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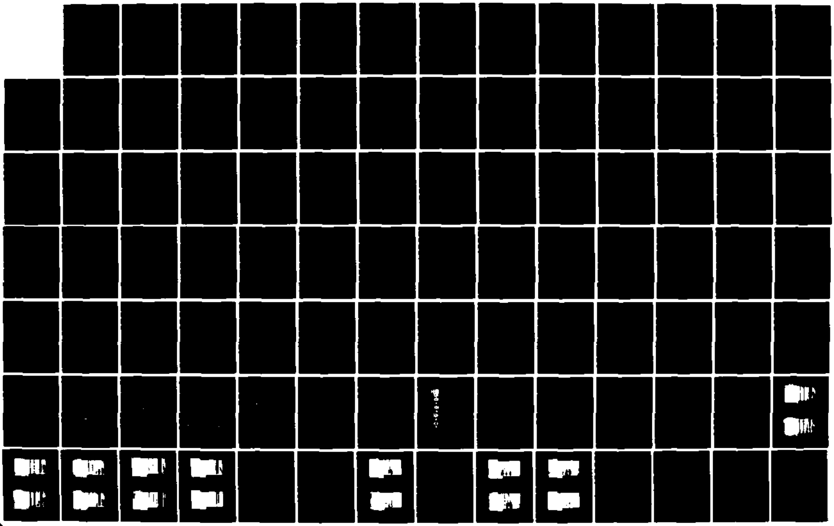

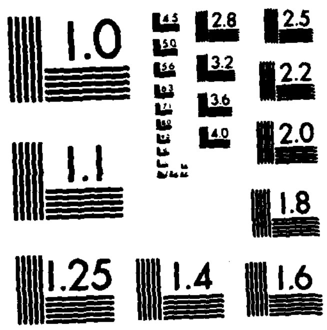

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AD-A149 054

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

STRUCTURES REPORT 398

IMPROVING THE FATIGUE LIFE OF THE MIRAGE IIIO WING MAIN SPAR

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J. Y. MANN, A. S. MACHIN and W. F. LUPSON

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JANUARY 1984

AR-003-004

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SUMMARY

An increased life-of-type requirement for Mirage IIIO aircraft operated by the Royal Australian Air Force (RAAF) was associated with a specific need to develop a refurbishment technique for extending the lives of fatigue-cracked wing main spars. This led to a comprehensive series of flight-by-flight fatigue tests on specimens of a geometry and thickness (32 mm) closely representing the inboard lower rear flange section of the spar.

Of the various options investigated, the most promising was the use of interference-fit steel bushes in bolt holes—either alone or in combination with a modified anchor-nut sub-assembly which eliminated the need for some rivets in the spar flange. Specimens with oversize reamed holes utilizing oversized sleeved bolts performed poorly, while cold-expansion of the critical bolt hole using the Boeing split-sleeve process was unsatisfactory because of small hole-to-spar edge distances and the proximity of small rivet holes.

This investigation has shown that acceptable extensions in fatigue life for wing main spars of the Mirage IIIO are possible by the use of combinations of standard bolts and 0.3% interference-fit steel bushes (of 1.5 mm wall thickness) in the critical bolt holes, with the provisos that pre-existing fatigue cracks are completely removed and that (after reworking) bolt hole/rivet hole separation distances are adequate. In some circumstances acceptable increases in life may be obtained by reducing the outside diameter of the bush and utilizing stepped undersize bolts.

The installation of interference-fit stainless steel bushes (which provide some potential for through-the-bush crack detection) has been adopted as the basic procedure for extending the fatigue lives of the wing main spars of the RAAF Mirage IIIO fleet.

POSTAL ADDRESS: Director, Aeronautical Research Laboratories,
Box 4331, P.O., Melbourne, Victoria, 3001, Australia

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1. INTRODUCTION

The Mirage III fighter aircraft, manufactured by Avions Marcel Dassault (AMD), St. Cloud, France entered service (as the IIIO version) with the Royal Australian Air Force (RAAF) early in 1964. The plan form of the aircraft, looking from underneath, is shown in Fig. 1. Each wing is constructed as a multi-spar torsion box consisting of the main spar—a large machined forging—front and rear spars and stressed skins. Integrally machined stiffened panels form the skin between the main and rear spars and the enclosed space forms the integral fuel tanks. All of the bending loads are carried by the main spar which is attached to the fuselage at frame 26 through a twin pin/lug joint.

Investigations which followed the completion of a full-scale fatigue test on a Mirage III airframe (incorporating unused wings) at the Eidgenoessisches Flugzeugwerk (F+W), Emmen, Switzerland in 1977 indicated a need to improve the fatigue performance of some parts of the wing structure if the life-of-type specified by the RAAF for its Mirage IIIO fleet was to be achieved. Of particular concern were the bolt and rivet holes along the front and rear lower flanges of the wing main spar, the general area being illustrated in Fig. 2. In order to more fully explore the fatigue performance of the structure a second full-scale fatigue testing program was commenced at the F+W in mid-1979, the test article incorporating a port (LH) wing taken from a Swiss Air Force (SAF) Mirage IIIS and a starboard (RH) wing taken from a RAAF Mirage IIIO. These wings had experienced 510 and 2,190 service hours respectively.

Because of the requirement to extend the fatigue life of the structure, a series of tests on small specimens was initiated at the Aeronautical Research Laboratories (ARL) to investigate methods for refurbishing the critical parts of the structure so that the increased life-of-type could be achieved. These tests were directed specifically at the inboard section of the rear lower flange (which is shown in Fig. 3) and initially were based on the concept that, at the time of refurbishment, there would be no significant fatigue cracking in this region.

In September 1979, during the course of the collaborative Australian/Swiss Investigation (Ref. 1), fatigue cracks were detected in bolt holes (containing bolts for attaching the tank bay skin panel) at the inboard section of the lower rear flange of the wing main spar of the RAAF test wing (Figs 2 and 3). This finding initiated a fleet-wide inspection of the corresponding holes in the wings of Mirage III aircraft operated by both the RAAF and SAF, which confirmed the presence of cracks at these locations in a large number of wings. There was immediate concern regarding the safety of the fleet and the ability of the aircraft to meet its required life-of-type. As a consequence, the initial concept of refurbishing a virtually uncracked main spar was expanded to the major problem of exploring methods for restoring and further extending the fatigue lives of wings which had developed significant fatigue cracks in service. This led to a comprehensive series of fatigue tests (at ARL) on specimens of a size and geometry closely representing the critical section of the spar.

At the commencement of the investigation the development of a refurbishment scheme was based upon a 'standard' test specimen (Figs 4, 5)* designed directly from drawings of the spar. However, subsequent detailed examination (Ref. 2) of spars from RAAF aircraft which had crashed (not as a result of structural failure) and from other in-service wings indicated a number of discrepancies between the actual spars and the drawings at the section thought to be most critical, i.e. the first bolt hole and associated single-leg-anchor-nut (SLAN) rivet holes. The most significant of these discrepancies were the use of 0·125 inch diameter 2117 aluminium alloy rivets instead of 2·5 mm A-U4G aluminium alloy rivets to hold the SLAN, and the tendency for the SLAN rivet holes to converge (at varying angles) towards the 8 mm bolt hole at the outer surface of the spar rather than be parallel to it, a condition referred to subsequently in this report as

* The numbering system adopted for bolt and rivet holes in this investigation is shown in Fig. 4 and will be used in the remainder of this report.

'inclined SLAN rivet holes'. These differences required that certain aspects of potential refurbishment schemes be investigated in greater detail than was originally anticipated. Furthermore, because of the continuous updating of 'in-service' information on cracking and wing conditions and the problems of life prediction, the task was broadened to include the determination of crack propagation rates, the residual static strengths of specimens with fatigue cracks of different sizes, the effects of spectrum truncation on fatigue behaviour, and some constant-amplitude fatigue tests.

Some results of this work have already been published elsewhere (Ref. 3) and in an interim ARL report (Ref. 4). This Report will cover the investigation of refurbishment options for the wing spar (both parallel and inclined SLAN rivet holes), while other publications will detail the results of residual static strength tests, and the assessment of crack propagation rates and spectrum truncation.

2. DEVELOPMENT OF REFURBISHMENT SOLUTION

2.1 Refurbishment Options

During the initial development of a method for extending the fatigue lives of the relevant parts of the Mirage wing spar it was considered essential that any existing fatigue cracks should be completely eliminated. Although the major effort was directed at improving the life at the section containing the first 8 mm bolt hole and the adjoining SLAN rivet holes, the information received on in-service cracking indicated that improvements in the fatigue life at the next four 10 mm holes would also be necessary. Evidence from in-service inspection of the RAAF Mirage fleet also indicated that the extent of cracking in some spars was such as to preclude the complete removal of cracks without an unacceptable reduction in the nett cross-sectional area. This finding led to the development of two crack size criteria; the first covering the maximum size at which effective refurbishment could be carried out, while the second (and greater) crack size was the maximum size crack which, if not removed, could be tolerated without significantly increasing the risk of in-flight structural failure. It is with the first situation that the current investigation is concerned.

The development and assessment of potential refurbishment schemes for the spar were based on the following criteria:

(a) enlargement of bolt and rivet holes would be necessary, at least for the purposes of cleaning up the holes for inspection or accurate sizing for a subsequent operation;

(b) all detected fatigue cracks should be removed by reaming;

(c) to provide additional confidence of crack removal, 0·5 mm depth of metal should be removed beyond the point at which an inspection indicated a 'crack-free' condition (i.e. for the first bolt hole the minimum oversize diameter would be 9 mm);

(d) the Mirage IIIO should be operated on a 'safe-life' basis until it achieved its life-of-type;

(e) the average fatigue life of specimens embodying such schemes should be at least equal to that of the relevant control group and preferably between 1·5 and 2·0 times greater;

(f) fasteners should be easily removable to allow the holes to be inspected in service and the tank-bay panels to be demounted;

(g) replacement of the whole spar should be considered only as a last resort.

Of the various refurbishment options available for the bolt holes those considered to be of potential application were:

(i) oversize reamed bolt holes, utilizing close-fit bolts;

(ii) interference-fit steel-bushed bolt holes, utilizing standard close-fit bolts;

(iii) bolt holes cold-expanded by the Boeing split-sleeve process.

Furthermore, various reworkings of the SLAN rivet holes and the use of modified anchor-nut/gang-nut strip assemblies were also considered. All of these involved reductions of edge distances between the three adjacent holes at the SLAN section, and between the bolt holes and rear edge of the spar, with an associated increase in the theoretical stress concentration factors (K_t) at the holes. All of the combinations of options are discussed in detail in the next section.

In assessing the various refurbishment proposals for specimens *not previously* fatigue tested, the assumption was made that these specimens would model a situation in which all fatigue cracks had been removed during the reworking process.

2.2 Oversize Reamed Holes

The simplest method of refurbishment considered was to ream out the bolt holes to remove the fatigue cracks and then to install close-fit bolts of the appropriate diameter* in the resulting enlarged holes. Initial estimates of fatigue crack depths in Mirage III wings suggested that it might be necessary to enlarge some bolt holes by 3 mm in diameter to ensure that the cracks were eliminated; but in order to cover a greater range of possible crack depths this investigation covered oversize holes (in specimens with parallel SLAN rivet holes) from 9 mm to 12 mm diameter, i.e. holes up to 4 mm oversize. In addition to the progressive increase in the K_t value at the side of the hole nearest to the side of the specimen (Fig. 6), another disadvantage associated with this proposal was the need to enlarge the corresponding holes in the skin. This was considered undesirable because of the proximity of a sealant groove between the bolt holes and the edge of the skin.

2.3 Oversize Bushed Holes

In the 1950s Fisher and his co-workers at the Royal Aircraft Establishment, Farnborough demonstrated that the incorporation of interference-fit bolts or bushes in lugs provided the potential for significant improvements in fatigue lives compared with lugs having clearance-fit bolts alone (Refs 5–7). During the next decade interference-fit tapered shank bolts were also shown to be capable of significantly improving the fatigue lives of multi-fastener joints (Refs 8, 9). Such improvements in life have been attributed, firstly, to a reduction in the relative movement between the bush (or bolt) and the lug hole (and hence a reduction in fretting) because of the radial pressure associated with the interference; secondly, to a decrease in the stress concentration factor at the side of the hole because of load transfer through the bolt; and thirdly, to the pre-stressing effect of the bush in the hole which, although increasing the tangential tensile mean stress at the boundary of the hole, can result in significant reductions in the local alternating stress range on the transverse diameter of the hole in the region of crack initiation under conditions of repeated external loading (Refs 9–14).

Although lugs incorporating interference-fit steel bushes are now quite commonly used in aircraft structures, the bushing of small bolt holes to enhance structural fatigue life has been used only rarely—the Vickers 'Viscount' wing spar being one example. There are two major geometric differences between bushed lugs and small bushed holes. Firstly, the dimensions of bushed lugs are usually much greater with holes of 20 mm to 50 mm in diameter being quite common; secondly, for lugs the ratio of lug thickness to hole diameter (t/d) is commonly 0·5 to 2·0, whereas for the critical holes in the Mirage spar the ratio is between 3 and 4.

Two potential advantages seen in using bushes in the refurbishment of the Mirage spar were that standard close-fit bolts could be used or reused for the assembly of the refurbished structure, and that it would not be necessary to enlarge the corresponding bolt holes in the skin. Under in-service conditions, disadvantages are that the routine removal and replacement of an interference-fit bush for the inspection of a hole in the spar would be an impracticable operation, and routine inspection of these holes with the bushes in-situ could be done only with greatly reduced sensitivity of crack detection.

* Standard bolts with pressed-on sleeves of SAE 4340 steel were used because of the unavailability of other suitable oversize bolts.

According to Goekgoel (Ref. 13) the optimum design for an interference-fit bush in a lug results in a bush thickness of 0·05 to 0·10 times the hole diameter; whereas Lambert and Brailey (Ref. 15) have stated that a bush must have a diameter ratio (external/internal) of at least 1·33 to produce the same effective interference as a solid pin of the same external diameter and to minimise distortion of the bush which, if it occurred, could result in a reduction in the interference stresses. Taking an 11 mm external diameter bush as typical of the size necessary for refurbishment at the first bolt hole, the wall thickness according to Goekgoel would be 0·55 to 1·1 mm and according to Lambert and Brailey 1·38 mm. So that standard 8 mm bolts could be re-used in hole (1) a bush with 1·5 mm wall thickness and 11 mm external diameter was adopted as the standard in this investigation, i.e. a diametral ratio of 1·38. Similarly, for the next four 10 mm holes (holes (5), (6), (8), and (9)) 1·5 mm wall thickness bushes of external diameter 13 mm were adopted as standard, and 10 mm bolts used. As discussed in later sections bushes of other diameters (both external and internal) were also investigated.

Published data on the effects of interference-fit pins and bushes on the fatigue behaviour of aluminium alloy lugs (Refs 5–7, 15–20) indicate that fatigue life improvement increases with the degree of interference and that significant improvements in fatigue life can be obtained with interferences of from 0·2% to 0·6%. In the case of interference-fit tapered-shank bolts interferences of greater than 2% have been investigated, but Ford *et al.* (Ref. 21) have suggested that an optimum value for steel fasteners in aluminium is about 1%. High degrees of interference introduce practical problems in the insertion of long parallel bushes in small holes*, and the resulting tensile hoop stresses which are induced in the aluminium increase the risk of stress-corrosion cracking (Refs 13, 22, 23).

A nominal interference of 0·3% was adopted for most of the present tests to ensure that, within achievable manufacturing tolerances for holes and bushes, an effective degree of interference of 0·25% to 0·35% could be obtained. These degrees of interference would induce tensile hoop stresses of about 140 and 195 MPa respectively in the material adjacent to the bushes (Ref. 24). To maintain the desired level of interference and achieve consistent life improvements it is necessary to machine both the hole and bush to very close tolerances. Furthermore, it is essential that scoring or pickup in the hole during bush insertion be prevented. Bushes were initially manufactured from normalised chromium–molybdenum steel equivalent to SAE 4130 steel (MIL-S-6758)†; however, in later tests grade 304 austenitic stainless steel‡ was used to provide potential for through-the-bush crack detection using rotating probe eddy current systems. The SAE 4130 steel and most of the stainless steel bushes were coated with a light oil and the holes in the specimens coated with Bolicone grease 73 before bush insertion. However, the stainless steel bushes used for one series of tests (see Table 2(*p*)) were passivated in nitric acid solution (Ref. 25) before insertion and (for these particular bushes) the corresponding holes in the specimens were given an Alodine 1200 treatment (Ref. 26) applied by brushing. A barium chromate paste was used as a lubricant and corrosion inhibitor during the insertion of the stainless steel bushes. The sequence of bush insertion was holes (9), (8), (6), (5) and (1). During the assembly of the bolts in steel bushes it was found essential to liberally coat both the bolt and the bore of the bush with an anti-seize compound to prevent the ground-finish close-fit bolts from binding in the bushes.

2.4 Oversize Cold-Expanded Bolt Holes

The plastic deformation associated with the passage, for example, of either oversize tapered mandrels or oversize steel balls through circular holes can result in the hole diameter being increased by cold expansion. Radial plastic expansion of a hole results in the development of a tangential (hoop) residual compressive stress field in the material adjacent to the hole (Refs 27–36) which can equal the compressive yield strength of the material. Although under the action of external tensile loadings some relaxation of the magnitude of these residual stresses may occur,

* At hole (1) the type of Mirage spar flange which was represented by the fatigue specimen is 31·5 mm thick.

† UTS = 987 MPa; 0·1% PS = 879 MPa.

‡ UTS = 1017 MPa; 0·1% PS = 786 MPa.

the compressive stresses effectively decrease the mean stress near the hole and result in a retardation of the development of any fatigue cracks which may form at the surface of the hole by (for example) fretting (Refs 27, 32, 37, 38).

Practical advantages of cold-expanding compared with the use of interference-fit bushes are a less critical requirement to maintain close machining tolerances for holes, and an improved capability of routine in-service inspection of holes for cracks. However, in the present circumstance, the requirement to use oversized bolts in cold-expanded holes has the same disadvantage as with oversize reamed holes in that the corresponding holes in the skin would need to be enlarged. Furthermore, the compressive hoop stresses adjacent to the hole (which can extend to a distance of up to a hole radius from the hole), are balanced by a residual tensile stress field further away from the hole and this may be of sufficient magnitude to increase the sensitivity of the material to stress corrosion cracking to an unacceptable level (Refs 39, 40).

