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MULTIPLE-SITE-DAMAGE FATIGUE OF RIVETED JOINTS

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J. Schijve

TU Delft

Delft University of Technology

Faculty of Aerospace Engineering

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J.Schijve
Faculty of Aerospace Engineering
Delft University of Technology

Abstract: Results of fatigue tests on riveted lap joints, including fractographic observations, are presented and analyzed. It indicates that the load transmission in a riveted lap joint is a rather complex phenomenon, as confirmed by quite different crack initiation mechanisms. It may not be expected that fracture mechanics predicts early crack growth with a practically useful degree of accuracy. Most important, the fractographic analysis reveals, that if there are visible cracks in a riveted lap joint, there are many small cracks at most rivet holes in the same critical row of rivets. An Multiple-Site Damage (MSD) situation is present. The conclusion also applies to fuselage lap joints. Scatter in laboratory tests on riveted lap joint specimens is relatively low, with $\sigma_{\log N}$ in the order of 0.10. However, scatter of riveted joints in a fleet of aircraft may be larger for several reasons. Crack growth in riveted lap joints may be sufficiently slow to allow a timely detection in service. For aging aircraft this should be confirmed by full-scale testing.

INTRODUCTION

For a long time the aircraft industry has been very much aware of the fatigue cracks occurring in service. Already in the fifties this has led to fatigue tests on full-scale structures, although it was sometimes done reluctantly in view of the high cost of such tests. Fatigue tests on joints were abundantly carried out, because experiences had clearly shown that natural fatigue cracks were frequently initiated in joints, i.e. in riveted joints, bolted joints and lug type joints. Many of such tests were carried out with constant-amplitude (CA) loading. Initially this type of loading was preferred, because the more complicated variable-amplitude (VA) was still experimentally problematic . However, the picture changed when understanding of fatigue damage accumulation increased, while at the same time the electro-hydraulic fatigue test machines with closed loop load monitoring was introduced. It was understood that fatigue tests, to be of direct technical relevance, must be carried out as realistically as possible. It requires:

(i) realistic test specimens and
(ii) realistic load histories in the fatigue tests.

For joints a realistic specimen is the joint itself, in order to avoid size effects or other non-representative features of simplified specimens. Similarly, a realistic load history should be truly representative for load histories as they occur in service. It thus requires information on load-time histories in service !

Two major aircraft components can and have been shown to be fatigue sensitive, especially so for transport aircraft:

- the tension skin of the wing and
- the skin structure of a pressurized fuselage.

A realistic simulation of the service load history seems to be problematic anyhow, because the test must be run in a much shorter time than the flying time of the aircraft. All our fatigue tests are accelerated tests because the time scale is compressed. That may lead to "frequency" or "load rate" effects, which could be related to environmental influences. It is generally believed that such effects will not be prohibitively large, provided that aggressive environmental conditions can be avoided in service. However, with respect to simulating the VA-loading in service, it is well understood that characteristic features of the service load history should be maintained in the tests. For a wing structure it implies that a random flight-by-flight load sequence with different types of flights is essential. The flight-simulation test is now a generally accepted testing procedure.

The situation is different for a pressurized fuselage. Although stiffness and stability offer significant design requirements, the allowable stress level in the fuselage skin structure with its extensive lap and butt joints is highly depending on fatigue. This has become a more stringent problem since aircraft are nowadays supposed to have a longer economical life (say 20 years) than in the past. Moreover, it should be recognized that some operators make numerous short flights every day. For a fuselage the fatigue life must be associated with the number of pressurization cycles, usually the number of flights. The design goal is a crack free life for a specified economical life, which can imply 60,000 flights in 20 years. Several present aircraft are plagued by fatigue cracks around doors[1], for which local repairs are then introduced. However, if the fatigue life of skin joints is insufficient, it can be an economic disaster, if not a fatal accident when cracks remain undetected. It is for this reason that the allowable hoop stress level is always carefully selected to avoid later trouble. The same should be true for the joint design, the selection of material, types of fasteners and riveting procedures. Experience with previous aircraft models is most instructive. One condition is more simple than for a wing structure. The service fatigue load, as a first approximation, may be considered to be constant-amplitude loading with a zero minimum load, and a maximum load, which is also fairly accurately known. In view of the large economical impact of fatigue problems in the skin joints, an ample safety margin is adopted. It could imply that the fatigue life of the numerous skin joints should be in the order of 300,000 cycles, a large number which should also account for scatter.

It may well be that the fatigue margins and past experience has led us to believe that fatigue of the skin joints was well kept under control. Nevertheless, the possibility of many collinear cracks and an explosive unzipping failure were recognized a long time ago, but it should not occur if sufficient fatigue life is available. A few warnings (i.e. explosive failures) were obtained in full-scale fatigue tests before the Aloha accident occurred. After that accident a fully different picture emerged and the problem got its name, MSD, a new illness of aging aircraft. Perhaps, the significance of multiple-site damage in riveted fuselage joints is overemphasized at the moment, but it would be incorrect not to pay adequate attention to the problem, knowing that more and more older aircraft will be flying around in the near future [1,2]. Wide spread efforts [3-6] seem to concentrate on:

- fatigue behaviour or riveted joints
- potential usefulness of fracture mechanics to predict the MSD behaviour, including fatigue crack growth and residual strength
- statistical aspects
- non-destructive inspections (NDI) of riveted joints
- proof loading and periodic overloading to ensure safety and an increase of life and inspection periods

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[1] Repair patches at the corner of a door in older aircraft can be observed by passengers when entering the aircraft.

The present paper primarily deals with the fatigue behaviour of riveted lap joints, but there are consequences of understanding this behaviour for the other subjects.

THE FATIGUE BEHAVIOUR OF RIVETED LAP JOINTS

The fatigue behaviour of a riveted lap joint is depending on a large number of variables in some main categories:

1. Rivet pattern (number of rivet rows, rivets in each row, rivets in line or staggered)
2. Dimensions (sheet thickness, rivet diameter, rivet pitch, distance between rows, overlap)
3. Type of fastener (countersunk rivet, snap rivet, dimpled holes, special types of rivets)
4. Riveting procedures (automatic or hand riveting, squeeze load, interfaying layer)

Some aspects are added between brackets, but the listing is not necessarily complete. Our information about the influences of the variables has largely been obtained by carrying out numerous fatigue tests, and more in particular by comparing fatigue lives as obtained under CA-loading. Unfortunately, the total fatigue life in numbers of cycles is the absolute minimum of what can be learned from a fatigue test. A closer examination of the specimens, the type of failure and the fracture surfaces gives valuable information.

Fatigue test programs on riveted joints are not often reported in the open literature. Results are documented in reports published by laboratories, and as S-N curves in the industry handbooks or other compilation documents (e.g.[7]). The designer prefers S-N curves in order to see the stress level effect on life for different designs of riveted joints. From laboratory investigations a qualitative picture of the load transmission in riveted joints has emerged. It turns out to be rather complex, which is not generally expected for such a simply defined problem as the load transmission from one thin sheet into another thin sheet. Analysis of the fatigue behaviour has indicated several important aspects, such as:

- *complex stress concentrations around rivet holes*
- *secondary bending due to built-in eccentricities*
- *fretting corrosion at the mating surfaces*
- *clamping the sheets together by the rivets*
- *filling up the hole during the riveting operation*
- *fastener flexibility*

Some comments on these aspects are made below.
Load transmission by a rivet implies a bearing pressure on the rivet hole (pin-loaded hole). It causes a local stress concentration at the edge of the hole, see rivet row 1 in Figure 1. Load transmission also occurs at row 2, which leads to a by-pass load for row 1. As a result, row 1 is critical in the upper sheet of Fig.1, whereas row 2 is critical in the other sheet for the same reasons. If there are more than two rows, the outer rows are the critical ones, due to the rivet load transmission and the by-pass load, see the arrows in Figure 2. Another argument is that sheet bending, induced by the eccentricities of the joint, has its maximum at these rows.

