FRETTING FATIGUE RESISTANCE OF ALUMINIUM JOINTS

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ABSTRACT

Bolted joints in aluminiun components and fretting effects are examined. The range of bolted applications in constructional engineering and the properties of a bolted connection also as a rehabilitation or repair technique, in the case of structural parts exhibiting fatigue cracks,is demonstrated. Recent results of respective research programs are reported.

KEYWORDS

Fretting, bolted joints, pretensioning and relaxation, fatigue, aluminium alloys

INTRODUCTION

Designing bolted joints care will be taken normally to keep stress concentration factors low so that they rarely exhibit values above 3.0. However, it is frequently observed that the net reduction factors in fatigue strength for larger joints may reach much higher values. Individual strength reduction factors K_f at endurance lives of $\approx 2*10^6$ cycles are reported [1] with values of 1.5-2.0 for the geometric stress concentration, 1.0-1.5 for load distribution effects, and 1.5-3.0 for other agencies, incidentally fretting.

CHARACTERISTICS OF FRETTING

When two contacting metallic faces are pressed together by an external load and simultaneously subjected to transverse cyclic loads, this results in relative motion with highly localized friction between the surfaces and subsequent metallic detachments and oxide particles, the latter harder than the metal itself in the case of aluminium, causing abrasion. This is termed as fretting, as long as the relative slip amplitudes are small or in order of magnitude to those developing under elastic stresses (generally not more than 0.1 mm). Fretting debris on the interface, mainly aluminium oxide and normally white, shows as black in reflected light. The amount of fretting is greatest under dry conditions and increases with contact load and slip amplitude; soft materials are more susceptible.

Lubricants and diverse insulations to prevent metal-to-metal contact will reduce frictional forces between the contact surfaces but cannot be considered in our case of friction-grip aluminium joints performed by high-strength bolts. These provide, as will be shown, the most efficient jointing method by increasing the interfacial clamping pressure and transfering the fluctuating loads from the bolts to the plate elements.

FRETTING AND FATIGUE IN ALUMINIUM

It is a common appearance in fatigue tests that aluminium specimens fail frequently by cracks initiated through fretting just inside the grips. For a wrought heat-treated 4.5%Cu-aluminium alloy or a cast heat-treated one a fretting fatigue strength value of ±70 MPa for 10^7 cycles is given. Again the 4.5%Cu-aluminium alloy specimens with clamp pads of similar material and a clamp force of 0/4/125 MPa exhibited at a tensile mean stress of 195 MPa at $2*10^7$ cycles fatigue strength range values of 250/108/80 MPa. It is interesting to note that a replacement of the aluminium pads by mild steel pads did not show any significant differences in the results. Corresponding tests at zero mean load showed considerably less reduction in fatigue strength [2].

Other investigations indicate that there is a critical stage in a fretting case after which the damage, and incidentally final failure, passes beyond the influence of the fretting mechanism. or in other words, once this limit is exceeded, a crack formed as a consequence of fretting is able to grow influenced only by the nominal cyclic stress and independent of any surface fretting effects. The fatigue behavior of a fretted part is governed by crack propagation, practically. Fretting reduces the initial fatigue strength though due to the high stress concentration at the edge of the fretted "microweld" area leading to crack initiation at this area. Regarding this changeover depth of a surface microcrack changing into a propagating crack we recognize that for a service stress level of the same proportion to the fatigue endurance limit this critical depth will be less for a high-strength alloy as compared to a low-strength alloy. Logically, a fretting crack propagating will be influenced by any residual compressive stresses on the contact surfaces.

Bolted joints of high-strength aluminium alloy plates will often develop fretting cracks away from the bolt hole itself, in friction-grip joints with high-strength pretensioned bolts this point will be normally at the edge of the bolt pressure cone. The fatigue strength of a bolted joint cannot be related to the base material fatigue strength nor to the ultimate static strength of the joint. Single-lap joints are always weaker than double-lap ones. Bolt number, position and spacing may also affect the result. The following table reproduces experimental results as reported in [2] for a 4.5%Cu-aluminium alloy tested at R=0.25, giving fatigue strength in MPa at $2*10^6$ cycles based on the net cross-section area of the joint:

Bolt configuration	plate thickness [mm] 2.5	9.0
base material, no bolts	170	170
single central bolt	58	39
3 equi-spaced bolts across plate	54	—
2 bolts in line	85	50
3 bolts in line	89	54
2 rows of 3 equi-spaced bolts across	—	54
3 rows of 3 equi-spaced bolts across	—	70