Although there are a number of publications dealing with the improvements in fatigue lives at fastener holes in aluminium alloys resulting from hole cold-expansion (Refs 27, 30, 32, 33, 36, 38, 41, 42) most have dealt with thin plate or sheet (e.g. 5 to 15 mm thickness) and not with material of thickness 26 to 32 mm as found in the Mirage spar flange.

2.5 Modified Gang–Nut/SLAN Assembly

The necessity for using SLAN rivet holes in existing spars could be eliminated by using an alternative system to attach the SLAN. Such a proposal is illustrated in Fig. 7. The essential feature is that the tapered aluminium shim associated with the gang–nut strip is extended; and that the shim, the SLAN and the gang–nut strip are riveted together to form a small sub-assembly.

Although the SLAN rivet holes in the spar would thus become redundant they, obviously, cannot be removed. As stress concentrators they remain as potential sources for fatigue crack initiation, and it was proposed that they be worked by some suitable method and then either filled with a close-fitting rivet, or left open so that they could be periodically inspected. Details of refurbishment methods for rivet holes are given in the appropriate sections.

3. SPECIMENS AND TEST CONDITIONS

3.1 Materials and Specimens

The main spar of the Mirage III is a large forging in aluminium alloy A-U4SG (equivalent to the American alloy 2014). In this investigation three batches of A7-U4SG aluminium alloy plate (equivalent to a later version of 2014—namely 2214) were used for the manufacture of fatigue specimens. Details of the test material are as follows:

(a) *Batch 1* (ARL serial No. GK)
One piece of 46 mm thick A7-U4SG-T651 plate measuring 854 mm wide × 2906 mm long, from which 60 specimens were made (Fig. 8).

(b) *Batch 2A* (ARL serial No. GN)
Four pieces of 48 mm thick A7-U4SG-T351* plate measuring 1250 mm wide × 500 mm long, from which 56 specimens were made (Fig. 9(*a*)).

(c) *Batch 2B* (ARL serial No. GT)
Three pieces of 48 mm thick A7-U4SG-T351 plate measuring 1254 mm wide × 793 mm long, from which 42 specimens were made (Fig. 9(*b*)).

(d) *Batch 3* (ARL serial No. GZ)
Three pieces of 55 mm thick A7-U4SG-T651 plate measuring 1000 mm wide × 2000 mm long, from which a total of 144 specimens could be taken (Fig. 10). Only plates GZ2 and GZ3 of this batch were used in the present investigation.

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* The specimens from Batches 2A and 2B were aged to the -T651 condition by heating to 160°C±3°C for 20 hours immediately prior to the machining of the bolt and rivet holes.

The specimens (Figs 4 and 5) were, essentially, low-shear-load transfer bolted joints designed to represent the spar flange at the critical location.* All specimens had their longitudinal axes parallel to the rolling direction of the plates. Particulars relating to the machining of the bolt holes are given in Appendix 1.

After fatigue testing tensile test specimens were taken from the test sections of a sample of the fatigue specimens from each batch and compact tension fracture toughness specimens of 25 mm thickness were manufactured from the end portions (Fig. 11). The orientation of the slit in the fracture toughness specimens was perpendicular to the rolling direction of the plates and in a direction corresponding to that of fatigue crack development in the test sections of the parent fatigue test specimens. The results of tensile and compact tension fracture toughness tests, together with the chemical composition of the plates are given in Table 1.

The 8 mm and 10 mm bolts connecting the skin plate to the 'spar' section were torqued to 7·9 and 19·2 Nm respectively. When A-U4G rivets† (in the solution-treated condition—30 minutes at 495°C) were used for the specimen assembly, the specimens were not fatigue tested until at least four days after rivet insertion to allow full precipitation hardening of these to occur.

This report covers tests on 181 specimens, 137 with parallel SLAN rivet holes and 44 with inclined SLAN rivet holes.

3.2 Fatigue Loading Conditions

The fatigue load spectrum adopted for this investigation was a simplified version (derived by AMD) of that used for the Swiss Mirage full-scale flight-by-flight test. It was transformed into a 100-flight load sequence consisting of four different flight types (A', A, B and C) as illustrated in Fig. 12. Cycles of $+6\cdot5\,g/-1\cdot5\,g$ and $+7\cdot5\,g/-2\cdot5\,g$ (a total of 39 cycles in 100 flights) were applied at a cyclic frequency of 1 Hz, whereas the remaining 1950 cycles per 100 flights were at 3 Hz. Sine wave loading was adopted for all fatigue tests.

Loads on the test specimens were based on the assumption that $+7\cdot5\,g$ corresponded to a *gross area* stress (not including the skin plate) of 180 MPa at the SLAN section, and that there was a linear stress/g relationship, i.e. the 1 g gross area stress was 24 MPa. Details of the nominal gross and nett area stresses at the various bolt and rivet stations of 'standard control' specimens are given in Appendix 2.

All fatigue tests were carried out in a Tinius-Olsen servo-controlled electro-hydraulic fatigue machine, the 100-flight load sequence being achieved by using an EMR Model 1641 programmable function generator controlled by a punched tape. At 7·5 g the testing machine load was nominally 404 kN (91 000 lbf).

4. FATIGUE TESTING PROGRAM AND RESULTS

4.1 Parallel SLAN Rivet Hole Specimens

All individual fatigue test results are recorded in Table 2 and a summary, with some statistical data in Table 3. However, not all the results given in Table 2 were used in the summary provided in Table 3. Those specimens not used and the reasons for their rejection are noted as

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* Unlike the requirements of the manufacturing drawings of the spar shown in Fig. 3, the fatigue test specimens did not incorporate the gang–nut strip and the tapered aluminium shim as a sub-assembly, but had the nut–strip and shim riveted right through the spar flange in three places at assembly. This was done to conform with the practice found in Mirage IIIO wings of Australian manufacture.

† The test specimens used in this investigation incorporated the following types of rivets to secure the SLAN: 2·5 mm (0·098 inch) and 3·0 mm (0·118 inch) diameter rivets of A-U4G aluminium alloy to French specification Pr.L21-200A of Oct. 1956; 0·125 inch (3·2 mm) diameter rivets of 2117 aluminium alloy tc the US specification MS20470AD-4 and 0·156 inch (4·0 mm) diameter rivets of 2117 to MS20426AD-5. Throughout the body of this report they will simply be referred as to 2·5 mm, 3·0 mm, 0·125 inch and 0·156 inch rivets respectively.

footnotes to Table 2. The statistical analysis of the data enabled the significance of differences in lives resulting from the various refurbishment options to be established; but the small sample sizes have, in some instances, limited the inferences which can be drawn from the data. It was possible, however, to pool the results from a number of similar test specimen configurations and this information is given in Table 4.

4.1.1 Control Tests

The purpose of these tests was to provide a benchmark for comparing the fatigue performance of the various rework proposals and for comparing the fatigue properties of the various batches of test material. Initially, the specimens used for this purpose were assembled with 2·5 mm diameter countersunk-head A-U4G aluminium alloy rivets at the SLAN section, inserted from the 'outer' or skin surface of the flange (as this size and type of rivet and assembly procedure was specified on the manufacturing drawings of the spar), but subsequently 3·0 mm diameter countersunk-head A-U4G rivets and 0·125 inch (3·2 mm) diameter 2117 aluminium alloy universal head rivets were used to secure the anchor nut to the specimen as these were the types found in SAF and RAAF wings respectively at this section. It should be noted that the 0·125 inch rivets were inserted from the 'inner' surface of the spar flange (i.e. with their heads against the anchor-nut leg) and peened into the countersinks at the 'outer' surface of the flange. For the 0·125 inch SLAN rivet configuration the diameter of the countersinks of the rivet holes was nominally 5·5 mm, and thus the separation distance from hole (1) (8 mm diameter) to the first rivet hole countersink was nominally 5·95 mm. This dimension could be measured accurately on actual spars without removing the rivets from the holes, and its significance will become apparent in later sections of this report.

Tables 2(*a*)–(*d*) list the flights* to failure for the individual control specimens. The significance of the lives to failure being associated (predominantly) with or close to flight 42 is that this flight contains the maximum load cycle (+7·5 g to −2·5 g) which occurs only once in the 100-flight sequence. Unless otherwise stated the final fracture occurred at the SLAN section.

The average† life of the control group of specimens with 2·5 mm SLAN rivets was 7309 flights, the average life for specimens with 0·125 inch rivets was 8213 flights and that for specimens with 3 mm SLAN rivets was 6852 flights. Statistically, there are no significant differences between the average lives of these three groups of control specimens. Their pooled average life is 7508 flights with a standard deviation of log. life (s.d.) of 0·098. For the 2·5 mm and 0·125 inch SLAN rivet control specimens only (covering the most common SLAN rivet sizes considered in this investigation), the average life is 7916 flights and s.d. 0·079.

During the early part of the testing program involving control specimens there was a high incidence of fatigue failures at the last 10 mm hole (hole (9)—see Table 2(*b*)), instead of at the SLAN section. To prevent fatigue failures at this location, subsequent control specimens and some refurbished specimens had a 0·3% interference-fit steel bolt, rather than a close-fit clearance bolt, installed at the hole (9) location.

Representative fractures of the control specimens are illustrated in Fig. 13.

4.1.2 Oversize Reamed Holes

Specimens with 2·5 mm SLAN rivets were tested with hole (1) diameters of 9 mm, 10 mm, 11 mm and 12 mm, while specimens with 0·125 inch SLAN rivets were tested with hole (1) diameters of 9 mm, 10 mm and 11 mm. Individual results are given in parts (e) and (f) of Table 2, and representative fractures shown in Fig. 14.

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* It should not be inferred that the 'flights' endured by the test specimens bear any direct relationship to the life status of Mirage III aircraft in the Swiss or Australian Air Forces. The current testing program was concerned essentially with the relative lives of the 'refurbished' specimens and the control specimens representing the original structural detail.

† All averages in this report are log. averages, i.e. the antilog. of the mean of the logarithms of the individual specimen lives. Statistical comparisons in this report have been made at a level of significance of 5%.

There are no significant differences in average lives (for the same hole (1) diameter) between specimens incorporating 2·5 mm SLAN rivets and those with 0·125 inch SLAN rivets, and so these results were pooled. The averages and standard deviations are: 9 mm, 6279 (0·058); 10 mm, 4535 (0·123); and 11 mm, 4172 (0·043). All specimens incorporating oversize bolts in reamed holes have lives significantly less than those of the control group with 8 mm bolts. Fig. 15 illustrates the relative lives of control specimens and specimens with oversize reamed holes. Compared with the 8 mm hole control group the lives are 79%, 57%, 53% and 35% for the 9, 10, 11 and 12 mm diameter oversize reamed holes respectively.

This general behaviour associated with oversizing of the bolt hole was predictable because of the increasing stress concentration at the 'rear' edge of the bolt hole resulting from reductions in the bolt hole to specimen edge distance (Fig. 6). Clearly the proposal to simply ream out cracks and fit oversize clearance-fit bolts would not meet the minimum life extension requirements of the refurbishment program (i.e. an average fatigue life at least equal to that of the control group).

4.1.3 Oversize Bushed Bolt Holes

Although press-fitted bushes (Fig. 16) with a nominal interference of 0·3% were finally adopted as standard in this investigation, an initial proposal was to use an interference of 0·6% and a differential thermal expansion technique for bush insertion was considered. However, the temperature difference required between the steel bush and aluminium specimen is too large for practical considerations. Difficulties were also experienced in pressing in bushes of 0·6% interference without damaging the surface of the holes.

The various test series employing interference-fit steel bushes can be conveniently divided into three sub-series.

Sub-Series (i)—Specimens with 2·5 mm SLAN rivets, SAE 4130 Steel Bushes

All of these specimens incorporated interference-fit SAE 4130 steel bushes (mainly 0·3%) of 11 mm, 12 mm, 13 mm and 14 mm outside diameter in hole (1), with an internal diameter to suit a standard 8 mm bolt, i.e. bush wall thicknesses of 1·5, 2, 2·5 and 3 mm respectively. The other bolt holes in the specimens (holes (5), (6), (8) and (9)) were fitted with bushes of 2 mm greater outside diameter than the corresponding bushes in hole (1) but with internal diameters to suit standard 10 mm bolts, i.e. wall thicknesses of 1·5, 2, 2·5 and 3 mm also. One specimen in this series had bushes inserted with 0·6% interference, two had bushes of 0·1% interference, and one specimen had a sliding fit bush at hole (1) (i.e. no interference bush) fitted. The results of these tests are listed in part (g) of Table 2 and representative fractures are shown in Fig. 17.

Sub-Series (ii)—Specimens with 0·125 inch SLAN Rivets and 0·3% interference SAE 4130 Steel Bushes

Bushes of 9 mm, 10 mm, 11 mm and 13 mm outside diameter were fitted in hole (1). The other bolt holes in the specimens (holes (5), (6), (8) and (9)) were fitted with bushes of 2 mm greater outside diameter than the bush in hole (1) except for one group of specimens in which hole (1) had an 11 mm outside diameter bush, hole (5) a 16 mm bush and holes (6), (8) and (9) 13 mm bushes. This group was tested to cover the case of a particularly large crack detected at the hole (5) location in a service wing. Specimens incorporating 9 mm and 10 mm outside diameter bushes in hole (1) were used to investigate the situations of either no cracks or very small cracks having been detected in hole (1) and a potential minimum oversizing requirement corresponding to the 0·5 mm deep 'confidence cut'. In these cases bushes of 1·25 mm and 1·75 mm wall thickness (diametral ratios of 1·38 and 1·54) respectively were used, together with stepped undersize bolts* as illustrated in Fig. 18. The other specimens in this sub-series used standard 8 mm bolts in hole (1) and 10 mm bolts in the other four bolt holes. Individual test results are given in part (h) of Table 2 and photographs of representative fractures are shown in Fig. 19.

* Stepped bolts were used because standard sized holes already existed in the wing skins of Mirage III aircraft and the use of a stepped bolt would reduce location and fuel sealing problems.

Sub-Series (iii)—Specimens with 0·125 inch SLAN Rivets, and 0·3% interference Type 304 Stainless Steel Bushes

Although a preliminary testing program involving smaller specimens (Ref. 43) had shown no significant differences between the fatigue lives of specimens fitted with low-alloy steel and stainless steel bushes, it was decided to check this finding in the current investigation using the more representative spar flange specimens. Specimens with 11 mm and 13 mm bushes at hole (1) (and 13 mm and 15 mm bushes, respectively, at the other bolt hole locations) were tested. The results are recorded in part (i) of Table 2 and photographs of representative fractures shown in Fig. 20.

Referring to Table 3, there are no significant differences in average lives between groups of specimens from the three sub-series which had bushes of the same outside diameter in hole (1). These results thus indicate that, for bushed hole specimens, differences in either the type of SLAN rivet or the bush material do not have any significant effect on fatigue life.

Specimens with bushes of 9 mm, 10 mm, 11 mm and 12 mm outside diameter fitted in hole (1) had significantly greater lives than those of the control specimens. For the four groups with 11 mm bushes at hole (1), i.e. lines (11), (17), (18) and (20) of Table 3, the pooled average life of 12 718 flights (s.d. = 0·075) is about 60% greater than that of the pooled average life of the control groups (Fig. 21). The pooled average life of the three groups with 13 mm diameter bushes at hole (1), i.e. lines (13), (19) and (21), is 9486 flights (s.d. = 0·124). This life is not significantly different to that of the pooled 2·5 mm and 0·125 inch control groups, but is significantly less than that of the pooled 11 mm diameter bushed specimens. The lives of specimens incorporating interference-fit bushes are significantly greater than those of specimens incorporating clearance-fit bolts in reamed holes of the same diameter, bushed specimens having lives about three times longer than similar specimens with reamed holes (Fig. 22).

The improvement in life associated with the use of 11 mm diameter interference-fit steel bushes (and those of smaller external diameter) compared to that of the control group satisfies the criterion for extending the fatigue lives of the Mirage spars at this particular section. However, the potential beneficial effects of an interference-fit bush depend on the magnitude of the residual stresses initially induced near the hole. If, as pointed out by Schuetz and Gerharz (Ref. 44), stress relief can occur because of too small a hole to specimen-edge distance, then the interference-fit will become less effective. This, together with reduced nett area, could explain the lower lives of specimens having 13 mm compared with those incorporating 11 mm bushes. Nevertheless, if the use of 13 mm bushes was dictated by the requirement to remove cracks of 2 mm in depth at hole (1) then they could provide an acceptable overall extension in fatigue life.

The higher average life—although not significantly greater—of specimens fitted with 16 mm bushes at bolt hole (5)—Table 3, (line (18))—compared with the standard 13 mm bush at this hole (Table 3, line (17)) could suggest that the larger bush had introduced some stress shielding at bolt hole (1).

Some investigators (Refs 13, 17) have suggested that the variability in combinations of tolerance for machining bushes and holes could introduce variability in the magnitude of the interference stresses induced in different specimens and hence increase the scatter in lives compared with, for example, reamed holes This suggestion is not, however, supported by the present results, the variances of the control specimens (Table 3, lines (1) and (3)) and the interference bushed hole groups specimens (lines (11) and (17)) being not significantly different.

4.1.4 Oversize Bushed Bolt Holes and Oversize or Cold-expanded Rivet Holes

The purpose of the two SLAN rivets is to secure the anchor nut for the 8 mm skin attachment bolt to the flange and they should not be structural load-carrying items. Nevertheless, the discovery of fatigue cracks at these holes in a spar from a crashed Mirage III wing and the occurrence of secondary fatigue cracks at hole (2) in control specimens indicated that some attempt should be made to improve the fatigue performance at these rivet holes.

A problem associated with these holes is their diameter relative to the minimum size of eddy-current crack detection probes available commercially, and the feasibility of being able to non-destructively inspect them. During the early stage of the investigation it was not possible to inspect the SLAN rivet holes without enlarging them to a diameter of about 4 mm. Removing any existing cracks from the SLAN rivet holes would be expected to extend the total fatigue life but, on the other hand (as may be seen from Fig. 23), any option involving hole enlargement would result in increased K_t values at the hole edges.

Initially, two alternatives were considered as possibilities for improving the fatigue performance of the SLAN rivet holes, but in this particular group of tests only hole (2) was treated.