Different stress concentration factors apply to the pin-loaded hole case and the by-pass load. Simple assumptions can be made for the K_t-factors. Unfortunately, more realistic information can not easily be obtained from FEM calculations. The pin-loaded hole case is problematic in view of the bearing pressure distribution on the hole (Hertz problem), friction between pin and hole, and more in particular the (unknown) load transmission by frictional forces between the mating sheets. Qualitative measurements of the friction around rivet holes were carried out by Hartman [8]. It confirmed that significant friction was present. Moreover the friction increased considerably during fatigue cycles, mainly in the first part of the fatigue life. The stress concentration of the by-pass load also offers a problem, because the rivet hole is not empty, it is filled by the rivet, and thus it will be lower than for an empty hole.

The above arguments apply to the riveted joint as a 2-d problem, but in reality the load transmission in a lap joint is a 3-d problem. The bearing pressure on the rivet hole is not homogeneously distributed over the sheet thickness, see the schematic picture in Figure 3. It should be expected that the hole bearing pressure is higher near the mating surface. At the same time, Figure 3 correctly suggests that the shape of the rivet head must also be considered. Another complicating aspect is the fit of the rivet in the hole (clearance or interference). Although calculation results are not available, it is easily recognized that a rivet, which tightly fills the hole, will give a more favourable distribution of the bearing pressure than a loose rivet.

Figure 3 does not yet include the occurrence of secondary bending, which is a consequence of the eccentricities, see Figure 4. Simple calculations of secondary bending are possible by solving a differential equation the type shown in Figure 4. Such calculations indicate that the secondary bending is a non-linear function of the applied load. The major virtue of the calculation is to indicate the severity of the bending and its dependence on the joint design. For instance, it shows that a large overlap gives less secondary bending. Fatigue tests have indeed confirmed that it improves the fatigue life. The significance of secondary bending is illustrated by the S-N curves in Figure 5 [9]. The symmetric joint without eccentricities is definitely superior to the lap joint and the single-strap butt joint. For the latter joints the fatigue limit is in the order of 13.5 MPa (2.0 ksi). This low value emphasizes that a riveted lap joint is a poor joint from a fatigue point of view.

Knowledge of the local stress around the rivet hole might appear to be helpful for predicting crack initiation lives. Unfortunately, fretting corrosion plays a dominant role in crack initiation in riveted joints. If clamping between the two sheets is absent, fretting corrosion will occur between the rivet and the hole. However, some clamping is always present, and thus fretting corrosion of the mating sheets does occur. The amount of clamping will determine where crack initiation occur [10-12]. If the clamping is limited, crack initiation starts at the hole (Fig.6a), whereas a tight clamping can lead to crack initiation outside the hole (Fig.6b) and to cracks, which no longer pass through the holes (Fig.6c). A tight clamping makes the holes less critical, and fretting corrosion more critical. It can be obtained by a more intensive riveting procedure. The industry is using machines for automatic drilling and riveting already for a long time, whereas in the older days hammer riveting was usual. The rivet shank is squeezed to form the driven rivet head and to obtain a good filling of the rivet hole. A larger squeezing load will lead to:

- a better filling of the hole,
- an increased clamping between the two interconnected sheets, and
- a larger driven rivet head.

Several consequences for the fatigue behaviour of the riveted lap joint should be recognized:

(i) The load transmission by frictional forces will increase.

(ii) The bearing pressure distribution in the thickness direction (Fig.3) will become more uniform.

(iii) Due to the more tight filling of the hole, the rivet shank is better embedded in the holes. The stiffness associated with fastener flexibility will be improved.

(vi) A more intensive filling of the hole will expand the rivet hole. It implies a kind of prestressing with the well known favourable reduction of the local stress amplitudes, which predominates the increased mean stress.

(v) A more tight fit of the rivet hole will also decrease the stress concentration of the by-pass load.

All these effects seem to be favourable for the fatigue strength. Illustrative results have recently been obtained in a cooperative test program from our laboratory with the Fokker Aircraft Industry. An important variable was the squeezing force of the automatic drilling and riveting machine. Some results are given in Figures 7 and 8. If the squeezing force was increased, the diameter of the closing head increased, while the height decreased (Fig.7). At the same time the hole expansion also increased. This geometric changes should be expected. Actually, the measurements agreed rather well with a constant volume of the plastically deformed rivet. Riveting occurred in the as quenched condition. The improvement of the fatigue life (Fig.8) for an increased riveting force is significant, which confirms the above listed effects.

The improvement of the fatigue life, caused by a more intensive riveting, was already known for a long time. The effect was found by Smith [13], Schütz [11] and Hartman [14]. They all measure the more intensive riveting by an increase of the rivet head. Hertel [12] measured the squeezing force and also observed an increased hole expansion and an improved fatigue life if larger squeezing forces are applied.

FRACTURE MODES, CRACK INITIATION, CRACK GROWTH AND FRACTURE MECHANICS

The literature on fracture modes of riveted joints is not abundant. Sometimes, the information is limited to indications whether the crack started in the sheet with the manufactured rivet head or in the sheet with the driven head. It is generally pointed out that fretting corrosion is significant for the crack initiation. The information in this chapter is largely based on NLR reports [9,10,14,15], some references from the literature [11,12,16] and a recent examination of the fracture surfaces of riveted lap joints tested by students in Delft [17,18].

Crack initiation sites

Crack initiation can start at different locations depending on the type of rivet and rivet clamping of the sheets. Common types observed are:

1. Crack initiation in the minimum section (rivet row) at the edge of the hole.

Hartman [10] observed this crack initiation site to be applicable to Avdel rivets, a type of blind rivets which do not give good clamping. However, the same location is frequently found for countersunk rivets, see Fig.6a. The latter case is highly relevant to pressurized aircraft fuselages, because they are usually riveted with countersunk rivets. The two critical locations indicated in Fig.2 are not equally critical. Usually, fatigue occurs at the edge of the countersunk hole (arrow A in Fig.2), because of the shape of the hole (knife edge if the countersunk is too deep). Sometimes, the other row (arrow B in Fig.2) was found to be critical. Also, if cracks at location A lead to failure, some cracks in the other outer row (location B) have been observed.

Crack initiation at the hole edge is also found for snap rivets. Hartman [15] observed that it mainly occurred in the sheet of the driven rivet head if the sheet thickness was low (0.6 and 1.0 mm), and more often in the sheet of the manufactured head for a thicker sheet (1.6 mm).

2. Crack initiation in the minimum section away from the hole, see Fig.6b. Crack initiation is then predominantly controlled by fretting corrosion. This type of failure is frequently found for snap rivets. Cracks are not always initiated along the center line of the rivet row, but slightly above that line. There is a tendency of cracks to grow around the rivet hole, rather than through the rivet hole. That may lead to:

3. Crack initiation outside the hole at a location in the "shadow" of the hole, see Fig.6c. This type of failure is especially found if the clamping is high, e.g. for special types of fasteners, such as Hilok bolts [10]. It is also found for well driven rivets as shown in Fig.6c. The crack initiation starts at the top of the fretted area (shaded area in Fig.9), usually at some neighbouring locations simultaneously. It can lead to rather chaotic fatigue cracks.
The nature of the load transmission has changed from a pin-loaded hole type to a kind of a contact-area load transmission. It is partly similar to a spot welded joint. The transmission by clamping occurs in an area, which is larger than the rivet hole, see the schematic picture in Figure 9. The peak stress now occurs at the top of the clamped area (point A in Fig.9), and no longer at the center line of the row

of rivets. Fretting at the edge of the clamped area can not be avoided. The maximum fretting displacements and the peak stress occur at the same location, which then becomes the crack initiation site. The crack no longer grows through the hole.
Hartman [14] found also the same crack initiation site for snap rivets if all surface treatments before riveting were omitted (dry riveting). It gave a small increase of the fatigue life.
Specimens with countersunk rivets tested in Delft [17] revealed a different behaviour at a low and a high stress level. For the low stress level (high endurance), crack initiation generally started outside the hole and the crack did not grow through the hole. However, for the high stress level (low endurance), the crack growth path was through the holes.

4. Riveted joints with dimpled holes in thin sheets are a special case. Crack initiation generally occurs outside the dimpled holes, again in the "shadow" of the hole, see Figure 6d. In general, the fatigue strength is lower than for countersunk rivets or snap rivets. The initiation occurs near the corner of the dimple, which may be due to the local stress concentration of the corner. Additionally, there is a positive bending stress at the same location, due to secondary bending. Moreover, a residual tensile stress is left from the dimpling operation. If the quality of dimpling and filling the hole by riveting are poor, the load transmission has a rather strange nature, because it will partly occur by the dimpled edges of the hole.