Considerable enhancement in fatigue strength may be reached by appropriately treating surfaces of bolted joints as reported in [1]: relative to the mean fatigue strength range of 194 MPa at $2*10^6$ cycles (R≈0.06) of base material in direct fluctuating stress cycles, bare double strap butt joints of the alloy DTD.683 with a single row of two bolts across showed only 114 MPa (R≈0.11), but were improved up to 172 MPa (R≈0.08) for joints with a thin film of plastic material in the interfaces. Respective tests on alloy DTD.363 joints with steel flange plates (cadmium plated) demonstrate the efficience of close tolerance bolts and higher torque tightness, bringing fatigue strength values from 30 to 60 MPa at $2*10^6$ cycles. Or otherwise expressed as a factor upon life an enhancement of 3.0 may be reached for close tolerance bolts and controlled torque tightening, as well as another ≈3.0 for anti-fretting treatments.

These results come from tests in aircraft joints, and in the case of the treated interfaces with a very low coefficient of friction (considerably below 0.1) and resulting shear load transfer to the bolts and bolt holes, failures occur now again as normal stress concentration cracks at the bolt hole lines.

On the other hand applications in civil engineering and general constructional engineering often call for friction-grip joints; consequently treatments improving the transfer of fluctuating loads from the bolts to the plate elements will be favoured.

Coefficients of friction for cleaned surfaces (removal of oil films or like) of aluminium plates in AlZn4.5Mg1 (7020), AlMgSi1 (6082) and AlMg4.5Mn (5083) at values of $\mu \approx 0.12$ have been measured; these are compared to the values over 0.50 for sandblasted surfaces [3,4]. A few fatigue tests reported at the time with riveted and high-strength and pre-tensioned bolted connections in the 7020 alloy show at 10^5 and $2*10^6$ cycles and R=+0.1 fatigue strength range values of approx. 90 and 75 MPa respectively [5]. These are roughly 50% of the respective values for similar joints in St37 steel.

The above investigations have all been performed with small specimens in the sixties or before and in the early seventies.

RECENT RESULTS

Regarding applications in structural engineering the following investigations offer an outline of achieved fatigue strengths in aluminium joints and the respective enhancement for treated surfaces, especially under fretting conditions.

Within the extensive investigations of welded aluminium beams at the Technical University of Munich [6,7] a number of interesting fretting fatigue failures were recorded at bolted joints on the beam flanges. These were intended as a repair measure for fatigue cracks forming at various weldments. The joints were manufactured as double strap joints with untreated steel plates of 12 mm thickness for the 15 mm flanges of the H-shaped 7020 beams and 6mm for the 6mm flanges of the box-shaped 6005A (AlMgSi1) beams. Steel plates were brought on both flanges of a beam to maintain symmetry of stress distribution during the subsequent cyclic loading. On the flange of the H-shaped 7020 beam two rows of two M16 (16 mm dia.) bolts across for each joint half were used, on the box-shaped and narrower 6005A beams there were two M12 bolts in line. Holes were drilled with a 0.3 mm tolerance in both cases. The bolts were high-strength bolts type 10.9 after DIN 6914, pretensioned with a torque of M =120 or 350 Nm (slightly oiled bolts) resulting in an axial bolt clamping force of 50 or 100 kN for the M12 or the M16 bolt respectively after DIN 18 800, part 7. The joint was regarded as a friction-grip bolted joint, with failures occurring out of the line of bolt holes, but it did not perform as a close tolerance joint, Fig. 1 and 2. Although sharp edges of the steel plates had been rounded off in one or two cases a fretting fatigue crack formed on the aluminium flange plate at the end of the steel strap, Fig. 3.