(i) Reaming to a diameter (approximately 4 mm)* at which they could be inspected using rotating probe eddy-current techniques and then attaching the anchor nut by soft close-fit rivets;

(ii) reaming and inspecting as in (i) above, but then cold-expanding the hole (with an oversize mandrel only) before using soft close-fit rivets to attach the SLAN. When cold-expansion of the SLAN rivet hole(s) was specified the sequence of operations was (i) bush insertion—if required; (ii) cold-expansion of hole (3)—if required; (iii) cold-expansion of hole (2).

Several fatigue tests covering these options were carried out. In all cases 0·125 inch 2117 aluminium alloy universal head rivets were used at hole (3), these being entered from the 'inside' and peened into the countersinks at the 'outer' surface of the spar in accordance with the practice in Australian-built wings. At hole (2) 0·156 inch diameter 2117 aluminium alloy countersunk rivets were used, these being entered from the 'outer' surface and having their tails formed against the leg of the SLAN. All specimens incorporated 13 mm outside diameter (2·5 mm wall thickness) 0·3% interference-fit 4130 steel bushes at hole (1) and 15 mm outside diameter bushes at the other bolt holes.

For specimens falling into group (1) above, hole (2) was reamed to 3·99 mm (0·157 inch); while for those in group (ii) hole (2) was reamed to 3·91 mm (0·154 inch) and cold-expanded to 0·156 inch diameter. Specially selected 2117 aluminium alloy close-fit rivets of (nominally) 0·156 inch diameter used in an attempt to 'fill' the hole. Details of the cold-expanding mandrel are given in Fig. 24. The holes were expanded by clamping the specimens on the table of a hydraulic testing machine and slowly pulling the mandrel through the holes. Before insertion of the mandrel in the holes both the mandrel and the bore of the hole were liberally coated with lanolin grease. Based on the Boeing definition of cold expansion (see Appendix 3) the cold-expansion of the rivet holes was 3·2%.

Part (j) of Table 2 lists the individual test results, and representative fractures are illustrated in Fig. 25. Cold expanding of the SLAN rivet holes was also employed for a number of other specimens, and details are given in later sections.

These tests showed that by simply reaming hole (2) to 4 mm diameter the average life (3690 flights) was significantly reduced compared to the pooled average (9486 flights—Table 4, line (10)) of the three 13 mm bushed groups with pairs of either 2·5 mm or 0·125 inch SLAN rivets. The large difference in life between the 'rivet-hole reworked' and 'standard' 13 mm bushed specimens is somewhat surprising as the maximum change in rivet hole diameter (and consequent reduction in bolt/rivet edge distance from 5 to 4·2 mm) would theoretically increase the K_t value at the edge of an unfilled hole by less than 10%. A further difference in the specimens was that the 'standard' group had 'loose-fit' rivets in drilled holes, compared with 'close-fit' rivets in reamed holes in the other group.

Specimens which had hole (2) reamed, then cold-expanded by 3·2% to a final diameter of 4 mm had an average life of 6445 flights, which is not significantly different from the pooled average (9486 flights—Table 4, line (11)) of similar 13 mm bushed specimens with unrefurbished SLAN rivet holes. However, this finding may be associated with large variances in the lives of both groups and the small sample size (two specimens) with cold-expanded SLAN rivet holes.

4.1.5 Interference-fit Bushes, Reworked SLAN Rivet Holes and a Modified Gangnut/SLAN Assembly

The use of the modified gang-nut/SLAN assembly (Fig. 7) obviates the need for using two through-the-spar rivets to attach the SLAN. Although the interference-fit bushing of bolt holes in the specimens has been demonstrated to be an effective way of extending the fatigue life of that detail there is also (for the reasons mentioned in the previous section (4.1.4) a need to

* In all cases the countersink diameters of the SLAN rivet holes was maintained at 5·5 mm.

improve the fatigue performance of the SLAN rivet holes (holes (2) and (3)) to maximise the fatigue life improvement at the SLAN/bolt hole (1) section of the specimen. The results of the specimen tests described in section 4.1.4 showed, however, that a simple reaming or cold working of these holes was not likely to further improve the overall fatigue life of a specimen with bushed bolt holes. Nevertheless, because of the desirability of periodic inspection of the holes for cracks, it was proposed that hole (2) (the critical hole) be either reamed or cold worked* and that both holes be either filled with close-fitting rivets or left open so that periodic inspection could be carried out. In this way an indication of the effect of filling the rivet holes could be obtained. It would not be feasible to remove the skin panel from in-service wings to inspect the SLAN rivet holes. However, the provision of holes in the skin panel opposite the SLAN rivet holes would enable in-service inspections to be made. This situation was simulated by machining an inspection slot in the skin plate of the specimens.

Ten specimens were tested, six with 11 mm diameter interference fit bushes in hole (1) and four with 13 mm diameter bushes in hole (1). Of the six 11 mm bush specimens, two had hole (2) cold expanded (3·2%) to 4 mm diameter and selected 2117 aluminium alloy close-fit 0·156 inch countersunk-head rivets inserted. The remaining four specimens had hole (2) reamed to 4 mm final diameter; two of these specimens had close-fit 0·156 inch rivets inserted and the other two had hole (2) left open. Of the four 13 mm bush specimens two had hole (2) reamed to 4 mm diameter and two had hole (2) cold-expanded (3·2%) to 4 mm final diameter, followed by the insertion of close-fit 0·156 inch rivets. In all cases hole (3) was filled with a 0·125 inch 2117 rivet, and the gang-nut/SLAN assembly fixed to the specimen with 0·156 inch close-fit rivets. Full details of the specimen conditions and results are recorded in Table 2(*k*), and are summarized in Table 3, lines (24)–(28). Representative fractures are shown in Fig. 26.

For the specimens with 11 mm bushes in hole (1) there are no significant differences in average lives between those with hole (2) reamed or cold-expanded, and no significant differences in average lives between those with SLAN rivet hole (2) filled or left open for inspection. Most importantly there is no significant difference in the pooled average life (10 642 flights) for the 11 mm bushed specimens incorporating the modified gang-nut/SLAN assembly (with hole (2) reworked) and the pooled average life (Table 4, line (9)) for the basic specimens with 11 mm bushes in which hole (2) was not reworked (12 718 flights). The life of 10 642 flights is also significantly greater than that of the pooled control groups. Furthermore, for specimens with 13 mm bushes there is no significant difference in average lives between specimens with hole (2) reamed and hole (2) cold-expanded. Neither is there any significant difference between the pooled average life (9432 flights) for these specimens and that for 13 mm bushed specimens without any reworking of the SLAN rivet holes (9486 flights—Table 4, line (11)).

These few results indicate that there are apparently no great additional advantages to be gained (from the fatigue viewpoint) by either cold-expanding the SLAN rivet holes or installing close-fit aluminium alloy rivets in them. Conversely (given the small number of test results available), providing the modified gang-nut/SLAN assembly is incorporated, the enlargement of hole (2) to 4 mm diameter (which might be necessary during refurbishment to remove cracks) does not significantly reduce the fatigue lives associated with the use of 11 mm and 13 mm interference-fit bushes at hole (1).

Nevertheless, a slightly reduced life for specimens having a 4 mm hole at position (2) would not have been unexpected because of:

(i) the larger size of this hole compared with 2·5 mm or 3·1 mm holes in the basic 11 mm and 13 mm bushed groups—which would result in a 3% to 4% increase in the nominal nett area stress at this section; and

(ii) a reduced edge distance both between the SLAN rivet holes and between hole (2) and the bushed hole (1) which would theoretically increase the K_t value at the side of an unfilled rivet hole by 5% to 10%.

4.1.6 Oversize Cold-expanded Bolt Holes

In this investigation three series of tests were carried out with specimens in which the bolt holes were cold-expanded using the Boeing Split-Sleeve Hole Cold-Expansion process (Ref. 27).

* To the size of the smallest available rotating eddy-current crack detecting probe.

The cold expansion was carried out by pulling the mandrel from the 'inner' to the 'outer' (skin) face of the specimens as would be required in the refurbishment of the Mirage main spar flanges. Complete details of the cold-expanding procedures are given in Appendix 3.

In the first series of tests the cold-expansion was carried out to conform with the high interference process requirements (nominally 3·5% to 4·0% expansion) and, because of the limited availability of tooling at the time, all five bolt holes in each specimen were treated in an identical manner to finish at 11·1 mm diameter. Of the six specimens in this series, two had close-fit sleeved bolts of 11·1 mm diameter fitted in the bolt holes. To avoid the necessity of increasing the diameter of the corresponding holes in the skin the remaining four specimens were fitted with bushes of either 0·1% or 0·3% interference and standard close tolerance bolts of 8 mm or 10 mm diameter used in the appropriate holes, i.e. bush wall thickness of 1·55 mm and 0·55 mm in hole (1) and the other four holes respectively. For this series of tests the 'standard' gang–nut strip sub-assembly was used. The results for this series are recorded in Table 2(*l*) and representative fractures illustrated in Fig. 27.

The second series of tests with cold-expanded bolt holes was carried out to explore a proposal for refurbishing Swiss Air Force wings and involved not only cold expanding the bolt holes but also two different reworks of the SLAN rivet holes (2) and (3) and the three gang–nut/strip rivet holes in the specimen, i.e. holes (5), (7) and (10). The modified gang–nut/SLAN sub-assembly referred to previously and illustrated in Fig. 7 was also used for all specimens in this series. In these tests the bolt holes were given a smaller amount of cold-expansion (nominally 2·5% to 2·8%), with corresponding reductions in the magnitude of the induced compressive stresses. The SLAN bolt hole (hole (1)) was finished to either 8·6 mm (4 specimens) or 10·3 mm diameter* (4 specimens) and the other bolt holes (holes (5), (6), (8) and (9)) to 10·9 mm diameter. For these tests standard *oversize* close-fit bolts of the appropriate diameters were used at the SLAN bolt hole. All rivet holes, i.e. holes (2), (3), (4), (7) and (10) in every specimen, were cold-expanded (between 1·8% and 2·4%) to a final diameter of 3·66 mm. For all specimens of this series the gang–nut/SLAN assembly *was not* attached to the specimen by the three through-the-specimen rivets, and the relevant holes were left empty. In half of each of the four specimens of 8·6 mm and 10·3 mm diameter at hole (1) the SLAN rivet holes, i.e. holes (2) and (3) were also left empty, whereas for the other four specimens they were filled with 2117 aluminium alloy close-fit rivets. Results are recorded in Table 2(*m*) and representative fractures shown in Fig. 28. It should be noted that during the fatigue tests on these specimens it was observed (through the empty rivet holes in the gang–nut strip/tapered shim assembly) that a relative slippage of about 1·5 mm had occurred between the 'wedge' surface of the tapered aluminium shim and the 'inner' surface of the specimen. This resulted in a loss of clamping force of about 50% between the 'skin' and the specimen.

The third test series, of four specimens, was a variation of the second series. Hole (1) *was not* cold-expanded but had a 10·3 mm diameter 0·3% interference 4130 alloy steel bush of 1·15 mm wall thickness fitted. All other bolt and rivet holes were treated in an identical manner to those of specimens in the second series described above. For two specimens *all* rivet holes were left open, whereas for the other two specimens the SLAN rivet holes (2) and (3) were again filled with 2117 close-fit rivets. Results are recorded in Table 2(*n*).

Before proceeding with a discussion of the fatigue lives of the cold-expanded bolt hole specimens it should be noted that, in the case of the Mirage spar (and the fatigue test specimens), the 'edge margins' (defined as the ratio of the distance from the hole centre to the edge of the plate divided by the hole diameter) are much less than the minimum value of 2·0 stipulated in Process Specification IWMF-2F76 issued by Industrial Wire and Metal Forming Inc., the marketers of the Boeing System. For specimens in the standard 'control' configuration the 'edge margins' at holes (1), (5) and (9) are 1·38, 1·35 and 1·5 respectively and these 'edge margins' decrease as the hole is reamed and cold-expanded to its final diameter. The fatigue lives of these cold-expanded hole specimens are therefore unlikely to equal those which might be achieved by specimens having minimum 'edge margins' of 2·0. One of the effects of reduced 'edge margins'

* 8·6 mm is the second standard oversize bolt after 8 mm. This hole size represents a rework of an 8 mm hole which, on inspection, would have given a nil-crack indication. 10·3 mm is the first standard oversize bolt after 10 mm.

was the permanent deformation observed along the sides of the specimens adjacent to the cold-expanded holes. The average maximum distortions at the middle of the side for the six specimens in the first series were 0·18, 0·11, 0·09, 0·08 and 0·08 mm for holes (1), (5), (6), (8) and (9) respectively. For the specimens in the second series the corresponding distortions were less (reflecting the smaller degree of cold-expansion and slightly smaller cold-expanded hole diameters) and averaged 0·02, 0·07, 0·06, 0·05 and 0·05 mm; and 0·10, 0·06, 0·05, 0·05 and 0·05 mm for the five bolt holes depending on whether hole (1) was finished to 8·6 mm or 10·3 mm diameter. In addition, surface deformations occurred on the faces of the specimens adjacent to both the entry and exit points of the mandrels. Similar deformation has been referred to in Ref. 32. To maintain good bearing surfaces for the shim and skin, the deformed regions on the faces were filed flat and polished before assembly of the specimens.

Specimens from the first series of tests with bolt holes cold-expanded to 11·1 mm diameter using the Boeing Split-Sleeve process and assembled with close-fit bolts have an average fatigue life of 5644 flights (Table 3, line (29)). Although, perhaps because of the small sample size, this life is not significantly less than that of the 2·5 mm SLAN rivet control group* it certainly is not an improvement in fatigue life. Furthermore, this average life is significantly less than that of specimens incorporating 11 mm interference-fit bushes (Table 3, line (11)). There is no significant difference between the average lives of the specimens with bushed cold-expanded holes (Table 3, lines (30) and (31)) and the specimens with close-fit bolts (Table 3, line (29)). The use of the Boeing Split-Sleeve cold-expansion process would appear to be an unsuitable technique for extending the fatigue life of the Mirage spar if the bolt holes were to be cold-expanded to 11·1 mm diameter (when the resulting 'edge margins' are much less than those recommended for the process).

For the second series of cold-expanded hole specimens (cold-expanded bolt holes and reworked rivet holes) there is no significant difference in lives between specimens with filled and with empty SLAN rivet holes when bolt hole (1) is the *same* diameter, i.e. 8·6 or 10·3 mm—compare lines (32), (33) and (34), (35) of Table 3. There is no significant difference between the pooled average life of the 10·3 mm diameter hole specimens and that of the pooled control group (7532 and 7916 flights respectively), nor was there any significant difference between the pooled average life of the 8·6 mm diameter specimens and the same pooled control group (9602 and 7916 flights respectively). The results of these tests indicate that the cold expansion of bolt hole (1) is not an effective way of improving upon the fatigue lives of the control specimens having the configuration of bolt and rivet holes required by the detail in the Mirage spar.

Of the four specimens in the third series of tests (which are similar to the second series specimens except that hole (1) had a 10·3 mm diameter interference bush), three failed at hole (9)—which had been cold-expanded but not bushed—at lives of 9742, 14 123 and 22 442 flights respectively, the fourth specimen failed through the SLAN section at a life of 17 150 flights. As the specimens of the second series (which had hole (1) cold-expanded to 10·3 mm) all failed through the SLAN section at an average life of 7532 flights, this behaviour supports the earlier conclusion that, for this particular structural configuration, interference-fit bushing is a more effective way of increasing the fatigue life than is cold-expanding of the bolt holes.

4.1.7 Part Fatigued and Refurbished Specimens

The refurbishment options so far explored had been carried out on specimens not previously fatigue tested, the assumption being made that the resulting lives would relate to a situation where all fatigue damage was removed during the reworking process. To explore this assumption tests were conducted in which specimens with 0·125 inch 2117 SLAN rivets (control type specimens) were part fatigued and then refurbished before being fatigue tested until failure. In all cases interference-fit bushes were installed in the five bolt holes and the modified gang-nut/SLAN sub-assembly incorporated after refurbishment.

* This life is, however, significantly less than the average life of the pooled 2·5 mm and 0·125 mm SLAN rivet control specimens.

Two test series were carried out. In the first, specimens were fatigue tested for a varying number of flights (between 2600 and 4200) with frequent inspections (using rotating probe eddy-current equipment)* of hole (1) until a crack of nominated length was detected. Four of these specimens were refurbished by the installation of 13 mm diameter 0·3% interference 4130 steel bushes at hole (1) and 15 mm diameter bushes at the other four bolt holes, while the remaining two had (nominally) 11 mm bushes fitted at hole (1) and 13 mm bushes at the remaining holes. No residual cracks were indicated during NDI of the holes immediately prior to bush insertion. Apart from carefully removing the SLAN and gang-nut strip during refurbishment and making the associated SLAN rivets flush with the 'inner' surface of the specimens, the SLAN rivets in the six specimens were not disturbed, i.e. there was no reworking of the SLAN rivet holes. The results of these tests are recorded in Table 2(*o*), and representative fractures illustrated in Fig. 29.

Whereas all the previous specimens incorporating steel bushes had been manufactured under workshop toolroom conditions and assembled without sealants, those in the second part-fatigued and refurbished series were refurbished under factory conditions using the actual tooling and procedures specifically developed for use in the overhaul of Mirage IIIO wings. They incorporated the complete fuel sealant treatment, etc. usually applied to service wings. In all cases the specimens were subjected to 2000 flights of the sequence and inspected for cracks before the refurbishment was undertaken. Refurbishment involved the installation of type 304 stainless steel bushes in all bolt holes, four specimens with 11 mm diameter bushes at hole (1) and 13 mm bushes at the other four holes; and four specimens with 13 mm and 15 mm bushes at the corresponding holes. For these tests 8·6 mm diameter bolts were used in hole (1) and 10·6 mm bolts† in the other holes (with correspondingly reduced bush wall thicknesses) to cover the case of the maximum oversize bolts permitted at these locations in the original structure. The SLAN rivet holes (holes (2) and (3) were cold-expanded (3%)), using the Boeing process, and then reamed to a final diameter of 4 mm‡ and 2117 rivets fitted in the holes. The other three rivet holes were reamed to 4 mm diameter. Fuel sealant was applied during assembly of the specimen. Before the bushes were inserted in the holes they were passivated using a nitric acid solution (Ref. 25) and the holes were brush alodined (Ref. 26). Bush insertion forces are given in Appendix 4. The results of these tests are recorded in Table 2(*p*) and representative fracture surfaces shown in Fig. 30.