The first small fatigue crack nuclei are initiated at the mating surfaces due to fretting corrosion. As a consequence, the fatigue nuclei initially grow as part through cracks. The secondary bending will also stimulate the part-through character. Figure 6 suggests that the part through crack can have a quarter-elliptical shape if the crack starts near the rivet hole edge, or a semi-elliptical shape if it is nucleated away from the hole. However, a closer look at the pictures reveals that the elliptical shape is a rough approximation only. In several cases several small cracks are nucleated at nearby locations to form one larger crack later. It can lead to quite erratic crack shapes.

As long as the fatigue crack is a part-through crack it can not be detected by a visual examination. Especially in thick sheets small fatigue cracks can remain hidden for a long part of the fatigue life. After penetration of the thickness, the fatigue crack becomes a through crack. However, the crack front will not rapidly turn over to an orientation perpendicular to the sheet surface, again as a result of secondary bending. Fatigue crack growth in riveted lap joints is rarely reported in the literature. Schütz [11] in the early sixties made observations on fatigue cracks after they became visible as through cracks. He reports that visible crack detection was possible late in the fatigue life, say in the last 10 percent of the life.

Nowadays, as a result of the MSD problem, more attention is paid to fatigue crack growth in riveted joints. An important reason is that more should be known about possibilities for detecting these cracks during service inspections with available or new NDI techniques.

Fracture mechanics

The above picture clearly illustrates that fatigue crack initiation and fatigue crack growth in riveted lap joints are rather complex phenomena. It is very difficult, if not practically impossible, to come to a trustworthy modelling of the cracking mechanism for the application of fracture mechanics. Accurate predictions can not be expected. The unfavourable situation is caused by the complex load transmission, clamping, fretting corrosion and secondary bending. The situation improves when the crack becomes larger, i.e. when the crack has grown outside the area where the load transmission occurs. This applies to the last part of the fatigue life, which is relatively short. It might also be possible to model the residual strength problem for a riveted lap joint with cracks, although it still is problematic to formulate a fracture criterion, keeping in mind that we are dealing with joints of a fairly ductile alloy (2024-T3).

FATIGUE OF RIVETED JOINTS AND STATISTICS

Scatter

The fatigue life can be defined as consisting of two parts: (1) the crack initiation period, including the growth of small invisible cracks, and (2) the crack growth period. In general, the first period is much more sensitive to the variability of circumstances for crack initiation. In the second period, crack growth is more depending on the crack growth resistance as a bulk property of the material. As a consequence, the crack initiation life usually shows significantly more scatter than the crack growth period.

Hence, the scatter of the total fatigue life predominantly reflects the variability of the crack initiation period. It then is quite remarkable that scatter of the fatigue life of riveted lap joints is relatively low in most test series. That might not be expected in view of the complex nature of the joint. However, it should be realized that the riveted lap joint is a poor joint, as illustrated by the low endurance limits in Fig.5. Whatever the complexity of the load transmission is, cracks will be nucleated. Moreover, there are many critical holes, which from a theoretical point of view will also promote a reduced scatter.

We will now consider some empirical information of scatter as observed in test series. Figure 10 shows the standard deviation of test series with constant-amplitude (CA) loading and variable-amplitude (VA) loading [19]. In the CA-tests $\sigma_{\log N}$ increased for a decreasing stress amplitude (S_a), and thus for an increasing fatigue life. The trend is generally observed in CA-fatigue test. The interesting result in Fig.10 is that scatter in the VA-tests remains approximately constant, independent of the fatigue life. The average standard deviation ($\sigma_{\log N}$) is about 0.1, similar to $\sigma_{\log N}$ for the CA-tests with the same maximum stress level. It suggests that $S_{\max}$ has a decisive influence on the fatigue failure mechanism, including the specimen properties on which scatter is depending.

Another illustration on scatter of riveted joints is presented in Figure 11. Two test series of 20 identical tests each [20] were the largest series on riveted lap joints found in the literature. The results are plotted on normal probability paper. They agree rather well with a log-normal distribution. However, the three-parameter Weibull distribution (dotted line) gives a similarly good agreement. Apparently, 20 results is still an insufficient number to express a preference for the Weibull distribution function. On physical grounds it is quite obvious that the latter function must be preferred, if compared to the log-normal distribution function. In the same graphs the 2-parameter Weibull distribution function with a zero lower limit (location parameter) is also indicated. This more simple function, sometimes adopted in statistical models, is not in agreement with the test results.

In a discussion on empirical data of scatter, the imperative question is: *which sources are causing scatter in fatigue tests ?* Three groups of sources should always be kept in mind :

1. fatigue resistance of the material
2. the manufacturing of the specimen
3. the fatigue machine and its operator

Which sources do we consider to be relevant ? Beyond any doubt, the third one is not a legitimate source. Theoretically, it seems that the first one is OK, while the second one is not. However, from a practical point of view the conclusion is too simple. With respect to the fatigue resistance of the material, it must be realized that there are certain variations between the fatigue resistance of different batches, and certainly between fatigue properties of nominally identical material from different material producers. The latter variability was studied on three types of specimens, including a riveted lap joint, produced from 2024-T3 Alclad from five different producers [21]. Fortunately the differences were fairly small in CA-tests. In program tests on the lap joints the average fatigue lives of the best and the worst material differed by a factor of 2.

The manufacturing of fatigue test specimens is traditionally done with great care in order to get similar specimens. For riveted joints, the riveting procedure is part of the manufacturing. Schütz [11] compared results of three nominally similar test series on 2024-T3 riveted lap joints, obtained in different periods of the same aircraft industry. He noted systematic differences between the three series up to a life factor of 1.7. He concluded that the difference had to be attributed to different riveting procedures as indicated by different head diameters of the driven head. The better results were obtained for the larger head diameters, which should be associated with more intensive riveting as discussed before. The only conclusion, which can be drawn here is that variations of the riveting procedure will introduce scatter in the fatigue life of the joint. The question is whether that should be accounted for if we consider consequences for a fleet of aircraft.

Crack nuclei at many holes ?

Numerous fatigue tests on riveted lap joint specimens have been carried out in many laboratories. Anyone, who examines the fracture surfaces, should be impressed by the large number of crack nuclei at many holes, see Figure 12. This was the general experience during numerous test series carried out at the National Aerospace Laboratory (NLR). In general the observations were not quantified. In [10] some numerical data are given by Hartman, who found that the number of nuclei was large indeed, while it was larger for higher S_a-values than for lower S_a-values. Schütz [11] tested lap joints until about 50 percent of the average fatigue life indicated by other specimens. He then pulled the lap joints to failure. Small part through cracks could be observed on the fracture surfaces. Fracture surfaces of a large number of specimens, tested by students [17,18] as part of their thesis project, have been re-examined recently. It consistently confirms that crack nuclei can be observed visually on the fracture surfaces at almost all holes. Some reasons can be mentioned to explain this observation.

1. The poor crack initiation behaviour of riveted lap joints imply a relatively short crack initiation period.
2. After one or more cracks have been initiated at a hole, the local stiffness becomes smaller, and as a consequence the load transmitted by the rivet is reduced. The crack driving force on the cracks becomes smaller.
3. If cracks have been initiated, the stress intensity (K) at the crack tips does not rapidly increase. It is a balance between the decreasing K of the pin-loaded hole case and the increasing K of the by-pass load. It has been confirmed in recent experiments by Pelloux et al. [22] in tests on 2024-T3 (t = 1 mm) riveted lap joints with countersunk rivets. A more or less constant crack growth rate was observed for a certain part of the life. The same trend was observed as a result of a much more sophisticated prediction model by Broek [23,24].

A conclusion postulated in [25] is: *If the fatigue life of a riveted lap joint is limited, cracks will occur at many rivets in the same row, and a potential MSD problem is present.*

Due to the statistical nature of fatigue, the crack will generally have different crack lengths, see again Figure 12. That is another reason why K-factor based predictions are problematic. Unequal crack length values were reported by Mayville and Warren [26] for an aircraft fuselage. In this case the non-homogeneous hoop stress between the frames is accentuating unequal values of the crack length at different holes.