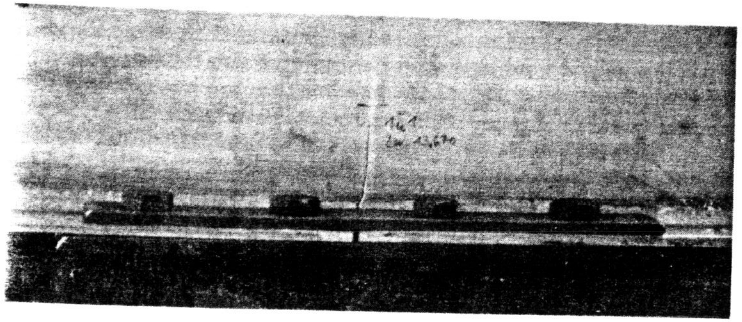

Fig.1: Bridging a weld fatigue crack with a bolted joint

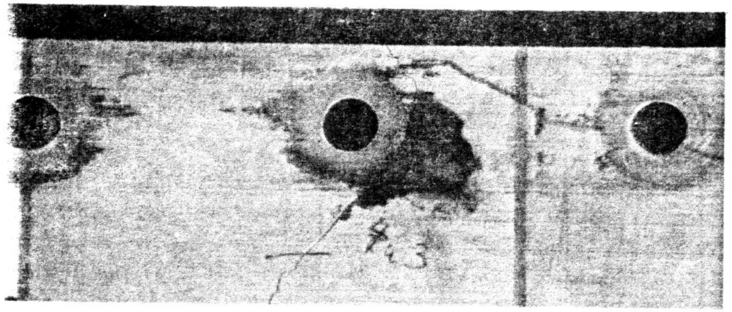

Fig.2: Fretting fatigue crack forming at edge of bolt pressure area

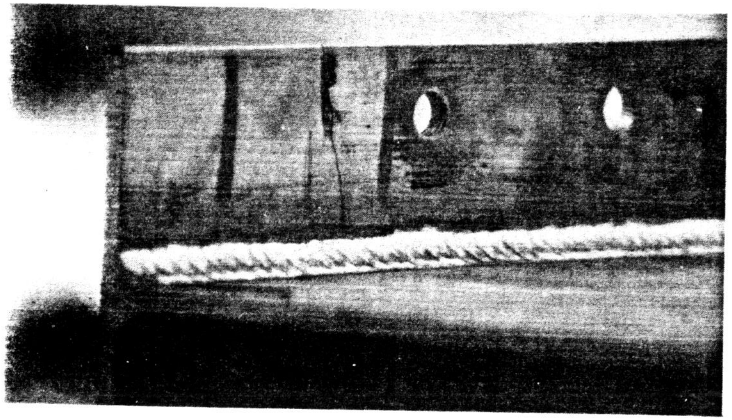

Fig.3: Fretting fatigue crack forming at end of steel plate

No subsequent re-tightening of the bolts was undertaken to allow for any creep effects in the joined aluminium parts since previous evidence had shown that such a reduction of the pre-tensioning load of the connection would be of the order of 10% or less [10] and not affect its overall behaviour significantly [4]. Results of these tests are shown on the S-N diagram of Fig. 4, described by the regression curve logN=-2.77*logS+10.86,a standard deviation on life s(logN)=0.190 and on strength s(logS)=0.069,stress range values at 10^5 or $2*10^6$ cycles of 131 or 44 MPa for the mean line and 94 or 32 MPa for the lower limit line of 97.5% probability of survival.

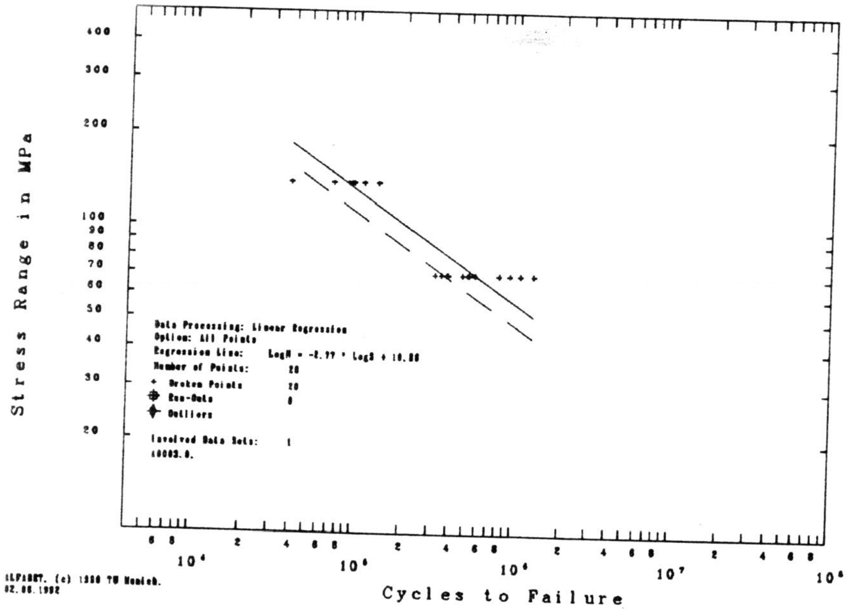

Fig. 4: Fretting fatigue data analysis from TUM beam tests

Out of the total of 20 data points there were 16 failures from 6005A beam joints; the rest from 7020 beams. The ultimate static strength and 0.2-yield strength values were as follows, with considerable scatter in the case of the 7020 alloy resulting from the different production sites and lots, yet not investigated further during these tests [7]:

		R_m [MPa]	$R_{p0.2}$ [MPa]
7020	AlZn4.5Mg1	357-446	290-402
6005A	AlMgSi0.7	324-335	294-304

Viewing the comparisons in Fig. 5 one notices that the above results fit exactly into the same scatter band of fatigue tests on riveted beam joints, reported elsewhere ([10] data set no. 7093), with a slope of -2.89, standard deviations of s(logN)=0.125 and s(logS)=0.043, and stress range values at 10^5 or $2*10^6$ cycles of 126 or 45 MPA for the mean line and 103 or 37 MPa for the mean minus two standard deviations line. They also relate in a satisfactory way to maximum or minimum attainable values at 10^7 for riveted joints as reported in [2].

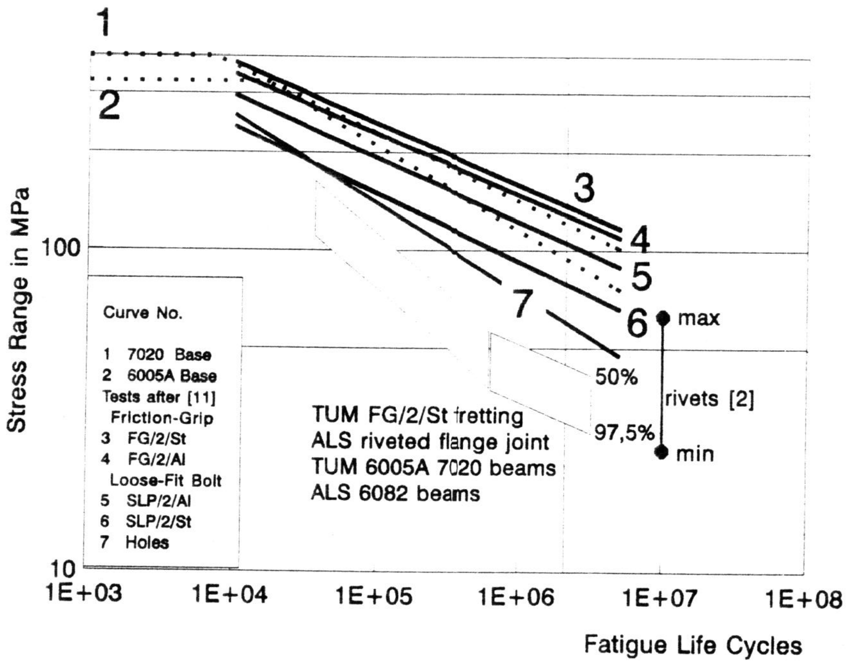

Fig. 5: Fretting fatigue behaviour of aluminium joints and influence of manufacturing parameters

Finally, results from another study on bolted aluminium connections [11], even allowing for the fact that the TUM tests have been on full-size components and that these had been cycled already until fatigue cracks formed at some weld detail and the bolted repair joint was undertaken, and also that these new results are only on small specimens, definitely demonstrate the advantages of contact surface treatments through sand blasting and some simple protection coating, both on aluminium and steel surfaces. Such friction-grip bolted connections, with either aluminium or steel straps, reach the fatigue strength values for the base material and are superior to loose-fit bolted connections. The latter showing advantages over specimens only with drilled holes as well, especially for the higher cycle regions.

CONCLUSIONS

The reported TUM tests represent the lower limit of untreated joints of aluminium parts with untreated steel strap plates in full-size components. Depending on the interface treatment, the use of adequate pretensioning through the bolts to activate interfacial frictional load transfer, the bolt tolerances, their number and spacing, considerable further fatigue strength enhancement may be achieved as reported in other recent investigations. Fretting may be thus controlled and, where manufacturing conditions allow or when repair is necessary, bolted connections may be introduced with predictable performance. Further experimental verification of manufacturing variables on full-size structural components is though strongly recommended as behaviour of riveted or bolted joints can only be assessed reliably from actual behaviour of the joint itself.

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