In the first test series the results from the four specimens with 13 mm bushes in hole (1) provide data to evaluate the effectiveness of a part-refurbishment after prior fatigue loading. Their average life *after* refurbishment is 8768 flights (Table 3, line (38)) and this is not significantly different to the pooled average life (9486 flights) of specimens tested 'ab initio' with 13 mm bushes (Table 4, line (11)). Moreover, the average *total* life to failure (sum of pre- and post-refurbishment lives) of 12 296 flights is significantly greater than the 8213 flights of the 0·125 inch control group (Table 3, line (3)). Because of an error in the fatigue loading of one specimen (GK1E7) and a machining error during refurbishment with another (GK1F6) which necessitated an 11·3 mm bush in hole (1) the data base to evaluate the effectiveness of refurbishing with an 11 mm bush after prior fatigue loading is minimal. All that can be said is that the lives after refurbishment are in the same order as those of specimens fitted 'ab initio' with 11 mm diameter bushes.

For the second series of specimens refurbished after prior fatigue loading, the average life after refurbishment of those with 11 mm bushes (12 151 flights—Table 3, line (40)) is not significantly different from the pooled average life of specimens tested 'ab initio' with 11 mm bushes (12 718 flights—Table 4, line (9)). One of the four 11 mm bush refurbishment results (specimen GZ3D4 which had a very short life after refurbishment) was rejected because on examination of the fracture surface it was found that hole (1) in the specimen was bell-mouthed to such an extent that no interference could have been present at the point of initiation of the

* Non-destructive inspections of holes were done using a Foerster Defectomat Type F2.825 rotating probe eddy-current instrument.

† The 8·6 mm and 10·6 mm bolts in these particular specimens were torqued to 12·2 and 27·1 Nm respectively because of a change in wing production requirements.

‡ After refurbishment the bolt hole (1) to rivet hole (2) countersunk distance was 4·45 mm for the 11 mm bushes and 3·45 mm for 13 mm bushes.

fatigue failure. The life of that specimen after refurbishment (5763 flights) was only slightly greater than the pooled average (4172 flights) of specimens incorporating 11 mm bolts at hole (1). This result emphasizes the need for careful control during manufacture and inspection of bushed holes.

Refurbished specimens with 13 mm bushes in hole (1) had an average life after refurbishment of 5775 flights (Table 3, line (41)). This life is significantly less than the pooled average life of specimens tested 'ab initio' with 13 mm bushes (9486 flights—Table 4, line (11)) and significantly less than that of the first series of 13 mm bushed refurbished specimens (8768 flights after refurbishment). These results support the findings in Section 4.1.4 for the 13 mm bushed specimens with 4 mm cold-expanded SLAN rivet holes which had an average life of only 6445 flights, and suggest that a deleterious interaction has occurred between the stress fields around the adjoining cold-expanded rivet holes and 13 mm diameter interference-fit bushed holes.

4.1.8 Fatigue Cracking Characteristics

Fatigue crack development in the test specimens occurred from multiple origins down the bores of both bolt and rivet holes, large cracks being formed by the continuing coalescence of smaller cracks to form a common crack front rather than by the propagation of a single dominant crack. Similar crack development has been observed at the bolt and rivet holes of spars in aircraft of the Mirage fleet. However, there were some marked differences in the fatigue cracking characteristics associated with the various refurbishment options investigated.

For the three control groups of specimens (Fig. 13) and those incorporating oversize bolts in reamed holes (Fig. 14) the primary crack initiation and subsequent growth was from the edge of hole (1) closest to the 'rear' side of the specimens. There was also some fatigue cracking from the 'forward' edge of hole (1) and, in most specimens, clear evidence of minor crack initiation at hole (2)—the first SLAN rivet hole. In some specimens very small cracks were detected at hole (3)—the second SLAN rivet hole. This pattern of fatigue cracking was not unexpected considering that, in this section of the specimens, the highest value of K_t occurs at the 'rear' edge of hole (1)—see Figs 6 and 23. The increase in stress concentration at this location for the specimens with oversize reamed holes is also reflected in the more extensive cracking between this hole and the 'rear' side.

A major difference in the cracking characteristics between the control specimens and those with oversize bolts in reamed holes on the one hand, and most of those incorporating interference-fit bushes and cold expansion of the bolt holes on the other, was the location of the primary crack initiation site. In contrast to those with reamed holes only, the primary initiation site in bushed and cold-expanded hole specimens was predominantly at the first SLAN rivet hole (hole (2)), usually at or near the countersink end of the hole (Figs 19, 20, 25(*i*), 26 and 27). Usually, only relatively small fatigue cracks developed from the 'rear' edge of hole (1). These may have initiated late in life as the result of changes in stress distribution at the section because of the development of large cracks at the adjacent SLAN rivet hole.

Despite similarities in the fatigue cracking characteristics of specimens with bushed and cold-expanded holes there were significant differences in their lives to failure. The use of interference-fit bushes effectively inhibits primary crack initiation at hole (1) and, in these cases, the failing lives are representative of specimens where the first SLAN rivet hole is the critical fatigue location in the section. This cracking characteristic is also shown in Fig. 29 which illustrates specimens where the original SLAN rivets were not removed during refurbishment. The much lower lives associated with rivet hole cracking exhibited by specimens with cold-expanded bolt holes are likely to be associated with the rivet hole (2) being within the bounds of the balancing tensile stress field resulting from the cold-expansion process.

The cold-expanding of the SLAN rivet holes also appeared to have some influence on the fatigue cracking characteristics of specimens incorporating 13 mm bushes. With non-cold-expanded hole specimens the pattern of major crack development from rivet hole (2) was maintained, whereas in some cases when the SLAN rivet holes were cold-expanded the primary crack initiation site reverted to the bolt-hole, hole (1). Substantial fatigue cracking also developed from hole (3) in at least four cases, originating about halfway through the section, e.g. Fig. 26(*ii*). This was particularly the case when the adjoining 4 mm hole was cold-expanded.

4.2 Inclined SLAN Hole Specimens

The spar refurbishment techniques discussed in Section 4.1 were developed, essentially, around the design detail for the SLAN rivets shown on the manufacturing drawings. However, in very few of the Mirage IIIO wing spars was this exact configuration of SLAN rivet holes found. Instead of the rivet holes being parallel to each other and to bolt hole (1) they were usually inclined relative to each other and to the bolt hole. Furthermore the relative angles varied from spar to spar. An early survey of a sample of about 10% of all Australian wing spars suggested that, in over 80% of cases, the spacing between holes (1) and (2) at the 'outer' surface of the spar was less than that specified on the drawings.

Inclined SLAN rivet holes introduce complications into the concept of refurbishment at the SLAN section. Reduced spacings between holes (1) and (2) and between holes (2) and (3) increase the K_t values at the hole edges (Fig. 23) and also seriously restrict the range of options for enlarging the diameters of the rivet holes for the purposes of either N.D.I. or to remove fatigue cracks. The maximum diameter to which hole (1) may be enlarged to ensure that it is crack free is also limited.

Another complication, because of the variability of SLAN hole inclination, is that of selecting a SLAN section specimen configuration which would best model the examples identified in the wing spars. Because of the progressive updating of information relating to rivet hole spacings and angles, the testing program eventually covered four different types of inclined SLAN rivet hole specimens. These are illustrated in Fig. 31.

(i) TYPE 1: The configuration of hole (2) in these specimens represented the average found in an early survey of Mirage IIIO spars. Only two specimens of this configuration were tested as they were regarded as a developmental design. Hole (3) in these specimens was machined parallel to bolt hole (1). Bolt hole (1) to rivet hole (2) countersink distance was 3·25 mm.

(ii) TYPE 2: This configuration of holes (2) and (3) represented the configuration of the SLAN rivet holes in the first RAAF wing incorporated in the full-scale fatigue test at the F+W. Bolt hole (1) to rivet hole (2) countersink distance was 3·25 mm.

(iii) TYPE 3: This specimen configuration represented the closest spacing between bolt and rivet holes found during the early survey of Mirage IIIO wing spars. Bolt hole (1) to rivet hole (2) countersink distance was 1·55 mm.

(iv) TYPE 4: This was based on the RAAF acceptance criteria for the standard refurbishment of the SLAN section specified in Annex 'A' of a RAAF document (Ref. 45). Bolt hole (1) to rivet hole (2) countersink distance was 3·05 mm.

All spars with inclined SLAN rivet holes incorporated 0·125 inch universal head 2117 rivets to connect the SLAN to the spar, these rivets having been entered from the inner surface of the flange. Therefore, all inclined SLAN rivet hole specimens in which the SLAN rivet holes were not reworked incorporated this rivet arrangement.

4.2.1 Control Tests

The purpose of these tests was to compare the lives of the four types of inclined SLAN hole specimen with those of control specimens having parallel SLAN rivet holes, to gain some insight into the potential effects of inclined SLAN rivet holes on the fatigue life of the Mirage spar, and to provide a benchmark for comparing the fatigue performance of the various rework proposals. The test results are reported in parts (a), (b), (c) and (d) of Table 5 and representative fractures are shown in Fig. 32.

For the TYPES 1, 2, 3 and 4 specimens the average lives and standard deviations are 7567 flights (s.d. 0·053), 7174 flights (s.d. 0·107), 7910 flights (s.d. 0·028) and 5576 flights (s.d.

0·176) respectively (Table 6, lines (1), (2), (3), (4)). The average fatigue lives of these four groups of specimens are not significantly different. This result (given the relatively short lives of TYPE 4 specimens) may be a reflection of the small sample size of the testing program.

Although the average lives of the TYPES 1, 2 and 3 inclined SLAN rivet hole control specimens and those of the 13 parallel SLAN rivet hole control specimens with 0·125 inch SLAN rivets (Table 3, line (3)) are not significantly different, the TYPE 4 inclined hole control specimens have an average life which is significantly less than those of the parallel SLAN rivet hole specimens. The lower average fatigue life of TYPE 4 inclined SLAN hole control specimens is surprising. An examination of the inclined SLAN rivet hole specimen configurations (Fig. 31) suggests that the TYPE 4 configuration is similar to the TYPE 2 configuration and should be less severe than the TYPE 3 configuration. However, it should be noted that the TYPE 4 control group included a specimen with a relatively short life—only about half the next lowest of any of the inclined SLAN hole control specimens—and this could explain the apparent anomalous finding. The fracture surface photographs (Fig. 32) show cracking patterns for TYPE 4 specimens which are similar to those for TYPE 2 specimens. TYPES 1, 2 and 4 have similar configurations of hole (2) and their pooled average life and standard deviation are 6490 flights and 0·137 respectively.

4.2.2 Part Fatigued and Refurbished Specimens—TYPE 2

Nine specimens were part fatigued, with frequent inspections, until a crack of about 8 mm length was indicated along the bore at the 'rear' side of hole (1). They were then refurbished and fatigue tested until failure. In the refurbishment process 11 mm diameter 0·3% interference-fit 4130 steel bushes were inserted in hole (1) (as was done in the F+W test article) and similar 13 mm diameter bushes were inserted in the other four bolt holes. All specimens incorporated the modified gang-nut/SLAN assembly, but there were differences in the reworking of holes (2) and (3). Also, an inspection slot was machined in the 'skin plate' adjacent to the SLAN rivet holes to represent a situation where the holes could be inspected in actual wings without removing the skin panel.

(i) Series 1 rework, (3 specimens). Standard 8 mm and 10 mm bolts used in the bushed holes (i.e. bush wall thickness of 1·5 mm), holes (2) and (3) reamed to 3·62 mm diameter and left empty.

(ii) Series 2 rework (2 specimens). Standard 8 mm and 10 mm bolts used in the bushed holes, holes (2) and (3) cold-expanded 1·8% to a final diameter of 3·62 mm and filled with 3·5 mm countersunk A-U4G rivets.

(iii) Series 3 rework (1 specimen). Standard 8 mm and 10 mm bolts used in the bushed holes, holes (2) and (3) cold-expanded 1·8% to a final diameter of 3·62 mm and left empty.

(iv) Series 4 rework (3 specimens). Second oversize bolts used in the bushed holes, 8·6 mm diameter in hole (1) ($D/d = 1{\cdot}28$), 10·6 mm diameter in the other four holes (i.e. bushes of 1·2 mm wall thickness). Holes (2) and (3) cold-expanded 1·8% to a final diameter of 3·66 mm and left empty.

After refurbishment the bolt hole (1) to rivet hole (2) countersink distance was 1·75 mm in each of the four series. The results of these tests are reported in Table 5(*e*) and lines (5) to (8) of Table 6. Typical fractures are shown in Fig. 33.

For none of the refurbishment procedures investigated did the average total lives (sum of pre- and post-refurbishment lives) of the refurbished specimens differ significantly from the average life of the TYPE 2 inclined SLAN rivet hole control specimens. The use of 11 mm diameter interference-fit bushes in hole (1) of specimens with this particular inclined SLAN rivet hole configuration is thus not a successful technique for providing an extension in fatigue life. It should be noted that the TYPE 2 specimen is not the 'worst case' configuration of SLAN rivet holes.

Comparisons may be made of the effectiveness of the different reworkings of hole (2) and (3), i.e. combinations of reaming, cold-expanding and filling or leaving empty. The series 1 rework of holes (2) and (3) was to ream and leave empty. For these specimens the post-refurbishment average life was 3811 flights (s.d. 0·154) (Table 6, line (5)). This compares with a post-refurbishment average life of 4720 flights (s.d. = 0·042) (Table 6, line (7)) for the series 4 specimens in which the SLAN rivet holes were cold-expanded and left empty. As there is no significant difference between these average lives it is not possible (with the limited sample tested) to distinguish between the effectiveness of reaming and cold-expanding as methods for reworking the SLAN rivet holes.

A comparison of the results from the series 2 and series 4 tests enabled the relative behaviour of specimens with filled and empty SLAN rivet holes to be assessed. The post-refurbishment average life of the series 2 specimens with filled holes (3391 flights, s.d. = 0·067—Table 6, line (6)) is not significantly less than those with empty holes (4720 flights, s.d. = 0·042—Table 6, line (7)). The advantage of leaving the SLAN rivet holes empty is that they can be readily inspected—a very desirable feature since, in the refurbished specimens, large cracks grew from hole (2) (Fig. 33).

4.2.3 Part Fatigued and Refurbished Specimens—TYPE 3

Seven specimens of this type were fatigue tested, with frequent inspections, until a crack of about 8 mm in length was indicated at the 'rear' edge of hole (1). The specimens were then refurbished and fatigue tested until failure. In this group of specimens hole (1) was only slightly oversized (to 8·6 mm diameter) during refurbishment, with the expectation that the residue of the fatigue crack would remain. In all cases (after refurbishment) 13 mm outside diameter interference-fit bushes of 4130 steel were installed in holes (5), (6), (8) and (9), the modified gang–nut/SLAN assembly was incorporated and the SLAN rivet holes left empty. Inspection slots were machined in the 'skin plates' of these specimens adjacent to the SLAN holes.

(i) Series 1 rework (2 specimens). Hole (1) reamed to 8·6 mm diameter and a clearance-fit bolt installed. SLAN rivet holes (2) and (3) cold-expanded 3% to a final diameter of 3·66 mm. On cold-expansion of rivet hole (2) deformation occurred at bolt hole (1) at the skin face.

(ii) Series 2 rework (3 specimens). An 8·6 mm diameter 4130 steel, 0·3% interference-fit bush installed in hole (1), the inside diameter of the bush sized to take a 6·3 mm diameter stepped bolt, i.e. a bush *D*/*d* ratio of 1·35. Holes (2) and (3) cold-expanded 3% to a final diameter of 3·66 mm.

(iii) Series 3 rework (2 specimens). An 8·6 mm diameter 4130 steel, 0·3% interference-fit bush installed in hole (1), the inside diameter of the bush sized to take a 6·3 mm diameter stepped bolt. Holes (2) and (3) reamed to 3·66 mm diameter, while holes (4), (7), (10) were reamed to 4 mm diameter and 0·156 inch 2117 rivets used to secure gang–nut strip.

After refurbishment (in all cases) the bolt hole (1) to rivet hole (2) countersink distance was 1·25 mm. The results of these tests are reported in Table 5(*f*) and lines (9) to (11) of Table 6. Typical fractures are shown in Fig. 34.

The series 1 specimens (which incorporated clearance-fit bolts in hole (1)) had an average total life of 5415 flights (s.d. 0·037) which is significantly less than the average life of the TYPE 3 control specimens (7910 flights, s.d. 0·028). For the series 2 and 3 specimens the average lives *after* refurbishment are 5321 flights (s.d. = 0·177) and 4953 (s.d. = 0·080) respectively. Although these lives are not significantly different, and are significantly greater than that of the series 1 specimens after refurbishment (2221 flights, s.d. = 0·035) they also are, nevertheless, significantly less than the average life of the TYPE 3 control specimens. Furthermore, the average total lives (pre- and post-refurbishment) of the series 2 (9657 flights, s.d. 0·089) and series 3 (9225 flights, s.d. 0·040) specimens are not significantly different from the average life of the TYPE 3 control specimens. These results show that none of the refurbishment methods investigated satisfied the requirement that the life *after* refurbishment be at least equal to the life of the relevant control specimens. However, the superiority of bushed holes (series 2 and 3) over reamed holes (series 1) is again illustrated. The lack of a significant difference between the average lives of specimens in series 2 and series 3 (incorporating cold-expanded and reamed SLAN holes respectively) also shows that, with the results available, it is not possible to differentiate between these two SLAN rivet hole reworking techniques.

4.2.4 TYPE 4 Specimens—Bushed, not Part Fatigued

A total of 16 specimens was tested using four different refurbishment schemes, to explore the effects of different bush sizes in hole (1) and the treatment of holes (2) and (3). These specimens were *not* part fatigued and then refurbished, but were modified before fatigue testing. In all cases type 304 stainless steel 0·3% interference bushes (13 mm outside diameter in holes (5), (6), (8) and (9)) were used as was the modified gang–nut/SLAN assembly.

(i) Series 1 (4 specimens). 9 mm diameter bush at hole (1), sized to accept a 6·5 mm stepped bolt, i.e. $D/d = 1 \cdot 38$. Holes (2) and (3) reamed to 4 mm diameter and left empty. The bolt hole (1) to rivet hole (2) countersink distance was 2·55 mm.

(ii) Series 2 (4 specimens). 9 mm diameter bush at hole (1), sized to accept 6·5 mm stepped bolt. Holes (2) and (3) cold-expanded 3% to a final diameter of 4 mm and filled with 2117 rivets.

(iii) Series 3 (4 specimens). 11 mm diameter bush inserted in hole (1). Holes (2) and (3) reamed to 4 mm and left empty. The bolt hole (1) to rivet hole (2) countersink distance was 1·55 mm.