DISCUSSION

The MSD problem is not restricted to riveted lap joints in pressurized fuselage structures. As recently discussed by Lincoln [27], is has occurred in wing structures. It these cases, it was related to high design stress levels and crack sensitive materials. There are several differences with MSD in riveted fuselage lap joints. In the latter case, numerous closely spaced rivets are present in the same rivet row, the sheet thickness is low, and the load spectrum is close to CA loading. The discussion here will be restricted to the significance of MSD for riveted lap joints in a pressurized fuselage.

Pertinent questions are :

1. At which age of the aircraft should the cracks be expected ?
2. How fast will they grow ?
3. Is there sufficient time to find the crack with economically acceptable inspection periods ?
4. How long does it take before a dangerous situation occurs, if cracks are overlooked during inspections, or if known cracks are not repaired immediately ?

The first question is a matter of the design stress level, the riveted joint design, and the manufacturing quality of the joints. Good indications can be obtained from fatigue tests on riveted lap joint specimens, provided the specimens are representative for the joints in the fuselage structure[2]. However, the more realistic information should come from full-scale fatigue tests on the fuselage structure. Interesting results have recently been published by Goranson and Miller [1,2], Gopinath [28] and Maclin [29] for fatigue tests on fuselages of Boeing aircraft models. Two old aircraft, purchased by Boeing from the airlines, were tested, a 737 fuselage (59,000 pressure cycles in service) and a 747-100 fuselage (20,000 pressure cycles in service). A new 747-400 forward fuselage (new) was also tested to check redesigned parts of the structure. Small cracks in the lap splices were found after 79,000 flights ($\approx$ 24 years) in the 737 fuselage. Linking up of cracks occurred at a later stage, with a decompression failure (flapping, total crack length $\approx$ 0.8 m) at 100,600 flights ($\approx$ 30 years). In the 747-100 cracks in some lap splices occurred after $\approx$ 30,000 flights onwards, with linking up at only one location before the test was stopped at 40,000 flights. In the new 747-400 forward fuselage cracks were detected from 33,500 pressure cycles onwards, with some linking up after an additional 10,000 to 20,000 cycles. By the end of the test (60,000 flights) the largest crack was about 0.48 m with some cracking in an adjacent bay, but without any unstable crack extension. For the estimated stress levels, the fatigue lives seem to be in the correct order of magnitude considering S-N data of riveted joints for countersunk rivets. The full-scale tests also showed that the cracks started predominantly at rivets midway between the frames. In this region the hoop stress is slightly larger (fuselage pillowing). The most important finding was that the damage development was rather slow in terms of crack growth per year. It thus should be possible to detect the cracks during scheduled inspections.

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[2] Riveted joint specimens should always be made with as many rivets in a row as possible.

The Douglas Aircraft Company purchased a 15 years old DC-9 (66,500 flights in service). It still was practically free from fatigue cracks. The fuselage was tested under cyclic pressure to a total of 208,000 flights. As reported by Hoggard [30] a tear down inspection did not show any fatigue crack at the rivet holes.

The above evidence suggests that the MSD problem in riveted lap joints, if it does occur, can be handled by the airlines, and it need not lead to catastrophic events. However, it did occur in the Aloha accident. The poor fatigue behaviour of that aircraft at a total life of 89680 flights was attributed to fatigue damage, enhanced by corrosion damage associated with poor maintenance [31]. It thus should be more appropriate to rephrase the statement: The MSD problem in riveted lap joints can be controlled by the operator, provided good maintenance and adequate inspections are supported. The operator should be aware of fatigue of aging aircraft, and he must be prepared to incorporate maintenance and inspection procedures for aging aircraft. The instructions for maintenance and inspections should come from the aircraft industry. Goranson [2] reports on Boeing activities: full-scale tests on old aircraft, and on the other hand sending groups of experts to the operators in order to inspect the maintenance quality of the operator. Such extensive activities are of vital importance if there is a problem with aging aircraft. It has been pointed out several times, recently by Mar [32], that the problem is the joined responsibility of the manufacturer, the operator, and the airworthiness authorities. The minimum information is a survey of "ages" of aircraft. An administration of "ages" should be mandatory. It must be judged in comparison to the life time when fatigue cracks will occur. This information should come from full-scale tests in the first place. Quite often, such a test is stopped after simulating twice the anticipated economical life of the aircraft. However, it is rather unfortunate to stop a fuselage full-scale fatigue test, if cracks have not yet turned up. Much money has been spent already, but pertinent information for aging aircraft has not been acquired.

It may be questioned whether there are alternatives to continued full-scale testing and testing of old aircraft. It is thought that fatigue tests on specimens can be very instructive to indicate the order of magnitude of life and crack growth and residual strength. Such investigations should be recommended anyhow, since the available empirical information is not abundant. However, the accuracy required for service inspection regulations should come from a full-scale test. A realistic representation of the structural components and a realistic load transmission are essential. Moreover, the human factor involved in inspections, can be considered in a more realistic way.

Another approach is developing prediction techniques for MSD. As pointed out before, it should not be expected that life times until cracks occur in riveted joints of a pressurized fuselage can be predicted with a sufficient accuracy and reliability for application to a real aircraft. The same conclusion applies to crack growth for MSD situations. The fatigue behaviour of a riveted lap joint is depending on the design and the material of the joint, but also on the manufacturing quality of the joint. Several sources of fatigue life variations can be indicated. As a result, the usefulness of statistical models for MSD should not be justified by the absolute accuracy of the prediction. Of course, a credible model should predict correct orders of magnitude. However at the moment, the value of a statistical model is that it can indicate the significance of various factors, which do influence the picture of multiple cracks in riveted fuselage joints. Broek's model [23] is probably the most advanced model, which can be formulated within the present state of the art. It is promising that his model predicts the occurrence of many cracks of different sizes between the fuselage frames in agreement with observations for real aircraft reported by Mayville and Warren [26]. Statistical models based on realistic assumptions, can also give indications for the philosophy on inspection procedures. It may be suggested here, that a selective inspection program for the oldest aircraft (lead the fleet principle) could be useful. It might also concentrate on local parts of the structure, where lower endurances should be expected.

One aspect has not yet been addressed here. MSD in riveted fuselage joints may have consequences for the damage tolerance of the structure. Swift [33] in 1983 drew attention to this question. The present experience on multiple cracks in riveted lap joints suggests that cracks in adjacent bays (between frames) should be considered. Experience of full-scale fatigue tests [1,2,26,28,29] confirms that such cracking patterns are possible. It was present in the Aloha accident. The relevant question for aging aircraft then appears to be whether the structure is sufficiently damage tolerant. According to the author, the more reasonable approach is that this type of MSD should be detected before it can become critical.

CONCLUSIONS

Results of fatigue tests on riveted lap joints, especially fractographic observations, have led to the following conclusions :

- The load transmission in a riveted lap joint is a rather complex phenomenon, which is confirmed by quite different crack initiation mechanisms.
- The crack initiation and early crack growth up till visible cracks covers the major part of the fatigue life. Unfortunately, in view of the first conclusion, it may not be expected that fracture mechanics can predict early crack growth with a practically useful degree of accuracy.
- If there are visible cracks in a riveted lap joint, it should be expected that there are many small cracks at most rivet holes in the same critical row of rivets. In other words, a finite life of a riveted lap joint implies that an MSD situation will be present. This conclusion applies to fuselage lap joints.
- Scatter in fatigue life of riveted lap joint specimens is relatively low, with a standard deviation of log N in the order of 0.10. However, the life of a lap joint is depending on the riveting technology procedures and production quality control. Scatter of riveted joints in a fleet of aircraft may thus be larger.
- The fatigue life of a riveted lap joint is significantly improved by an increasing riveting force.

In the discussion it was pointed out that :

- Crack growth in riveted lap joints may be sufficiently slow to allow a timely detection in service. However, for aging aircraft this should be shown by full-scale testing.
- Insufficient empirical information is available on fatigue crack growth and residual strength of riveted lap joints. Investigations should be recommended.

