice for the design of steel bridges", BS.5400.
2. SPIERS, R. & CULLIMORE, M.S.G. : "Fretting fatigue failure in friction grip bolted joints". J. Mech. Eng. Sci., Vol. 10, No. 5 (1968).
3. SPIERS, R. & CULLIMORE, M.S.G. : "Geometrical factors influencing the fatigue of friction grip bolted joints". Hungarian Acad. of Sciences, 3rd Conf. on Dimensioning and Strength Calculations, Oct. 1968.
4. CULLIMORE, M.S.G. & ECKHART, J.B. : "The distribution of clamping pressure in friction grip bolted joints". Struct. Eng., Vol. 52, No. 5 (1974).
5. CULLIMORE, M.S.G. : "Bolted connections - Research affecting current design practice". The Design of Steel Bridges, Granada, London 1981.

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