(iv) Series 4 (4 specimens). 11 mm diameter bush inserted in hole (1). Holes (2) and (3) cold-expanded 3% to a final diameter of 4 mm and filled with 2117 rivets.

The results of these tests are reported in Table 5(*g*) and lines (12) to (15) of Table 6. Typical fractures are shown in Fig. 35.

The pooled average life (7311 flights, s.d. = 0·100) of specimens with 9 mm bushes in hole (1) (series 1 and 2) is not significantly different from the average life of the TYPE 4 control specimens (5576 flights (s.d. 0·176)) or significantly different from the average life (8213 flights, s.d. 0·085) of parallel SLAN rivet hole control specimens with 0·125 inch rivets. These comparisons suggest that for specimens of the TYPE 4 configuration, the incorporation of 9 mm bushes in hole (1) and stepped bolts will result in fatigue lives after refurbishment equivalent to the fatigue life to failure without refurbishment. The average life of the specimens with 11 mm bushes is significantly less than that of those with 9 mm bushes and thus, in this SLAN configuration, the use of the larger size bush would not provide an effective refurbishment technique.

The effects of the treatments of holes (2) and (3) may be assessed by comparing either the series 1 results (7454 flights, s.d. 0·085) to the series 2 results (7171 flights, s.d. 0·125), or the series 3 results (3226 flights, s.d. 0·203) to the series 4 results (3329 flights, s.d. 0·134). In neither of these two groups is there any significant difference between the average lives and so, on the results available, it is again not possible to distinguish between reaming or cold-expansion as refurbishment techniques for the SLAN rivet holes.

4.2.5 Fatigue Cracking Characteristics

Multiple crack initiation along the bores of both the bolt and SLAN rivet holes also characterized the development of the fatigue failures in inclined SLAN hole specimens. In both the parallel and inclined hole control specimens the cracking characteristics were similar in that the primary crack initiation and greatest subsequent growth was from the edge of hole (1) closest to the 'rear' side of the specimens. However, in the inclined hole specimens, considerable crack growth also occurred from the 'forward' edge of hole (1) and from both sides of hole (2), the latter being especially apparent in TYPE 3 specimens where the pitch between holes (1) and (2) was the least of the four types of inclined SLAN hole specimens. In some specimens small cracks were also identified at hole (3).

The installation of interference-fit bushes in inclined SLAN hole specimens also tended to inhibit the initiation of fatigue cracks from the 'rear' edge of hole (1) and concentrate the fatigue crack development around the SLAN rivet holes. Figures 33 to 35 clearly show, however, that the major fatigue crack development has occurred from the rivet holes and not the forward edge of hole (1). Hole (2) in particular has played the major role in controlling the fatigue life.

5. DISCUSSION

This investigation has considered a number of refurbishment options for the SLAN section of the Mirage IIIO wing main spar and, for the parallel SLAN rivet specimens, their relative effectiveness is summarized in Fig. 36. Of the various refurbishment options investigated in this program, only interference-fit bushing of the bolt hole has demonstrated the potential for successfully increasing the lives of spars in which fatigue cracks have developed at the SLAN section bolt hole. This method has the advantages that standard bolts may be reused and that the corresponding holes in the skin panel need not be enlarged. The other refurbishment options considered (i.e. oversize reaming of the bolt holes and fitting clearance-fit bolts, and cold-expansion of the bolt holes) did not provide adequate lives to meet the fatigue-life extension criteria following crack removal. The Boeing split-sleeve hole cold-expansion process could provide an acceptable increase in life for cases in which no fatigue cracks were detected at bolt hole (1), i.e. when the hole oversizing requirements to utilize the process are minimal. However, when the removal of fatigue cracks prior to cold-expansion is necessary, the resulting decrease in fatigue lives associated with larger hole sizes and reduced edge distances preclude using this process as a refurbishment option. The simplest refurbishment procedure of reaming out the bolt holes to remove fatigue cracks and then installing oversize clearance-fit bolts is not a satisfactory solution, because it not only provides no potential for increasing the fatigue life but could result in a significant reduction in fatigue life compared with the original detail configuration.

After some preliminary tests with other values of bush interference, a nominal value of 0·3% was adopted for the investigation. This value provides an adequate increase in fatigue performance, maintenance of dimensional accuracy is achievable without undue difficulty, and the bush insertion forces are acceptable (in the order of 9 kN). A low degree of interference also reduces the problem of stress corrosion in the specimen parent metal. Initially the bush material was 4130 steel, but in later specimens type 304 stainless steel bushes were used to allow some potential for 'through-the-bush' inspection of the holes.

The fatigue tests on parallel SLAN rivet hole specimens demonstrated that the life enhancement criteria could be met even by the use of bushes of up to 13 mm outside diameter at hole (1), (i.e. the potential to remove cracks at this hole of 2 mm in depth).

Except for the TYPE 4 inclined SLAN rivet hole control specimens, the average lives of the other three types of inclined hole control specimens are not significantly less than those of the parallel hole control specimens. This is not surprising as the primary fatigue crack initiation and growth in all control specimens (whether parallel or inclined SLAN rivet holes) was from the 'rear' edge of bolt hole (1). However, the extent to which oversize bushes can be used is considerably reduced as the distance between hole (1) and the first SLAN rivet hole becomes less.

In the parallel SLAN rivet hole configuration the use of an 11 mm or 13 mm outside diameter bush results in nominal distances of 4·45 mm and 3·45 mm respectively from the bolt hole to the countersink of the first rivet hole, whereas for inclined rivet hole specimens of TYPES 2 and 4 fitted with 11 mm diameter bushes these distances are reduced to 1·75 mm and 1·55 mm respectively. This dimensional change is reflected in the very low average lives after 'refurbishment' of the groups of specimens of these two types incorporating 11 mm bushes, i.e. 4114 flights for TYPE 2 and 3277 flights for TYPE 4 (which are not significantly different) compared with an average of 11123 flights for all parallel SLAN hole specimens having this size of bush, reworked SLAN rivet holes and the modified gang-nut/SLAN assembly. Furthermore, for the TYPE 2 inclined hole configuration, in no case was the total life (sum of pre- and post-refurbishment) significantly different to that of the TYPE 2 control specimens.

In situations where only small cracks are present at bolt hole (1) and the edge distances from the bolt hole to rivet hole (2) preclude the use of an 11 mm outside diameter bush, the adoption of bushes with an outside diameter of less than 11 mm combined with the use of undersize bolts (i.e. less than 8 mm diameter) provides the opportunity to make a satisfactory refurbishment and obtain useful extensions in life. This is clearly shown in Fig. 36 for specimens having parallel SLAN rivet holes, and is demonstrated by the TYPE 4 inclined hole rivet specimens incorporating 9 mm outside diameter bushes. By analogy with the behaviour of specimens incorporating 11 mm diameter bushes it is likely that useful extensions in the post-refurbishment lives of TYPE 2 specimens could have been expected by using 9 mm outside diameter bushes—providing the fatigue cracks had been completely removed.

The TYPE 3 inclined SLAN hole specimens incorporated the closest bolt to rivet hole countersink distance of any specimen configuration tested, i.e. only 1·25 mm after refurbishment with either an 8·6 mm diameter clearance-fit bolt or 8·6 mm outside diameter bush and stepped undersize bolt. Furthermore, there was no certainty, with these particular specimens, that the fatigue cracks developed prior to refurbishment had been completely removed during reworking of the holes. The very low life (after refurbishment) of the specimens with clearance-fit bolts and the development of significant cracking from both sides of the bolt hole (see Fig. 34(*i*)) tends to support this contention. However, the benefits of bushing are again apparent in this case, as the average total life of TYPE 3 specimens incorporating the 8·6 mm outside diameter bushes is both significantly greater than specimens with 8·6 mm clearance-fit bolts and not significantly different from that of the TYPE 3 control specimens.

The improvements in fatigue lives associated with the use of interference-fit bushes of 11 mm or less outside diameter (compared with the specimens representing the original structural configuration) are much less than some claimed improvements in fatigue life associated with the interference-fit bushing and hole cold-expansion life-enhancement systems. Reported improvements in life by factors of 4 to 10 are quite common (Refs 7, 17, 22, 32, 42, 44, 46). However, the magnitude of the fatigue life improvement in particular cases is dependent upon:

(i) the material involved;

(ii) the specimen configuration, e.g. open hole, low- or high-load transfer joints;

(iii) the type and severity of the fatigue loading sequence.

Several investigators (Refs 20, 22, 32, 47) have shown that the improvements in fatigue life are much greater with materials of high rather than low yield strengths because they are capable of sustaining higher values of residual compressive stresses, e.g. comparing the higher yield strength 7075 series aluminium alloys with the lower yield strength 2000 series. The alloy A7-U4SG is within the latter category. Similarly, the greatest improvements in fatigue life have been found under loading sequences which do not incorporate high stresses, i.e. low-stress constant-amplitude loading and gust loading sequences (Refs 7, 19, 22, 32). Under high-load constant-amplitude cycling (Refs 19, 22) and manoeuvre loading sequences the improvements are much less, e.g. being less than 2 : 1 for 2024-T351 interference-bush lugs under manoeuvre spectrum loading (Ref. 20). Again the reason for this is that high external loads are more likely to cause tensile yielding in the tensile residual stress region which would, in turn, cause relaxation of the beneficial compressive stresses adjacent to the hole.

The problems of the non-achievement of the anticipated life as a result of incorrectly fitted bushes have been highlighted in Section 4.1.7. It cannot be overemphasized that the effectiveness of the interference-fit bushing process in providing consistent improvements in the fatigue lives of bolted joints relies strongly on the maintenance of the specified bush interferences. This, in turn, requires careful quality control of the bush and hole machining procedures and the insertion of the bush in the hole. Similar production requirements are also necessary for most other fatigue life-enhancement systems (Ref. 48).

Fatigue cracks have been detected in the SLAN rivet holes (holes (2) and (3)) of actual spars. Thus enlargement of these holes during refurbishment is essential for at least two reasons, (i) they must be inspected during refurbishment, but the smallest available probe has a diameter larger than the original hole diameters; and (ii) interference-fit bushing of hole (1) promotes cracking from hole (2) and so any existing cracks there should be removed. By using a modified gang-nut/SLAN assembly of the type developed during this investigation (which makes the through-the-flange SLAN rivet holes redundant) the reworking of these holes can be done without significantly affecting the fatigue life improvements caused by the interference-fit bushing of hole (1). Although only small numbers of specimens (both parallel and inclined SLAN rivet hole) were tested with a variety of bush sizes at bolt hole (1) to assess the relative merits of reamed or cold-expanded SLAN holes, either left empty or filled with aluminium alloy rivets, the results when taken as a whole do not indicate any significant advantages (from the fatigue viewpoint) of any one treatment compared with another. There is some evidence, however, that the combination of cold-expanded rivet holes and a large diameter interference-fit bush at hole (1) (e.g. 13 mm) may tend to cause a reduction in life. Under those circumstances, the most simple rework of the holes, i.e. reaming to a size commensurate with the removal of cracks and then leaving the holes unfilled so that they could be easily inspected during subsequent service, would appear to be the best alternative.

In summary, if there is an adequate separation between the first bolt hole and the first SLAN rivet hole, satisfactory extensions in fatigue life (by factors of 1·5 or more) can be achieved for specimens representing the lower inboard section of the wing spars of the Mirage III aircraft by the use of interference-fit steel bushes in bolt holes. There is the proviso, however, that in the first instance any existing fatigue cracks in the bolt and SLAN rivet holes are completely removed.

A major consideration in the implementation of the interference-fit bush refurbishment scheme is the distance, after crack removal, from the bolt hole to the first SLAN rivet hole. In the configuration of parallel bolt and SLAN rivet holes, the use of interference-fit bushes of up to 13 mm outside diameter (which might imply the removal of a crack at the bolt hole of 2 mm in depth) could provide an acceptable increase in life. This situation would result in a bolt hole to countersink edge distance of 3·45 mm.* If the depth of fatigue cracks were such that they could be removed with only slight oversizing of the bolt holes, the use of bushes with an internal diameter of less than 8 mm combined with the use of stepped undersize bolts could provide considerable increases in fatigue life.

With a reduction in the distance between the first bolt and rivet hole the refurbishment options and the maximum permissible bush external diameters are reduced. It is in this situation where the use of bushes of small internal diameter and undersize bolts could be used to greatest advantage. However, the tests on specimens with inclined SLAN rivet holes suggest that an acceptable increase in fatigue life can be obtained only if the distance from the edge of hole (1) to the countersink of hole (2) is not less than 2·55 mm. If 2·55 mm was then specified as the minimum acceptable separation distance it follows that an 11 mm external diameter bush (which would be necessary to cover the removal of a crack of 1 mm in depth) could be used in situations where the centre-to-centre distance between the bolt hole and first rivet hole was not less than 10·8 mm.

Thus, providing a minimum bolt to rivet hole countersink edge distance of 2·55 mm can be maintained after refurbishing, the standard rework proposal for increasing the fatigue life of the SLAN section of the Mirage III spar is:

(i) to install, at the bolt hole, an 0·3% interference-fit stainless steel bush with a nominal bore diameter of 8 mm and minimum wall thickness of approximately 1·5 mm.

(ii) to incorporate a modified gang–nut/SLAN assembly which obviates the need for the two through-the-flange SLAN rivets;

(iii) to ream out the SLAN rivet holes to 4 mm diameter (but not fill them with rivets so that the holes may be inspected in service if required) and fit Teflon plugs to prevent entry of fuel sealant.

This proposal effectively allows the use of bushes with external diameters ranging from about 9 mm to 13 mm, depending upon the separation distance between bolt hole (1) and the first SLAN rivet hole and the extent of fatigue cracking at the bolt hole. It has been implemented in the lower rear flange of the main spar of a RAAF Mirage IIIO wing being subjected to a full-scale fatigue test at the F+W in Switzerland (Ref. 1) except that in the test wing the SLAN

* A competing requirement is to maintain an adequate distance from the 'rear' edge of hole (1) to the side of the specimen. This requirement effectively precludes the use of bushes exceeding 13 mm diameter at this location.

rivet holes were cold-expanded to 3·66 mm rather than simply being reamed. In addition an inspection slot was cut in the appropriate position in the skin panel to allow for eddy-current inspections during the course of the fatigue test.

6. CONCLUSIONS

This investigation has shown that acceptable extensions in the fatigue life of specimens representing the wing main spars of the Mirage IIIO are possible by the use of combinations of standard bolts and 0·3% interference-fit steel bushes (of 1·5 mm wall thickness) in the critical bolt holes, and the incorporation of a modified gang–nut/SLAN assembly which eliminates the need to secure the SLAN directly to the spar. There are the provisos, however, that existing fatigue cracks are completely removed and that (after reworking) bolt hole/rivet hole separation distances in the SLAN region are adequate. More detailed conclusions are as follows:

1. A reduction in fatigue life results if the 8 mm diameter SLAN bolt hole is reamed to larger diameters and fitted with an oversize close-fit bolt. For an 11 mm bolt the average life is about 60% that of the 8 mm control group.

2. Interference-fit bushed holes of up to 11 mm in diameter at least provide a significant increase in fatigue life when compared with holes of the same diameter fitted with close-fit bolts and also with 8 mm diameter SLAN bolt hole control specimens. For example, specimens fitted with bushes of 11 mm outside diameter at the SLAN section have average fatigue lives about three times those of specimens with 11 mm diameter oversize close-fit bolts in reamed holes and 1·75 times those of the control specimens with 8 mm diameter holes. The fitment of 13 mm bushes at this section results in a life equivalent to that of the control group.

3. The fatigue lives of specimens with the SLAN bolt hole cold-expanded using the Boeing split-sleeve process were significantly less than those of similar specimens incorporating interference-fit bushes at this hole. It is the close proximity of SLAN rivet holes and the small hole/spar edge distance (which is less than that recommended for the Boeing process) which militate against the use of cold-expansion at this particular section of the Mirage IIIO wings.

4. Although the average lives of control specimens with inclined SLAN rivets are only marginally less than those of corresponding specimens with parallel SLAN rivets, the increased incidence of cracking from the rivet holes and 'forward' edge of the 8 mm bolt hole introduce serious problems in the implementation of a 'standard' refurbishment scheme for wings with inclined SLAN rivet holes.

5. For cases in which only small or nil crack indications are demonstrated at the SLAN bolt hole but the bolt hole/rivet hole separation distance is relatively small, acceptable increases in life may be obtained by reducing the outside diameter of the bush and utilizing stepped undersize bolts.

6. Without exception, fatigue crack development occurred from multiple origins down the bores of either or both bolt and rivet holes; large cracks being formed by the coalescence of smaller cracks to form a common crack front.

7. Marked differences in the fatigue cracking characteristics occurred with the different bolt hole treatments investigated. In the case of specimens with parallel SLAN rivet holes and reamed bolt holes, crack development started at the rear edge of the SLAN bolt hole; whereas for specimens with bushed or cold-expanded bolt holes crack initiation at the bolt hole was almost completely inhibited, and the tendency was for crack development to occur mainly from the first SLAN rivet hole. For specimens with inclined SLAN rivets crack development tended to be from both sides of the SLAN bolt hole and both sides of the two SLAN rivet holes.

8. Although various techniques, including combinations of oversize reaming, cold-expansion, filling with rivets or leaving empty, were explored in an attempt to further improve the fatigue performance at the SLAN rivet holes, none of these provided any significant additional increases in fatigue life compared with that provided by the use of interference-fit bushes.

ACKNOWLEDGEMENTS

This investigation has been supported, to a considerable extent, by the Workshops staff in the Engineering Facilities Division of the Aeronautical Research Laboratories. The authors wish to express their appreciation for the close co-operation and assistance at all levels which they received in the development of tooling and techniques, in the production and inspection of test specimens and in the maintenance of the fatigue testing equipment. Their grateful thanks are also expressed to members of Materials Division and Structures Division for assistance in the non-destructive inspection of fatigue specimens and in determining the chemical composition, tensile and fracture toughness properties of the test material.

Appreciation is also expressed to staff of the Commonwealth Aircraft Corporation Ltd (CAC), in particular Mr K. J. Kennedy, for the provision of technical information, for the heat treatment of rivets and plates and for the manufacture and installation of bushes in fatigue specimens; and to Mr R. H. Stevens of Qantas Engineering and Maintenance Base, Sydney, for the use of the Boeing cold-expansion tooling.