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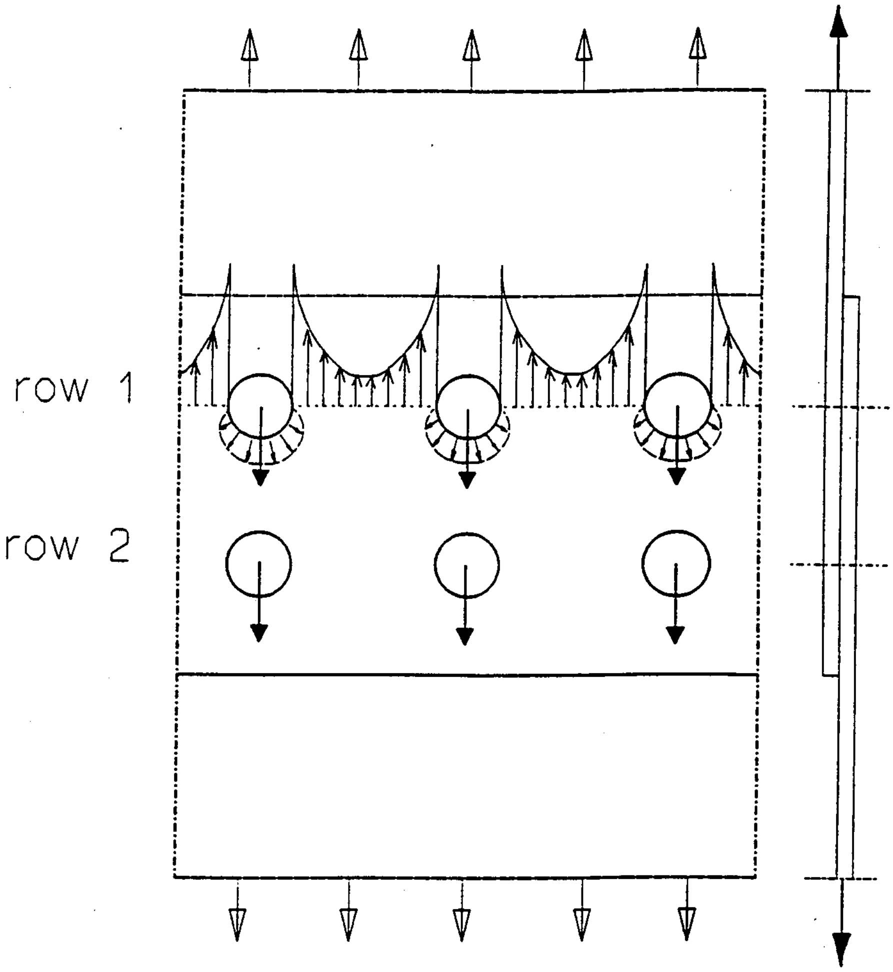


Fig.1 : In row 1, pin-loaded hole case and by-pass load of row 2.

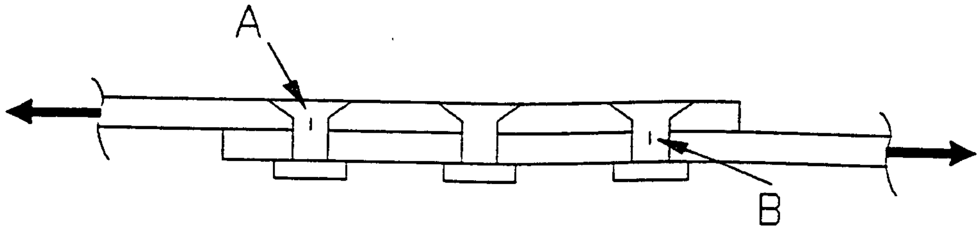


Fig.2 : Critical locations A and B in outer rows of rivets, A in the upper sheet, B in the lower sheet. Usually, A is more critical than B.

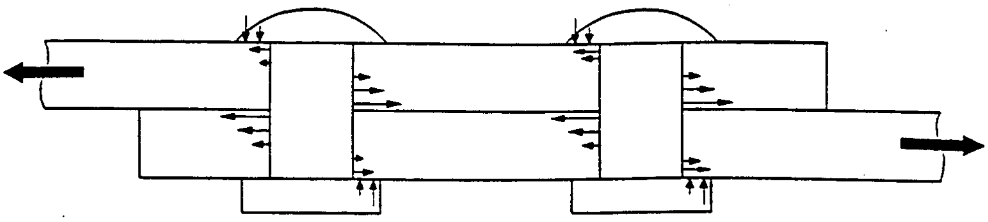


Fig.3 : Inhomogeneous distribution of rivet loads on the sheets in thickness direction.

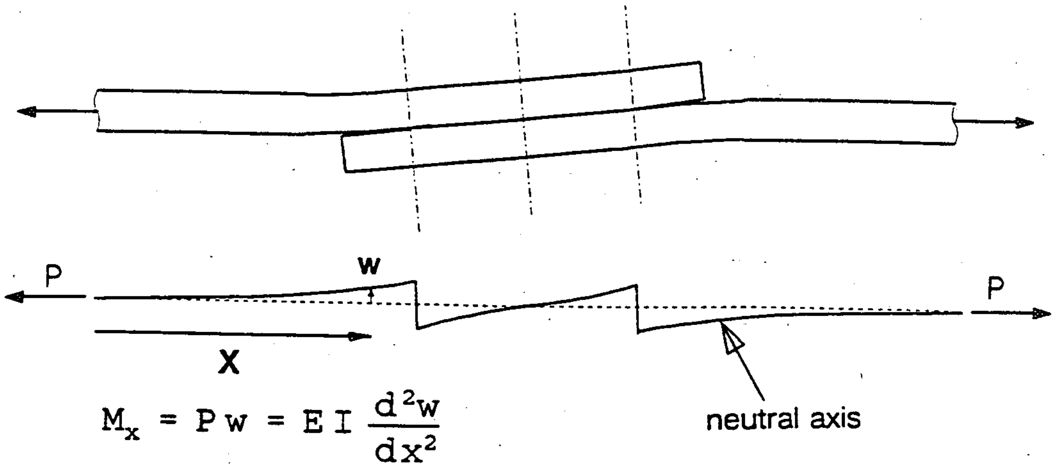


Fig.4 : Secondary bending in a lap joint, due to built-in eccentricities.

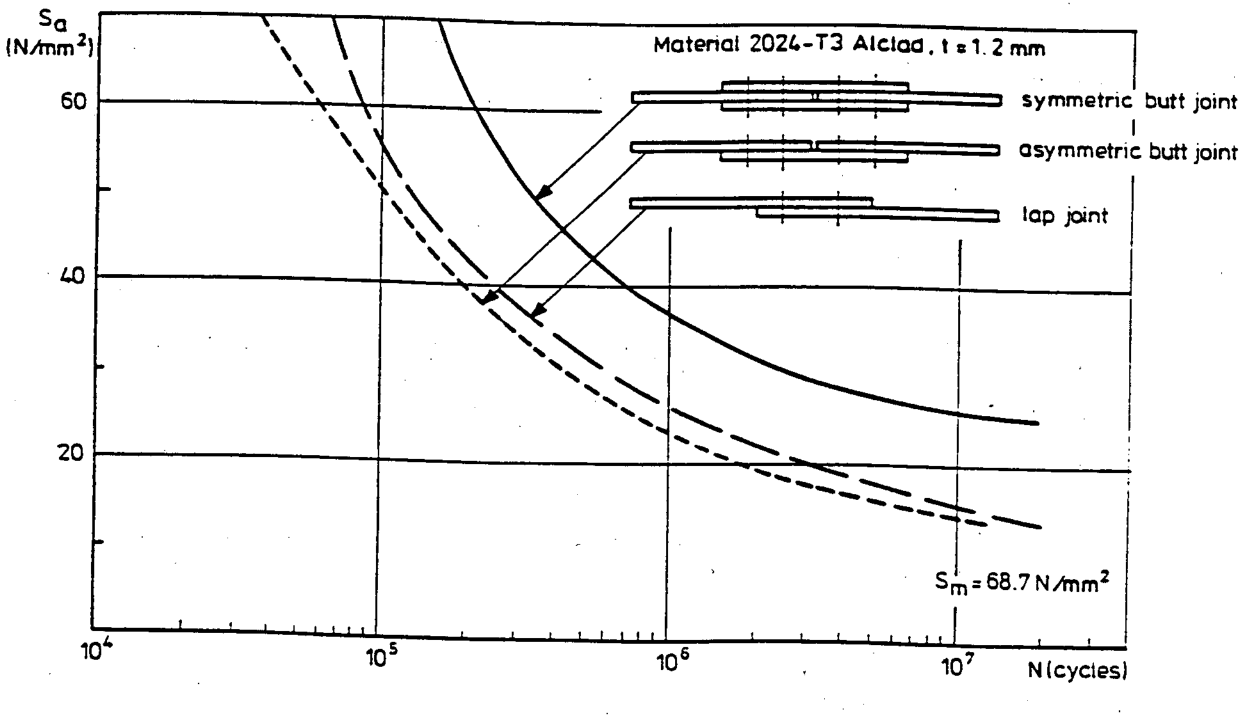


Fig.5 : S - N curves of symmetric and non-symmetric riveted joints (10 rivets in each row, rivet diameter 4 mm).

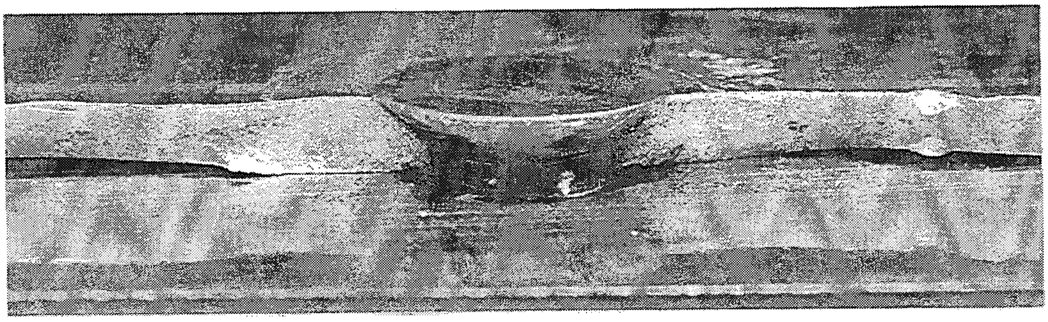


fig.6a : Cracks start at both sides of the countersunk hole.

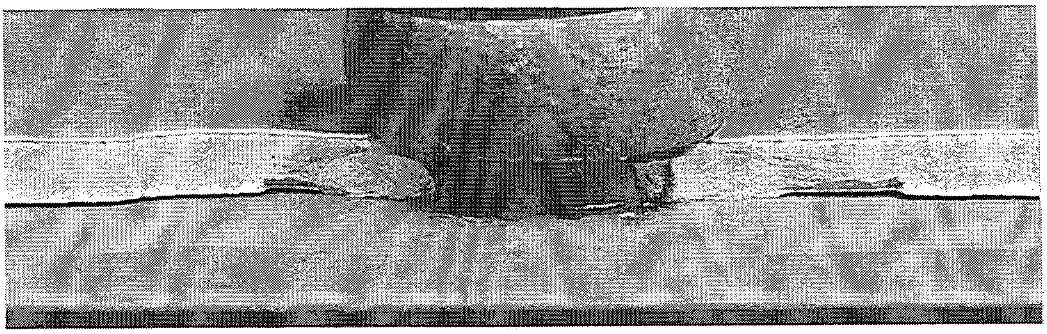


fig.6b : Semi-elliptical crack nuclei, initiated away from the hole.

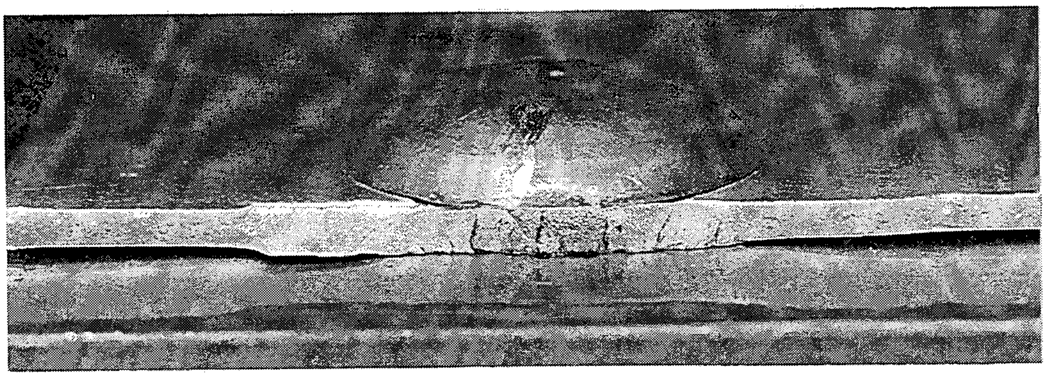


fig.6c : Cracks started ahead of the rivet. Crack path no longer through hole (good clamping).

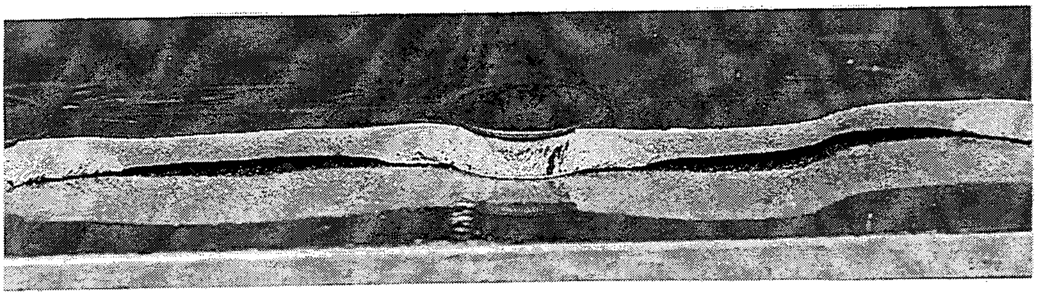


fig.6d : Crack at dimpled hole, started at edge of dimple.

Fig.6 : Different types of fatigue crack nuclei in riveted lap joints.

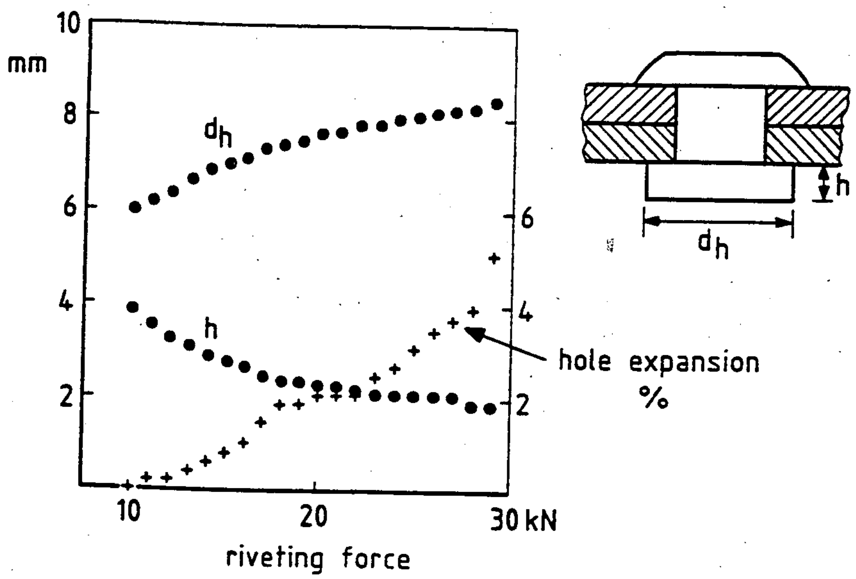


Fig.7 : Deformation of the driven rivet head and hole expansion due the riveting, as affected by the rivet squeezing force (2 mm 2024-T3 sheets, rivet diameter 4.8 mm).