Thanks are also expressed to the RAAF Resident Engineer at CAC, members of RAAF Support Command and DEFAIR, Canberra for their willing co-operation in the acquisition of test material and components for test specimens. During a period of attachment to ARL, Corporals A. Green and S. Nicholl provided valuable assistance in the preparation of fatigue specimens and in photographing fracture surfaces.

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APPENDIX 1

Machining of Bolt Holes

Hole diameter (mm)		Drilling	Reaming
8	Size	'N' Drill	8 mm
	revs (r.p.m.)	1700	810
	feed (mm/min)	64	61
10	Size	9·6 mm	10 mm
	revs (r.p.m.)	400	127
	feed (mm/min)	30	10
11	Size	27/64 inch	11 mm
	revs (r.p.m.)	525	100
	feed (mm/min)	40	8
12	Size	29/64 inch	12 mm
	revs (r.p.m.)	525	100
	feed (mm/min)	30	8
27/64 inch	Size	13/32 inch	27/64 inch
	revs (r.p.m.)	660	127
	feed (mm/min)	60	10
13	Size	12·8 mm	13 mm
	revs (r.p.m.)	520	170
	feed (mm/min)	30	14
14	1. Size	9·6 mm	
	revs (r.p.m.)	400	
	feed (mm/min)		
	2. Size	13·5 mm	14
	revs (r.p.m.)	400	100
	feed (mm/min)	30	8

Cutting fluid: Synthetic POLAR-CHIP EP BLUE M.

APPENDIX 2

Areas and Stresses at Various Stations of 'Control' Specimens

Station	Gross Area (mm^2)	Gross Area Stress (MPa)		Nett Area (mm^2)	Nett Area Stress (MPa)	
		1 g	7·5 g		1 g	7·5 g
SLAN section 2·5 mm rivet 3·0 mm rivet 0·125 inch rivet	2238	24·0	180	1828 1797 1786	29·4 29·9 30·1	220 224 226
Hole (4) 3·0 mm rivet	2203	24·4	183	2108	25·5	191
Hole (5) 10 mm bolt	2173	24·7	185	1875	28·7	215
Hole (6) 10 mm bolt	2109	25·5	191	1825	29·4	221
Hole (7) 3·0 mm rivet	2076	25·9	194	1991	27·0	202
Hole (8) 10 mm bolt	2044	26·3	197	1775	30·3	227
Hole (9) 10 mm bolt	2072	25·9	194	1817	29·6	222
Hole (10) 3·0 mm rivet	2065	26·0	195	1988	27·0	203

APPENDIX 3

Cold-Expanding of Bolt Holes

A. *FIRST COLD-EXPANDED SERIES* (all five holes)

Starting hole diameter:	0·421 to 0·424 inch (10·69 to 10·77 mm)
Sleeve thickness:	0·010 inch (0·25 mm)
Mandrel diameter (maximum):	0·418 inch (10·62 mm)
Finished hole size (after reaming):	0·4377 to 0·4380 inch (11·12 to 11·14 mm)
Nominal cold-expansion:	4·0 to 3·3%

The tooling for this Series was in inch sizes.
Sequence of hole cold-expansion was holes (8), (6), (5), (9), (1).

B. *SECOND COLD-EXPANDED SERIES*

Hole (1)

Starting hole diameter:	8·344 to 8·353 mm	10·013 to 10·028 mm
Sleeve thickness:	0·2 mm	0·25 mm
Mandrel diameter (maximum):	8·156 to 8·184 mm	9·779 to 9·793 mm
Finished hole size (after reaming):	8·613 to 8·628 mm	10·316 to 10·334 mm
Nominal cold-expansion:	2·9% to 2·4%	2·8% to 2·5%

Holes (5), (6), (8) and (9)

Starting hole diameter:	10·616 to 10·634 mm
Sleeve thickness:	0·25 mm
Mandrel diameter (maximum):	10·399 to 10·414 mm
Finished hole size (after reaming):	10·916 to 10·934 mm
Nominal cold-expansion:	2·8% to 2·5%

Sequence of hole cold-expansion was holes (1), (5), (6), (8) and (9).

In all cases the slit in the split-sleeve was aligned with the longitudinal axis of the specimen.

APPENDIX 4

Bush Insertion Forces for Specimens Listed in Table 2(p)

Specimen No.	Hole No. (1) Diam. (mm)	(1) Force (kN)	(5) Diam. (mm)	(5) Force (kN)	(6) Diam. (mm)	(6) Force (kN)	(8) Diam. (mm)	(8) Force (kN)	(9) Diam. (mm)	(9) Force (kN)
GZ3A12	11	9·5	13	9·5	13	9·5	13	13·3	13	19·0
GZ3D7	11	5·7	13	5·7	13	17·1	13	11·4	13	11·4
GZ3B9	11	14·3	13	10·5	13	11·4	13	13·3	13	9·5
GZ3D4	11	15·2	13	18·1	13	10·5	13	13·3	13	18·1
Average	—	11·2	—	11·0	—	12·1	—	12·8	—	14·5
GZ3D12	13	14·8	15	8·6	15	10·0	15	16·2	15	6·7
GZ3D5	13	19·0	15	19·0	15	16·2	15	12·9	15	16·2
GZ3B10	13	9·5	15	13·3	15	28·6*	15	10·5	15	11·9
GZ3B1	13	14·3	15	10·5	15	16·2	15	29·5*	15	17·1
Average	—	14·4	—	12·9	—	17·8	—	17·3	—	13·0
Average excluding *						14·1		13·2		

* Holes finally lapped, not reamed, to size.

TABLE 1

Properties of test material

(a) *Chemical composition*

*Specification A7-U4SG (2214) (%)	Plate batch serial no.			
	GK	GN	GT	GZ
Cu 3·9–5·0	4·56	4·40	4·26	4·43
Mg 0·2–0·8	0·38	0·33	0·35	0·36
Mn 0·4–1·2	0·62	0·60	0·66	0·62
Fe 0·30 max.	0·24	0·24	0·14	0·19
Si 0·5–1·2	0·73	0·77	0·73	0·72
Ti 0·15 max.	0·01	0·02	0·02	0·02
Cr 0·10 max.	} Not analysed			
Zn 0·25 max.				

(b) *Static tensile*

	*Specification A7-U4SG-T651 (2214-T651)	Plate batch serial no.			
		GK	GN	GT	GZ
0·1% proof stress (MPa)	—	440·5	444·7	449·5	450·8
0·1% proof stress (psi)		63,900	64,500	65,200	65,400
0·2% proof stress (MPa)	390	446·3	451·0	455·2	457·9
0·2% proof stress (psi)	56,600	64,700	65,400	66,000	66,400
Ultimate stress (MPa)	450	488·3	493·2	497·1	508·8
Ultimate stress (psi)	65,300	70,800	71,500	72,100	73,800
Elongation (%) ($5 \cdot 65 \sqrt{A}$)	5	10·1	12·3	11·4	11·5
0·1% PS/Ult	—	0·90	0·90	0·90	0·89

(c) *Fracture toughness*

	Plate batch serial no.								Pooled values (34 tests)	
	GK (10 tests)		GN (11 tests)		GT (5 tests)		GZ (8 tests)			
	Average	s.d.	Average	s.d.	Average	s.d.	Average	s.d.	Average	s.d.
$MPa.m^{\frac{1}{2}}$	30·3	0·5	33·2	1·2	32·4	1·8	32·0	0·5	31·9	1·5
$ksi.in^{\frac{1}{2}}$	27·6	0·4	30·2	1·1	29·5	1·6	29·1	0·5	29·1	1·4

* *Conditions de controle des produits lamines en alliages d'aluminium utilises dans les constructions aerospatiales.* Ministere de la Defense, Direction Technique des Construction Aeronautiques AIR 9048, Edition No. 1, 26 Dec. 1978, p. 91.

TABLE 2(a)

Parallel SLAN rivet holes: Control specimens with 2·5 mm diameter A-U4G SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1A4	Hole (1) 8 mm diameter	6642	Not recorded	Large crack rear side hole (1), crack forward side hole (1), small cracks at hole (2)
GK1B2		6342	374	As above
GK1C6		7342	351	As above. See Fig. 13(*a*)(*i*)
GK1D6		8742	370	As above plus small cracks at hole (3)
GN10		8242	388	As above plus small cracks at hole (3). See Fig. 13(*a*)(*ii*)
GN2E		6842	394	As above plus small cracks at hole (3)

TABLE 2(b)

Parallel SLAN rivet holes: Control specimens with 2·5 mm diameter A-U4G SLAN rivets—fatigue failure through hole (9)*

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1A7	Hole (1) 8 mm diameter	6442	Not recorded	Origin at hole (9). Large cracks at hole (1)
GK1A5		6142	Not recorded	Origin at hole (9). Cracks at hole (1)
GK1A3		7742	Not recorded	Origin at hole (9). Small cracks at hole (1)
GK1A9		5942	349	Origin at hole (9). Large cracks at hole (1)
GK1C9	As above. In addition bolts in holes (5), (6) not fully torqued	7182	338	Origin at hole (9). Very small cracks at hole (1)

* Not used in any statistical comparisons of fatigue lives because of failure location. Log. mean life = 6657 flights, s.d. of log. life = 0·048.

TABLE 2(c)

Parallel SLAN rivet holes: Control specimens with 3·0 mm diameter A-U4G SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GN1P	Hole (1) 8 mm diameter	7742	397	Large crack rear side hole (1), crack forward side hole (1), cracks at countersink of hole (2), small cracks at hole (3)
GN2G		9442	403	As above. See Fig. 13(*b*)(*i*)
GN4C		4442	391	As above
GN3A		4342	374	As above. See Fig. 13(*b*)(*ii*)
GN3E		8742	402	As above
GN4E		6535	324	As above
GT1G		6244	300	As above
GZ3C10		6842	403	As above
GZ3A11		8460	300	As above
GZ2B10		9042	241	As above
GZ2D8		5942	394	As above

TABLE 2(d)

Parallel SLAN rivet holes: Control specimens with 0·125 inch diameter 2117 SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1B7	Hole (1) 8 mm diameter	9362	300	Large crack rear side hole (1), crack forward side hole (1), small cracks at hole (2)
GK1D9		8642	348	As above plus small crack at hole (3). See Fig. 13(*c*)(*i*)
GK1E10		8542	403	Same as GK1B7
GN1D		9042	392	As above plus small cracks at hole (3)
GN2R		15442*	380	Failed through hole (8)
GN3B		8542	397	Large crack rear side hole (1), crack forward side hole (1), small cracks at holes (2) and (3)
GN4B		7742	374	As above, except no cracks at hole (3)
GT10		9240	340	Same as GN3B
GT3F		7642	384	Same as GN3B
GT2G		7648	346	Same as GN4B
GZ3A10		11861	344	Same as GN3B. See Fig. 13(*c*)(*ii*)
GZ3C8		8323	344	Same as GN4B
GZ2A5		5058	268	Same as GN4B
GZ2C12		6940	319	Same as GN4B

* Not used in any statistical comparisons of fatigue lives because of failure location.

TABLE 2(e)

Parallel SLAN rivet holes: Oversize reamed bolt holes with oversize, close-fit (sleeved) bolts. 2·5 mm diameter A-U4G SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GN3N	Hole (1) reamed to 9 mm diameter	7050	324	Large crack rear side hole (1), crack forward side hole (1), cracks at hole (2), small crack at hole (3)
GT2B		6846	341	As above
GN3J	Hole (1) reamed to 10 mm diameter	3742	368	Large crack rear side hole (1), crack forward side hole (1), small cracks at hole (2)
GT2J		6566	341	As above
GK1A10	Hole (1) reamed to 10 mm diameter, hole (5) reamed to 12 mm diameter	4142	Not recorded	As above plus very small cracks at hole (3)
GK1A8		3642	Not recorded	Same as GN3J
GK1B6	Hole (1) reamed to 11 mm diameter	4598	285	Large crack rear side hole (1), crack forward side hole (1), small cracks holes (2) and (3). See Fig. 14(*a*)(*i*)
GK1D5		3842	377	As above
GK1E8		4142	393	As above
GK1A1	Hole (1) reamed to 12 mm diameter	2742	382	Large crack rear side hole (1), crack forward side hole (1), cracks hole (2)
GK1B10		2742	378	As above. See Fig. 14(*a*)(*ii*)

TABLE 2(f)

Parallel SLAN rivet holes: Oversize reamed bolt holes with oversize, close-fit (sleeved) bolts. 0·125 inch diameter 2117 SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GT2E	Hole (1) reamed to 9 mm diameter	5245	342	Large crack rear side hole (1), crack forward side hole (1), small crack at hole (2). See Fig. 14(*b*)(*i*)
GT3L		6142	380	Large crack rear side hole (1), crack forward side hole (1)
GT2M	Hole (1) reamed to 10 mm diameter	3642	404	Large crack rear side hole (1), crack forward side hole (1), small cracks at hole (2)
GT3A		6442	404	As above
GT2N	Hole (1) reamed to 11 mm diameter	4615	330	Large crack rear side hole (1), crack forward side hole (1), small cracks at hole (2). See Fig. 14(*b*)(*ii*)
GT3G		3742	380	As above, except no cracks at hole (2)

TABLE 2(g)

Parallel SLAN rivet holes: interference-fit bushes of 4130 steel. 2·5 mm diameter A-U4G SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1C8	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). 0·3% interference	14242	391	Large cracks both sides hole (2), cracks at hole (3), small cracks rear hole (1). See Fig. 17(*i*)
GK1C2	As above	10619	288	Large crack rear side hole (1), cracks both sides hole (2), small cracks hole (3)
GK1B9	As above, but 0·1% interference	14042	387	Large cracks both sides hole (2), crack forward side hole (3), crack rear side hole (1)
GK1B1	As above, but 0·1% interference	10042*	382	Failed through hole (9)
GK1C1	11 mm *sliding fit* bush	3636*	311	Large crack rear side hole (1), crack forward side hole (1), small cracks at hole (2)
GK1A2	12 mm bush in hole (1). 14 mm bushes in holes (5), (6), (8) and (9). 0·3% interference	8642	385	Large cracks both sides hole (2), cracks at hole (3), small cracks rear side hole (1)
GK1B3	As above	9981	348	As above
GK1A6	As above, but 0·6% interference†	6442	384	As above
GK1E4	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9). 0·3% interference	11035	345	Large cracks both sides hole (2), cracks at hole (3), crack rear side hole (1). See Fig. 17(*ii*)
GK1C3	As above	8440	348	As above
GK1D8	14 mm bush in hole (1). 16 mm bushes in holes (5), (6), (8) and (9). 0·3% interference	4542	398	Large cracks both sides hole (2), small cracks hole (3), small crack rear side hole (1)
GK1F4	As above	3909	348	Large cracks both sides hole (2), crack rear side hole (1), very small cracks hole (3)

* Not used in any statistical comparisons of fatigue lives.

† Difficulty in inserting bush, hole surface damaged, life not used in statistical analysis.

TABLE 2(h)

Parallel SLAN rivet holes: Interference-fit bushes of 4130 steel. 0·125 inch diameter 2117 SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GT3D	9 mm bush in hole (1). 11 mm bushes in holes (5), (6), (8) and (9). Stepped bolts used	14342*	384	Failed through hole (10)
GZ3B11	As above	15200	349	Cracks both sides hole (2), crack rear side hole (1), small cracks at hole (3)
GZ2B1	As above	21107	333	Large cracks both sides hole (2), large crack forward side hole (3), crack rear side hole (1). See Fig. 19(*i*)
GZ2C8	As above	10642*	377	Failed through hole (9)
GT3K	10 mm bush in hole (1). 12 mm bushes in holes (5), (6), (8) and (9). Stepped bolts used	20342*	389	Failed through hole (10)
GZ3D11	As above	13123	348	Large cracks both sides hole (2), crack forward side hole (3), crack rear side hole (1)
GZ2D6	As above	12131	346	As above
GZ2A2	As above	17842	364	As above
GZ3A2	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9)	12491	346	Large cracks both sides hole (2), crack forward side hole (3), crack rear side hole (1)
GZ3C9	As above	12907	346	As above
GZ2A7	As above	11742	384	Large cracks both sides hole (2), crack rear side hole (1), small cracks forward side hole (3). See Fig. 19(*ii*)
GZ2C11	As above	9383	324	Large crack rear side hole (1), cracks at holes (2) and (3)

TABLE 2(h) (Continued)

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GT3P	11 mm bush in hole (1). 16 mm bush in hole (5). 13 mm bushes in holes (6), (8) and (9)	20239	330	Large cracks both sides hole (2), crack forward side hole (3), crack rear side hole (1)
GZ3C7	As above	13942	364	As above
GZ3C12	As above	14042	378	Large cracks both sides hole (2), crack rear side hole (1), small crack forward side of hole (3)
GZ3B7	As above	12542	372	Large crack rear side hole (2), cracks forward sides holes (2) and (3), crack rear side hole (1)
GZ3B5	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9)	8642	384	Large cracks both sides hole (2), crack rear side hole (1), small crack forward side hole (3)
GZ3D1	As above	9240	336	Large cracks both sides hole (2), crack forward side hole (3), crack rear side hole (1)
GZ2C4	As above	16742	348	As above

* Not used in any statistical comparisons of fatigue lives because of failure location.

TABLE 2(i)

Parallel SLAN rivet holes: 0·3% Interference-fit bushes of Type 304 stainless steel. 0·125 inch diameter 2117 SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GZ3D2	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9)	12442	390	Large cracks both sides hole (2), crack forward side hole (3), crack rear side hole (1). See Fig. 20(*i*)
GZ3A7	As above	11742	382	As above
GZ2B6	As above	11382	340	As above
GZ2D3	As above	11815	344	As above
GZ3C1	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9)	7542*	390	Failed through hole (9)
GZ3D6	As above	7642	384	Large cracks both sides hole (2), crack rear side hole (1), small crack forward side of hole (3)
GZ2A11	As above	7266	348	As above. See Fig. 20(*ii*)

* Not used in any statistical comparisons of fatigue lives because of failure location.