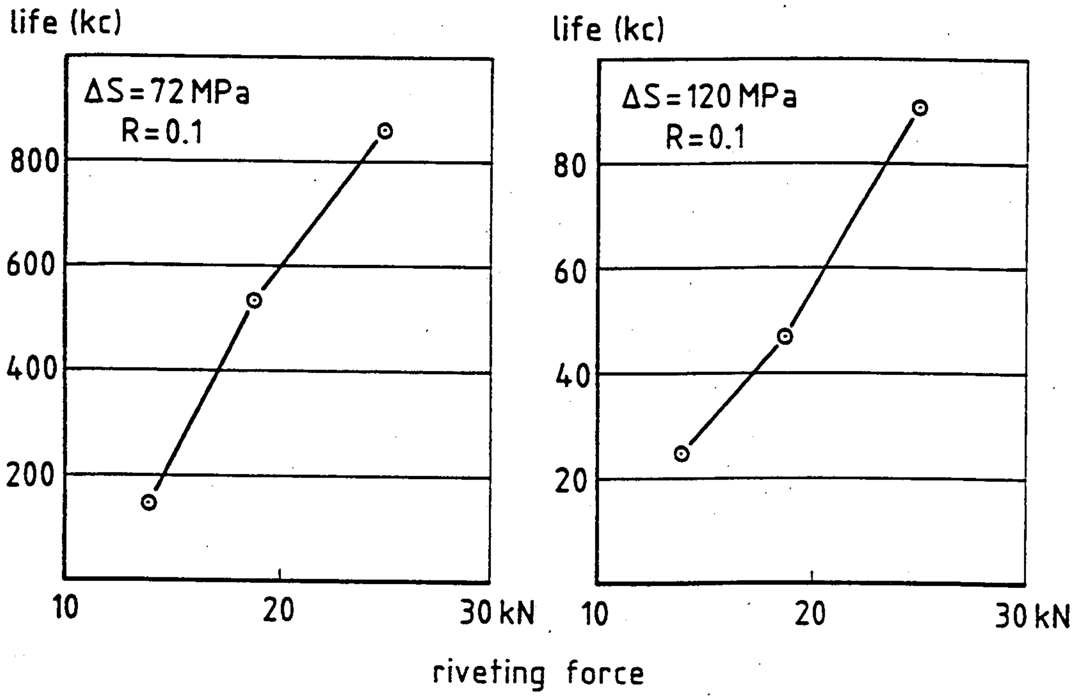


Fig.8 : Improvement of the fatigue life of a riveted lap joint by increasing the rivet squeezing force (2 rows of rivets, diameter 4.8 mm, average results of 3 tests).

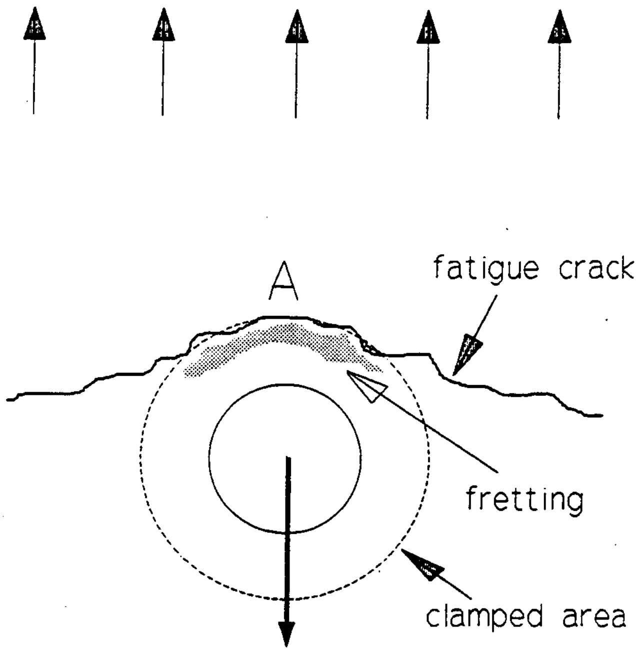


Fig.9 : Load transmission in clamped area by the rivet and frictional forces. Before crack initiation maximum stress at A.

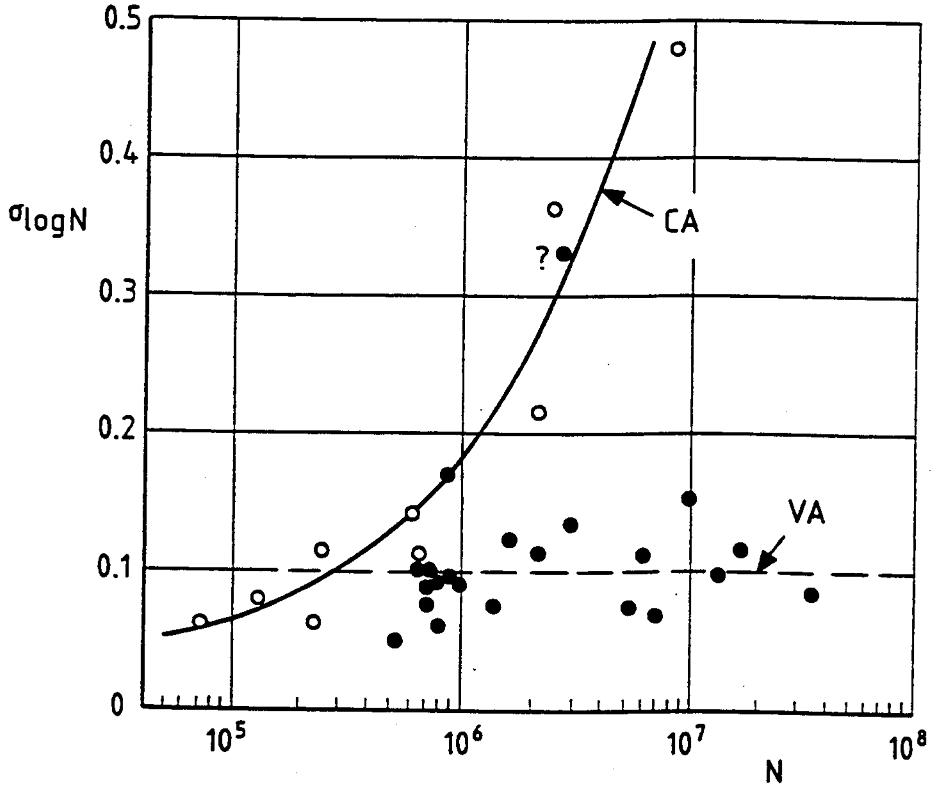


Fig.10 : Results of fatigue tests on riveted lap joints, 2024-T3 Alclad and 7075-T6 Clad sheets [17]. Standard deviation ($\sigma_{\log N}$) for constant-amplitude (CA) loading (10 specimens for each σ) and for variable-amplitude (VA) loading (7 specimens for each σ).