TABLE 2(j)

Parallel SLAN rivet holes: 0·3% Interference-fit bushes of 4130 steel. Reworked SLAN rivet holes

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1D4	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9). Hole (2) reamed to 4 mm and a 0·156 inch 2117 aluminium alloy rivet fitted. Hole (3) drilled to 0·125 inch diameter and a 0·125 inch 2117 aluminium alloy rivet fitted	3211	347	Large cracks both sides hole (2), small crack forward side hole (3), crack rear side hole (1). See Fig. 25(*i*)
GK1F3	As above	4242	348	Large cracks both sides hole (2), crack rear side of hole (1)
GK1E5	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9). Hole (2) reamed then cold-expanded (3·2%) to 4 mm final diameter and a 0·156 inch 2117 aluminium alloy rivet fitted. Hole (3) drilled to 0·125 inch and a ·0125 inch 2117 aluminium alloy rivet fitted	4698	336	Cracks both sides hole (1), small cracks both sides hole (2), very small cracks both sides of hole (3). See Fig. 25(*ii*)
GK1D10	As above	8842	390	Large cracks both sides hole (3), cracks both sides hole (1), small cracks both sides of hole (2)

TABLE 2(k)

Parallel SLAN rivet holes: 0·3% Interference-fit bushes of 4130 steel. Reworked SLAN rivet holes and modified gang-nut/SLAN assembly

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1F2	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Hole (2) reamed to 4 mm and left open. Hole (3) drilled 0·125 inch diameter and filled with a 0·125 inch 2117 aluminium alloy rivet	8699	350	Large cracks both sides hole (2), crack rear side hole (1), small cracks hole (3). See Fig. 26(*i*)
GK1D3	As above	7942	396	As above
GK1E1	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Hole (2) reamed to 4 mm and 0·156 inch 2117 aluminium alloy rivet fitted. Hole (3) drilled 0·125 inch diameter and filled with a 0·125 inch 2117 aluminium alloy rivet	12042	397	Large cracks both sides hole (2), crack forward side hole (3), crack rear side hole (1)
GK1F8	As above	10475	326	As above
GK1D7	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Hole (2) reamed then cold-expanded (3·2%) to 4 mm final diameter and a 0·156 inch 2117 aluminium alloy rivet fitted. Hole (3) drilled 0·125 inch diameter and filled with a 0·125 inch 2117 aluminium alloy rivet	15242	386	Very large cracks both sides hole (3), crack rear side hole (1), small crack rear side hole (2). See Fig. 26(*ii*)
GK1E2	As above	10935	346	As above

TABLE 2(k) (Continued)

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1E3	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9). Hole (2) reamed to 4 mm and 0·156 inch 2117 aluminium alloy rivet fitted. Hole (3) drilled 0·125 inch diameter and filled with a 0·125 inch 2117 aluminium alloy rivet	7669	348	Large cracks both sides hole (2), crack rear side hole (1), small crack forward side hole (3)
GK1F5	As above	16303	345	Large cracks both sides hole (3), cracks both sides hole (1), small cracks both sides hole (2)
GK1D2	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9). Hole (2) reamed then cold-expanded (3·2%) to 4 mm final diameter and a 0·156 inch 2117 aluminium alloy rivet fitted. Hole (3) drilled 0·125 inch diameter and filled with a 0·125 inch 2117 aluminium alloy rivet	9530	347	Large cracks both sides hole (3), cracks both sides hole (1), small cracks both sides hole (2)
GK1E9	As above	6642	392	As above

TABLE 2(l)

Parallel SLAN rivet holes: Bolt holes cold-expanded by Boeing split-sleeve process (3·6% expansion). 2.5 mm diameter A-U4G SLAN rivets

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1C7	All bolt holes 11·1 mm diameter. Oversize close-fit (sleeved) bolts	5023	350	Large cracks both sides hole (2), crack rear side hole (1), small cracks both sides of hole (3). See Fig. 27(*i*)
GK1B4	As above	6342	362	As above
GK1B5	All bolt holes 11·1 mm diameter. 0·3% interference-fit bushes inserted, standard bolts used	7342	399	Large cracks both sides hole (2), crack forward side of hole (3). See Fig. 27(*ii*)
GK1C10	As above	6742	391	As above
GK1B8	All bolt holes 11·1 mm diameter. 0·1% interference-fit bushes inserted, standard bolts used	6642	374	As above plus crack rear side hole (1)
GK1C5	As above	6742	394	Same as GK1B5

TABLE 2(m)

Parallel SLAN rivet holes: Bolt holes cold-expanded by Boeing split-sleeve process (2.7% expansion). All rivet holes reworked and modified gang-nut/SLAN assembly used

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GN1C	Hole (1) cold-expanded to 8·6 mm. Holes (5), (6), (8) and (9) cold-expanded to 10·9 mm. All rivet holes (holes (2), (3), (4), (7) and (10)) cold-expanded (1·8–2·4%) to 3·66 mm diameter and left open	11642	399	Large cracks both sides hole (1), small cracks holes (2) and (3)
GN2N	As above	11342	393	As above. See Fig. 28(*i*)
GN1E	Hole (1) cold-expanded to 8·6 mm. Holes (5), (6), (8) and (9) cold-expanded to 10·9 mm. All rivet holes (holes (2), (3), (4), (7) and (10)) cold-expanded (1·8–2·4%) to 3·66 mm diameter. Holes (2) and (3) filled with 2117 aluminium alloy close-fit rivets, other rivet holes left empty	9142	402	Large cracks both sides hole (1), small cracks holes (2) and (3)
GN2L	As above	7042	390	As above, except no cracks at hole (3)
GN2B	Hole (1) cold-expanded to 10·3 mm. Holes (5), (6), (8) and (9) cold-expanded to 10·9 mm. All rivet holes (holes (2), (3), (4), (7) and (10)) cold-expanded (1·8–2·4%) to 3·66 mm diameter and left open	7146	342	Large crack rear side hole (1), cracks both sides of hole (2)
GN1G	As above	8010	336	As above. See Fig. 28(*ii*)

TABLE 2(m) (Continued)

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GN2A	Hole (1) cold-expanded to 10·3 mm. Holes (5), (6), (8) and (9) cold-expanded to 10·9 mm. All rivet holes (holes (2), (3), (4), (7) and (10)) cold-expanded (1·8–2·4%) to 3·66 mm diameter. Holes (2) and (3) filled with 2117 aluminium alloy close-fit rivets, other rivet holes left empty	7446	345	Large crack rear side hole (1), crack forward side hole (1), small cracks holes (2) and (3)
GN1L	As above	7550	342	As above, except no cracks at hole (3)

TABLE 2(n)

Parallel SLAN rivet holes: Hole (1) bushed, other bolt holes cold-expanded by Boeing split-sleeve process (2·7% expansion). All rivet holes reworked and modified gang-nut/SLAN assembly used

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GN3C	10·3 mm diameter 0·3% interference-fit bush in hole (1). Holes (5), (6), (8) and (9) cold-expanded to 10·9 mm. All rivet holes (holes (2), (3), (4), (7) and (10)) cold-expanded (1·8–2·4%) to 3·66 mm diameter and left open	9742*	404	Failed through hole (9)
GN4F	As above	22442*	362	As above
GN3F	10·3 mm diameter 0·3% interference-fit bush in hole (1). Holes (5), (6), (8) and (9) cold-expanded to 10·9 mm. All rivet holes (holes (2), (3), (4), (7) and (10)) cold-expanded (1·8–2·4%) to 3·66 mm diameter. Holes (2) and (3) filled with 2117 aluminium alloy close-fit rivets, other rivet holes left open	14123*	345	Failed through hole (9)
GN4A	As above	17150	345	Large crack rear side hole (1), crack forward side of hole (1), cracks both sides of hole (2)

* Not used in any statistical comparisons of fatigue lives because of failure location.

TABLE 2(o)

Parallel SLAN rivet holes: 0·125 inch diameter 2117 SLAN rivets, specimens part-fatigued, refurbished with 0·3% interference-fit 4130 steel bushes, modified gang-nut/SLAN assembly. SLAN rivets not removed during refurbishment

Specimen No.	Specimen details	Refurbishment			Total flights to failure	Failing load (kN)	Failure details
		Flights before refurbishment	Crack length (mm)	Flights after refurbishment			
GK1F7	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9)	2600	8·5	10442	13042	396	Large cracks both sides hole (2), crack forward side hole (3), small crack rear side hole (1)
GK1D1	As above	2900	6·0	9742	12642	396	As above, see Fig. 29(*i*)
GK1F1	As above	4200	9·0	7442	11642	Not recorded	As above
GK1F10	As above	4100	9·0	7807	11907	338	Large cracks both sides hole (2), cracks both sides hole (3), small crack rear side hole (1)
GK1E7	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8), and (9)	2600	6·5	13642*	16242*	394	Large cracks both sides hole (2), crack forward side hole (3), small crack rear side hole (1)
GK1F6	11·3 mm† bush in hole (1), 13 mm bushes in holes (5), (6), (8) and (9)	2900	6·5	10942	13842	400	As above, see Fig. 29(*ii*)

* Loading error *after* refurbishment. First 9700 flights, maximum negative load −1·2 g. Result not used for comparisons.
† Machining error necessitated use of 11·3 mm diameter bush.

TABLE 2(p)

Parallel SLAN rivet holes: 0·125 inch diameter 2117 SLAN rivets, specimens part-fatigued, refurbished under factory conditions using 0·3% interference-fit bushes of Type 304 stainless steel and modified gang-nut/SLAN assembly

Specimen No.	Specimen details	Refurbishment			Total flights to failure	Failing load (kN)	Failure details
		Flights before refurbishment	Crack length (mm)	Flights after refurbishment			
GZ3A12	11 mm bush in hole (1) (bush internal diameter to suit 8·6 mm bolt). 13 mm bushes in holes (5), (6), (8) and (9) (bush internal diameter to suit 10·6 mm bolt). Holes brush alodined and bushes passivated prior to fitting. Holes (2) and (3) cold-expanded to 4 mm by Boeing process and filled with close-fit 2117 aluminium alloy rivets. Holes (4), (7) and (10) reamed to 4 mm diameter and filled. Fuel sealant applied during assembly. 8·6 mm bolts torqued to 12·2 Nm, 10·6 mm bolts torqued to 27·1 Nm	2000	NCI	15262	17262	342	Cracks both sides hole (1), small cracks at holes (2) and (3)
GZ3D7	As above	2000	NCI	10550	12550	342	As above
GZ3B9	As above	2000	2·5	11142	13142	324	As above, see Fig. 30(*i*)
GZ3D4	As above	2000	NCI	5762*	7762	291	As above

TABLE 2(p) (Continued)

Specimen No.	Specimen details	Refurbishment			Total flights to failure	Failing load (kN)	Failure details
		Flights before refurbishment	Crack length (mm)	Flights after refurbishment			
GZ3D12	13 mm bush in hole (1) (bush internal diameter to suit 8·6 mm bolt). 15 mm bushes in holes (5), (6), (8) and (9) (bush internal diameter to suit 10·6 mm bolt). Holes brush alodined and bushes passivated prior to fitting. Holes (2) and (3) cold-expanded to 4 mm by Boeing process and filled with close-fit 2117 aluminium alloy rivets. Holes (4), (7) and (10) reamed to 4 mm diameter and fiilled. Fuel sealant applied during assembly. 8·6 mm bolts torqued to 12·2 Nm, 10·6 mm bolts torqued to 27·1 Nm	2000	NCI	5446	7446	313	Large cracks both sides hole (2), crack rear side hole (1), very small cracks hole (3)
GZ3D5	As above	2000	2·5	5623	7623	316	As above
GZ3B10	As above	2000	NCI	5640	7640	324	As above
GZ3B1	As above	2000	NCI	6442	8442	342	As above

NCI = Nil Crack Indications.

* Bell-mouthed hole resulted in no bush interference. Result rejected.

TABLE 3

Summary of fatigue test results—parallel SLAN rivet hole specimens

	Table	Specimen type	Log. average (flights)	No. in sample	s.d. log. life
A. CONTROL					
(1)	2(*a*)	2·5 mm A-U4G SLAN rivets	7309	6	0·055
(2)	2(*c*)	3·0 mm A-U4G SLAN rivets	6852	11	0·117
(3)	2(*d*)	0·125 inch 2117 SLAN rivets	8213	13	0·085
B. REAMED OVERSIZE BOLT HOLES (2·5 mm SLAN RIVETS)					
(4)	2(*e*)	Hole (1) 9 mm diameter	6947	2	0·009
(5)	2(*e*)	Hole (1) 10 mm diameter	4388	4	0·119
(6)	2(*e*)	Hole (1) 11 mm diameter	4183	3	0·039
(7)	2(*e*)	Hole (1) 12 mm diameter	2742	2	0·000
C. REAMED OVERSIZE BOLT HOLES (0·125 inch SLAN RIVETS)					
(8)	2(*f*)	Hole (1) 9 mm diameter	5676	2	0·048
(9)	2(*f*)	Hole (1) 10 mm diameter	4844	2	0·175
(10)	2(*f*)	Hole (1) 11 mm diameter	4156	2	0·064
D. 4130 STEEL INTERFERENCE BUSHES (2·5 mm SLAN RIVETS)					
(11)	2(*g*)	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9)	12854	3	0·072
(12)	2(*g*)	12 mm bush in hole (1). 14 mm bushes in holes (5), (6), (8) and (9)	9287	2	0·044
(13)	2(*g*)	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9)	9651	2	0·082
(14)	2(*g*)	14 mm bush in hole (1). 16 mm bushes in holes (5), (6), (8) and (9)	4214	2	0·046
E. 4130 STEEL INTERFERENCE BUSHES (0·125 inch SLAN RIVETS)					
(15)	2(*h*)	9 mm bush in hole (1). 11 mm bushes in holes (5), (6), (8) and (9)	17912	2	0·101
(16)	2(*h*)	10 mm bush in hole (1). 12 mm bushes in holes (5), (6), (8) and (9)	14162	3	0·089
(17)	2(*h*)	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9)	11545	4	0·062
(18)	2(*h*)	11 mm bush in hole (1). 16 mm bush in hole (5). 13 mm bushes in holes (6), (8) and (9)	14931	4	0·091
(19)	2(*h*)	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9)	11016	3	0·158
F. TYPE 304 STAINLESS STEEL INTERFERENCE BUSHES (0·125 inch SLAN RIVETS)					
(20)	2(*i*)	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9)	11839	4	0·016
(21)	2(*i*)	13 mm bush in hole (1). 15 mm bushes in holes (5), (6), (8) and (9)	7452	2	0·015

TABLE 3 (Continued)

	Table	Specimen type	Log. average (flights)	No. in sample	s.d. log. life
G. 4130 STEEL INTERFERENCE BUSHES, REWORKED SLAN RIVET HOLES					
(22)	2(*j*)	13 mm bush in hole (1). Hole (2) reamed to 4 mm and 0·156 inch rivet fitted	3690	2	0·086
(23)	2(*j*)	13 mm bush in hole (1). Hole (2) cold-expanded to 4 mm and 0·156 inch rivet fitted	6445	2	0·194
H. 4130 STEEL INTERFERENCE BUSHES, REWORKED SLAN RIVET HOLES AND MODIFIED GANG-NUT/SLAN ASSEMBLY					
(24)	(2*k*)	11 mm bush in hole 1. Hole (2) reamed to 4 mm and left open	8312	2	0·028
(25)	2(*k*)	11 mm bush in hole (1). Hole (2) reamed to 4 mm and 2117 rivet fitted	11231	2	0·043
(26)	2(*k*)	11 mm bush in hole 1. Hole (2) cold-expanded to 4 mm and 2117 rivet fitted	12910	2	0·102
(27)	2(*k*)	13 mm bush in hole (1). Hole (2) reamed to 4 mm and 2117 rivet fitted	11182	2	0·232
(28)	2(*k*)	13 mm bush in hole (1). Hole (2) cold-expanded to 4 mm and 2117 rivet fitted	7956	2	0·111
I. COLD-EXPANDED BOLT HOLES (3·6%). (2·5 mm SLAN RIVETS)					
(29)	2(*l*)	All bolt holes 11·1 mm diameter. Oversize (sleeved) bolts	5644	2	0·072
(30)	2(*l*)	All bolt holes 11·1 mm diameter. 0·3% interference bushes inserted	7036	2	0·026
(31)	2(*l*)	All bolt holes 11·1 mm diameter. 0·1% interference bushes inserted	6692	2	0·005
J. COLD-EXPANDED BOLT HOLES (2·7%), ALL RIVET HOLES REWORKED AND MODIFIED GANG-NUT/SLAN ASSEMBLY					
(32)	2(*m*)	Hole (1) cold-expanded to 8·6 mm, all rivet holes cold-expanded to 3·66 mm and left open	11491	2	0·008
(33)	2(*m*)	Hole (1) cold-expanded to 8·6 mm, all rivet holes cold-expanded to 3·66 mm. SLAN rivet holes filled	8024	2	0·080
(34)	2(*m*)	Hole (1) cold-expanded to 10·3 mm, all rivet holes cold-expanded to 3·66 mm and left open	7566	2	0·035
(35)	2(*m*)	Hole (1) cold-expanded to 10·3 mm, all rivet holes cold-expanded to 3·66 mm, SLAN rivet holes filled	7498	2	0·004
K. HOLE (1) BUSHED, OTHER BOLT HOLES COLD-EXPANDED. ALL RIVET HOLES REWORKED AND MODIFIED GANG-NUT/SLAN ASSEMBLY					
(36)	2(*n*)	10·3 mm bush in hole (1). All rivet holes cold-expanded to 3·66 mm and left open*	14786	2	0·256
(37)	2(*n*)	10·3 mm bush in hole (1). All rivet holes cold-expanded to 3·66 mm, SLAN rivet holes filled	17150	1	—

TABLE 3 (Continued)

	Table	Specimen type	Log. average (flights)	No. in sample	s.d. log. life
L. SPECIMENS PART-FATIGUED, REFURBISHED WITH BOLT HOLES BUSHED (4130 STEEL) SLAN RIVETS UNDISTURBED AND MODIFIED GANG-NUT/SLAN ASSEMBLY					
(38)	2(*o*)	13 mm bush in hole (1). LIFE AFTER REFURBISHMENT	8768	4	0·072
(38a)	2(*o*)	13 mm bush in hole (1). TOTAL LIFE	12296	4	0·023
(39)	2(*o*)	11·3 mm bush in hole (1). LIFE AFTER REFURBISHMENT	10942	1	—
(39a)	2(*o*)	11·3 mm bush in hole (1). TOTAL LIFE	13842	1	—
M. PART-FATIGUED, REFURBISHED WITH BOLT HOLES BUSHED (304 STAINLESS STEEL) RIVET HOLES COLD-EXPANDED, RIVETS FITTED, MODIFIED GANG-NUT SLAN/ASSEMBLY, FULL SEALANT TREATMENT					
(40)	2(*p*)	11 mm bush in hole (1). LIFE AFTER REFURBISHMENT	12151	3	0·087
(40a)	2(*p*)	11 mm bush in hole (1). TOTAL LIFE	14173	3	0·075
(41)	2(*p*)	13 mm bush in hole (1). LIFE AFTER REFURBISHMENT	5775	4	0·032
(41a)	2(*p*)	13 mm bush in hole (1). TOTAL LIFE	7779	4	0·024

* Failed through hole (9), inserted for comparative purposes only, not used in analysis.