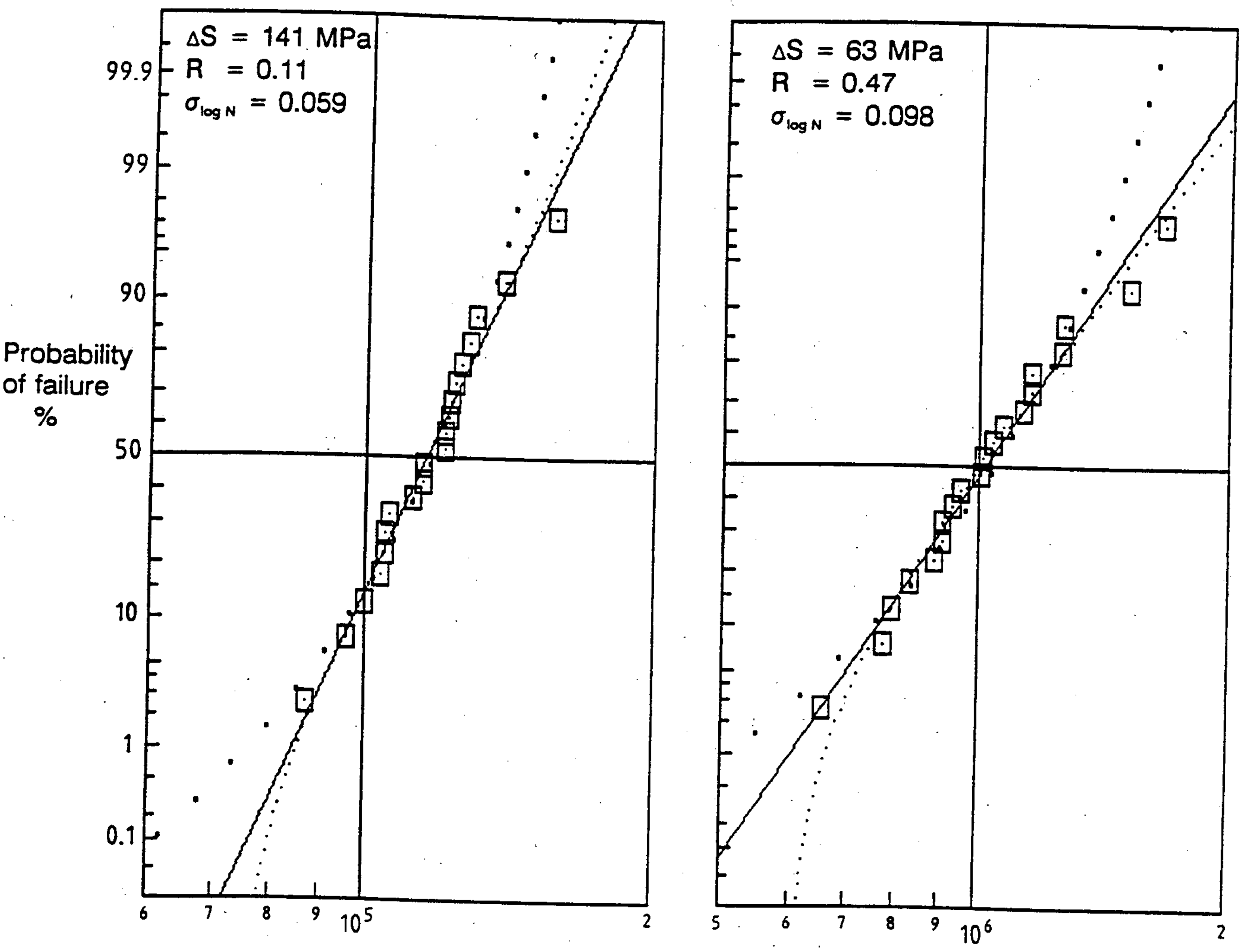
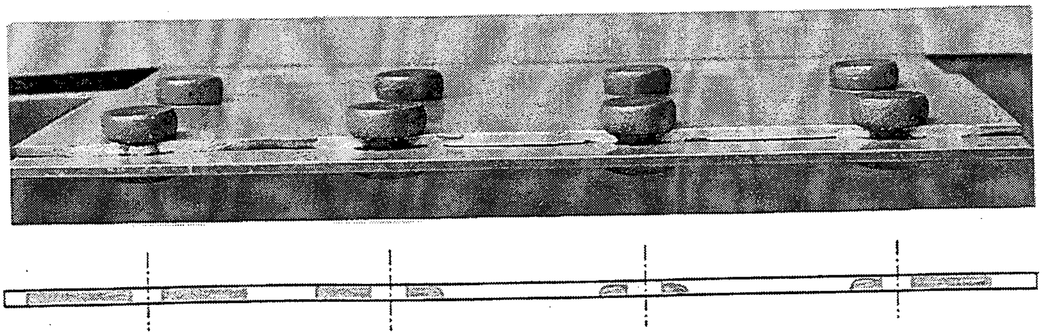
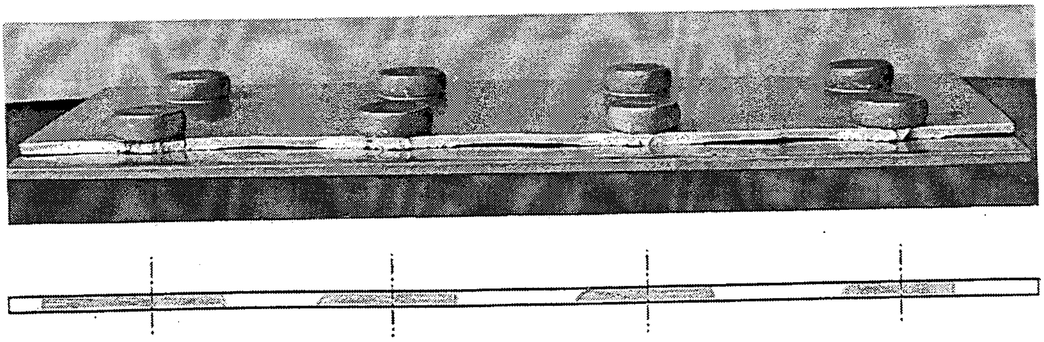


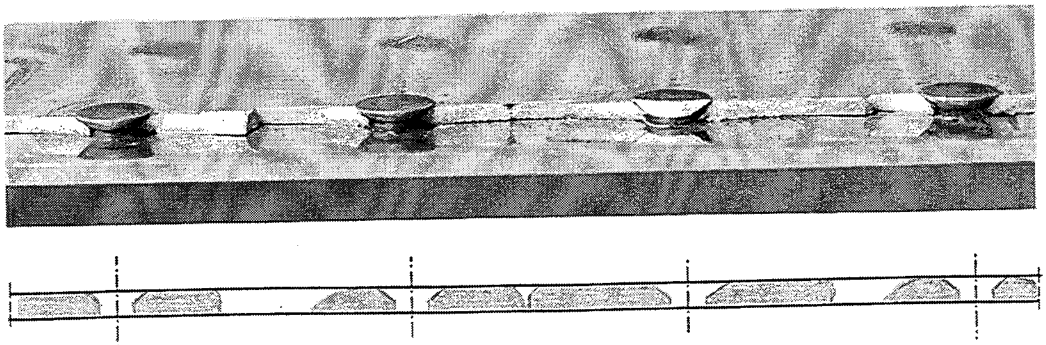
Fig.11 : Scatter in two test series of 20 riveted lap joints. Comparison between the log-normal distribution (full line), the Weibull 3-parameter distribution (small dots) and the Weibull 2-parameter distribution with zero location parameter (larger dots).



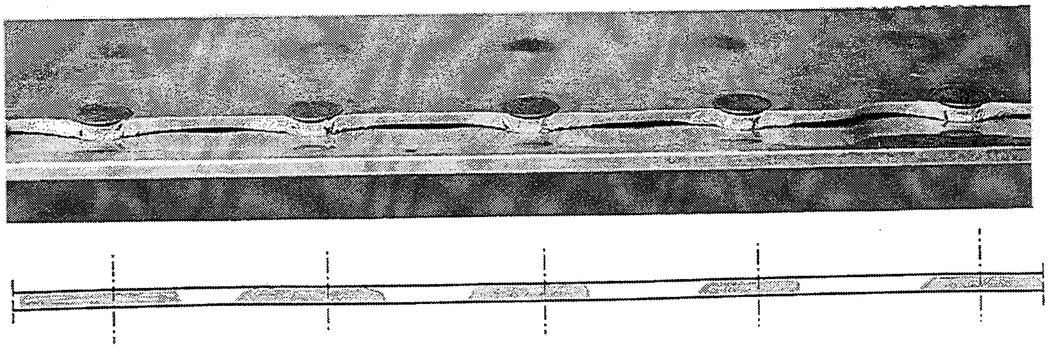
7075-T6
t = 1.2 mm
d = 4.8 mm
s = 25 mm
ΔS = 118 MPa
R = 0.12
N = 89,238 cycles



2024-T3
t = 1.2 mm
d = 4.8 mm
s = 25 mm
ΔS = 118 MPa
R = 0.12
N = 152,267 cycles



2024-T3
t = 1.6 mm
d = 3.2 mm
s = 20 mm
ΔS = 105 MPa
R = 0.01
N = 67000 cycles



2024-T3
t = 1.6 mm
d = 3.2 mm
s = 20 mm
ΔS = 105 MPa
R = 0.01
N = 46000 cycles
dimpled holes

Fig.12 : Fatigue cracks at all rivet holes (MSD) in lap joint specimens with 4 or 8 rivets in each row.

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