TABLE 4

Parallel SLAN rivet holes: Pooled results covering different treatments of bolt hole (1)

	Tables pooled	Specimen type	Log. average (flights)	No. in sample	s.d. log. life
A. CONTROL					
(1)	2(*a*) 2(*c*) 2(*d*)	All control specimens	7508	30	0·098
(2)	2(*a*) 2(*d*)	0·125 inch and 2·5 mm SLAN rivet specimens only	7916	19	0·079
B. REAMED OVERSIZE BOLT HOLES					
(3)	2(*e*) 2(*f*)	Hole (1) 9 mm diameter. (2·5 mm and 0·125 inch SLAN rivets)	6279	4	0·058
(4)	2(*e*) 2(*f*)	Hole (1) 10 mm diameter. (2·5 mm and 0·125 inch SLAN rivets)	4535	6	0·123
(5)	2(*e*) 2(*f*)	Hole (1) 11 mm diameter. (2·5 mm and 0·125 inch SLAN rivets)	4172	5	0·043
(6)	2(*e*)	Hole (1) 12 mm diameter. (2·5 mm SLAN rivets only)	2742	2	0·000
C. INTERFERENCE-FIT BUSHES					
(7)	2(*h*)	9 mm bush in hole (1). (4130 bushes, 0·125 inch SLAN rivets only)	17912	2	0·101
(8)	2(*h*)	10 mm bush in hole (1). (4130 bushes, 0·125 inch SLAN rivets only)	14162	3	0·089
(9)	2(*g*) 2(*h*) 2(*i*)	11 mm bush in hole (1). (4 groups pooled)	12718	15	0·075
(10)	2(*g*)	12 mm bush in hole (1). (4130 bushes, 2·5 mm SLAN rivets only)	9287	2	0·044
(11)	2(*g*) 2(*h*) 2(*i*)	13 mm bush in hole (1). (3 groups pooled)	9486	7	0·124
(12)	2(*g*)	14 mm bush in hole (1). (4130 bushes, 2·5 mm SLAN rivets only)	4214	2	0·046
D. BOLT HOLES COLD-EXPANDED					
(13)	2(*l*)	Hole (1) cold-expanded (3·6%) to 11·1 mm diameter	5644	2	0·072
(14)	2(*m*)	Hole (1) cold-expanded (2·7%) to 8·6 mm diameter	9602	4	0·101
(15)	2(*m*)	Hole (1) cold-expanded (2·7%) to 10·3 mm diameter	7532	4	0·021

TABLE 5(a)

Inclined SLAN rivet holes: TYPE 1 specimens, control tests

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GK1F9	Hole (1) 8 mm diameter	6940	338	Large crack rear side hole (1), crack forward side hole (1), small cracks at hole (2)
GK1E6	As above	8250	348	As above. See Fig. 32(*a*)(*i*)

TABLE 5(b)

Inclined SLAN rivet holes: TYPE 2 specimens, control tests

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GN20	Hole (1) 8 mm diameter	9442	385	Large crack rear side hole (1), crack forward side hole (1), small cracks both sides of holes (2) and (3)
GN1M	As above	6642	396	As above. See Fig. 32(*a*)(*ii*)
GT30	As above	5887	336	As above

TABLE 5(c)

Inclined SLAN rivet holes: TYPE 3 specimens, control tests

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GN2K	Hole (1) 8 mm diameter	7865	349	Large crack rear side hole (1), crack forward side hole (1), large cracks at hole (2), small cracks hole (3). See Fig. 32(*b*)(*i*)
GN1F	As above	7438	312	As above
GT2L	As above	8460	342	Large crack rear side hole (1), crack forward side hole (1), cracks at holes (2) and (3)

TABLE 5(d)

Inclined SLAN rivet holes: TYPE 4 specimens, control tests

Specimen No.	*Specimen* details	Flights to failure	Failing load (kN)	Failure details
GZ3A5	Hole (1) 8 mm diameter	6050	347	Large crack rear side hole (1), crack forward side hole (1), cracks both sides hole (2)
GZ3D3	As above	6246	328	As above
GZ2A6	As above	3142	378	As above. See Fig. 32(*b*)(*ii*)
GZ2D2	As above	8142	404	As above plus small cracks both sides hole (3)

TABLE 5(e)

Inclined SLAN rivet holes: TYPE 2 specimens, part-fatigued, refurbished with 0·3% interference-fit bushes of 4130 steel, reworked SLAN rivet holes, modified gang–nut/SLAN assembly, inspection slot in 'skin'

Specimen No.	Specimen details	Refurbishment			Total flights to failure	Failing load (kN)	Failure details
		Flights before refurbishment	Crack length (mm)	Flights after refurbishment			
GN1J	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) reamed to 3·62 mm diameter and left empty	2800	7·0†	2742	5542	396	Large cracks both sides hole (2), crack rear side hole (1) and forward side hole (3). See Fig. 33(*i*)
GN2P	As above	2000	8·0†	3642	5642	400	As above
GN1R*	As above	3800	8·0†	5542	9342	401	As above
GN2D	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) cold-expanded (1·8%) to 3·62 mm diameter and filled with 3·5 mm A-U4G aluminium alloy rivets	3200	7·0† 3·5‡	3779	6979	344	Cracks both sides of holes (1) and (2), small cracks both sides hole (3)
GN1K	As above	5200	8·5†	3042	8242	363	As above

TABLE 5(e) (Continued)

Specimen No.	Specimen details	Refurbishment			Total flights to failure	Failing load (kN)	Failure details
		Flights before refurbishment	Crack length (mm)	Flights after refurbishment			
GN2C	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) cold-expanded (1·8%) to 3·62 mm diameter and left empty	2600	7·0†	5042	7642	397	Cracks both sides of holes (1), (2) and (3)
GT2A	11 mm bush in hole (1) (bush internal diameter to suit 8·6 mm bolt). 13 mm bushes in holes (5), (6), (8) and (9), (bush internal diameter to suit 10·6mm bolt). Holes (2) and (3) cold-expanded (1·8%) to 3·62 mm diameter and left empty	2500	6·5†	5042	7542	384	Cracks both sides of holes (1) and (2), small cracks both sides hole (3). See Fig. 33(*ii*)
GT3E	As above	4500	7·5†	4219	8719	334	As above
GZ3A4	As above	4600	7·0† 5·5‡	4942	9542	373	Cracks both sides of holes (1), (2) and (3)

* Hole (2) oval—elongated in direction parallel to longitudinal axis of specimen.
† Crack length at rear side of hole.
‡ Crack length at forward side of hole.

TABLE 5(f)

Inclined SLAN rivet holes: TYPE 3 specimens, part-fatigued, reworked SLAN rivet holes, modified gang–nut/SLAN assembly, inspection slot in 'skin'

Specimen No.	Specimen details	Refurbishment			Total flights to failure	Failing load (kN)	Failure details
		Flights before refurbishment	Crack length (mm)	Flights after refurbishment			
GN1N	Hole (1) reamed to 8·6 mm diameter and close-fit bolt installed, 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) cold-expanded (3%) to 3·66 mm diameter and left empty	3400	8·0† 4·0‡	2350	5750	351	Large crack rear side hole (1), crack forward side hole (1), cracks both sides hole (2), small cracks hole (3). See Fig. 34(*i*)
GN2F	As above	3000	8·0† 5·0‡	2099	5099	348	As above
GN2M	8·6 mm 4130 steel 0·3% interference-fit bush, internal diameter to suit 6·3 mm bolt, in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) cold-expanded (3%) to 3·66 mm diameter and left empty	3600	8·5† 2·5‡	5000	8600	350	Large crack rear side hole (1,) cracks both sides hole (2)
GN1B	As above	4900	11·0† 7·5‡	3661	8561	344	As above plus small cracks hole (3)
GZ3C11	As above	4000	8·0† 4·0‡	8231	12231	325	Same as GN2M

TABLE (5f) (Continued)

Specimen No.	Specimen details	Refurbishment			Total flights to failure	Failing load (kN)	Failure details
		Flights before refurbishment	Crack length (mm)	Flights after refurbishment			
GZ3B8	8·6 mm 4130 steel 0·3% interference-fit bush, internal diameter to suit 6·3 mm bolt in hole (1). 13 mm bushes in hole (5), (6), (8) and (9). Holes (2) and (3) reamed to 3·66 mm diameter and left empty. Holes (4) and (7), (10) reamed to 4 mm diameter and filled with 2117 aluminium alloy rivets	3000	10·5†	5642	8642	403	Large crack rear of hole (1), cracks both sides hole (2), small cracks at hole (3). See Fig. 34(*ii*)
GN4N	As above	5500	9·0† 5·0‡	4381	9848	313	As above, except no cracks at hole (3)

† Crack length at rear side of hole.
‡ Crack length at forward side of hole.

TABLE 5(g)

Inclined SLAN rivet holes: TYPE 4 specimens, 0·3% interference-fit bushes of Type 304 stainless steel, reworked SLAN rivet holes, modified gang-nut/SLAN assembly

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GZ2C1	9 mm bush in hole (1), 6·5 mm stepped bolt used. 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) reamed to 4 mm diameter and left empty	7938	348	Large cracks both sides hole (2), large crack forward side hole (3), large crack rear side hole (1)
GZ3A9	As above	7440	345	As above. See Fig. 35(*i*)
GZ2A3	As above	9142	360	As above
GZ2B11	As above	5719	345	Large cracks both sides hole (2), large crack rear side hole (1), crack forward side hole (3)
GZ3B3	9 mm bush in hole (1), 6·5 mm stepped bolt used. 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) cold-expanded to 4 mm and and filled with 2117 aluminium alloy rivets	5507	343	Large cracks both sides hole (2), large crack rear side hole (1), crack forward side hole (3)
GZ2A10	As above	10542	378	As above
GZ3A1	As above	7540	343	Large cracks both sides hole (2), large crack rear side hole (1), small crack forward side hole (3)
GZ2C5	As above	6042	392	As above

TABLE 5(g) (Continued)

Specimen No.	Specimen details	Flights to failure	Failing load (kN)	Failure details
GZ2B8	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) reamed to 4 mm diameter and left empty	2375	347	Large cracks both sides hole (2), large crack rear side hole (1), crack forward side hole (3)
GZ3B2	As above	3613	342	As above
GZ2D12	As above	2123	345	As above
GZ3C5	As above	5942	391	Large cracks both sides hole (2), large crack forward side hole (3), small crack rear side hole (1). See Fig. 35(*ii*)
GZ3A6	11 mm bush in hole (1). 13 mm bushes in holes (5), (6), (8) and (9). Holes (2) and (3) cold-expanded to 4 mm and filled with 2117 aluminium alloy rivets	5177	345	Large cracks both sides hole (2), large crack rear side hole (1), small cracks hole (3)
GZ3D9	As above	3099	343	As above
GZ2B4	As above	2515	345	As above
GZ2C9	As above	3042	393	As above

TABLE 6

Summary of fatigue test results—inclined SLAN rivet hole specimens

	Table	Specimen type	Log. average (flights)	No. in sample	s.d. log. life
A. CONTROL					
(1)	5(*a*)	'TYPE 1'	7567	2	0·053
(2)	5(*b*)	'TYPE 2'	7174	3	0·107
(3)	5(*c*)	'TYPE 3'	7910	3	0·028
(4)	5(*d*)	'TYPE 4'	5576	4	0·176
B. 'TYPE 2' PART-FATIGUED, REFURBISHED, 11 mm BUSH IN HOLE (1)					
(5)	5(*e*)	SERIES 1: Holes (2) and (3) reamed to 3·62 mm and left open. LIFE AFTER REFURBISHMENT	3811	3	0·154
(5a)	5(*e*)	SERIES 1: TOTAL LIFE	6635	3	0·129
(6)	5(*e*)	SERIES 2: Holes (2) and (3) cold-expanded to 3·62 mm and filled. LIFE AFTER REFURBISHMENT	3391	2	0·067
(6a)	5(*e*)	SERIES 2: TOTAL LIFE	7584	2	0·051
(7)	5(*e*)	SERIES 4: Oversize bolts and holes (2) and (3) cold-expanded to 3·66 mm and left open. LIFE AFTER REFURBISHMENT	4720	3	0·042
(7a)	5(*e*)	SERIES 4: TOTAL LIFE	8561	3	0·052
(8)	5(*e*)	SERIES 4 plus SERIES 3: LIFE AFTER REFURBISHMENT	4798	4	0·037
(8a)	5(*e*)	SERIES 4 plus SERIES 3: TOTAL LIFE	8321	4	0·049

TABLE 6 (Continued)

	Table	Specimen type	Log. average (flights)	No. in sample	s.d. log. life
C. 'TYPE 3' PART-FATIGUED, REFURBISHED					
(9)	5(*f*)	SERIES 1: 8·6 mm bolt in hole (1). Holes (2) and (3) cold-expanded and left empty. LIFE AFTER REFURBISHMENT	2221	2	0·035
(9a)	5(*f*)	SERIES 1: TOTAL LIFE	5415	2	0·037
(10)	5(*f*)	SERIES 2: 8·6 mm bush in hole (1). Holes (2) and (3) cold-expanded and left empty. LIFE AFTER REFURBISHMENT	5321	3	0·177
(10a)	5(*f*)	SERIES 2: TOTAL LIFE	9657	3	0·089
(11)	5(*f*)	SERIES 3: 8·6 mm bush in hole (1). Holes (2) and (3) reamed and left empty. LIFE AFTER REFURBISHMENT	4953	2	0·080
(11a)	5(*f*)	SERIES 3: TOTAL LIFE	9225	2	0·040
D. 'TYPE 4' BUSHED—NOT PART-FATIGUED					
(12)	5(*g*)	9 mm bush in hole (1). Holes (2) and (3) reamed and left empty	7454	4	0·085
(13)	5(*g*)	9 mm bush in hole (1). Holes (2) and (3) cold-expanded and filled	7171	4	0·125
(14)	5(*g*)	11 mm bush in hole (1). Holes (2) and (3) reamed and left empty	3226	4	0·203
(15)	5(*g*)	11 mm bush in hole (1). Holes (2) and (3) cold-expanded and filled	3329	4	0·134

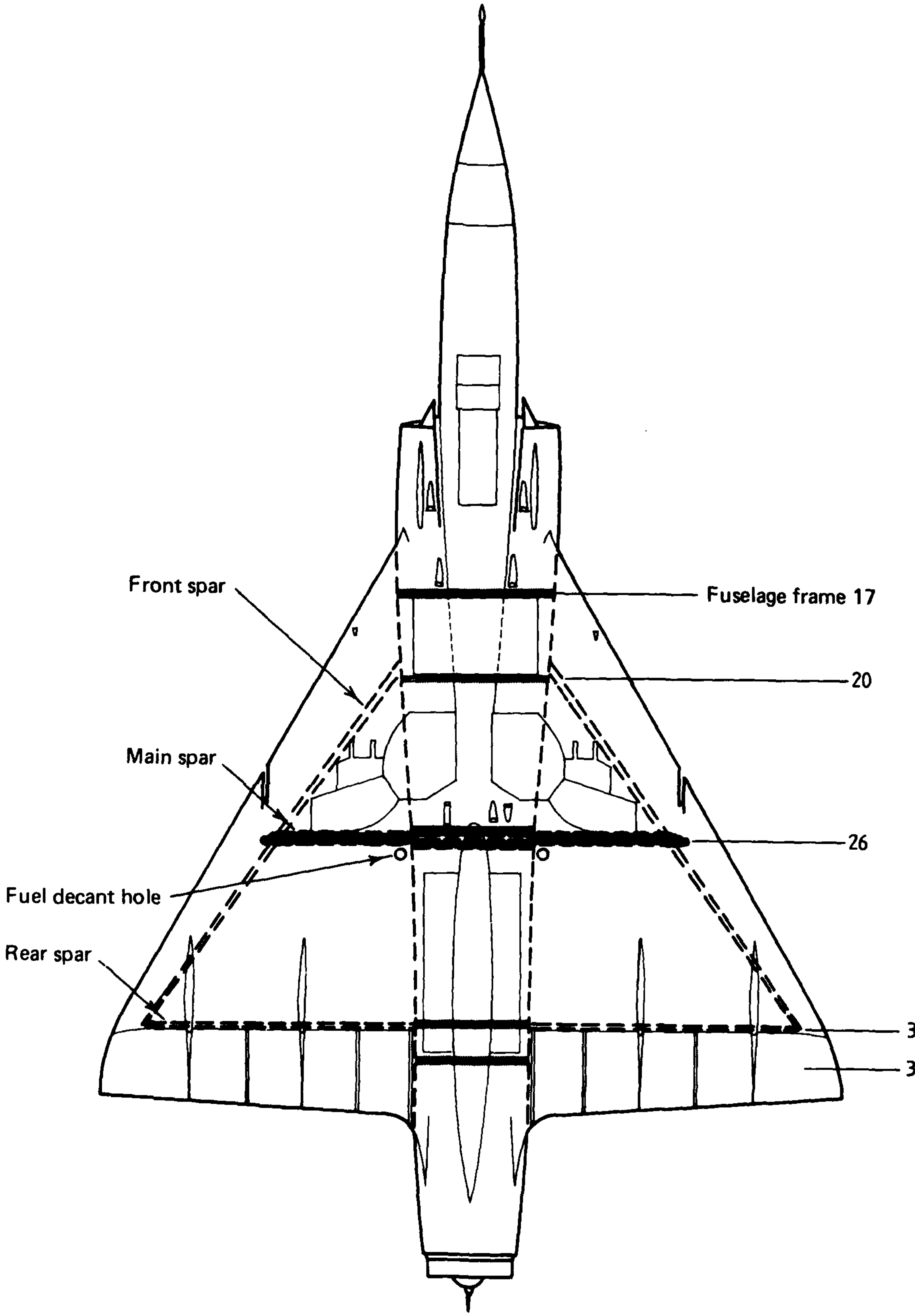


FIG. 1 MIRAGE III LOWER SURFACE SHOWING POSITIONS OF WING SPARS

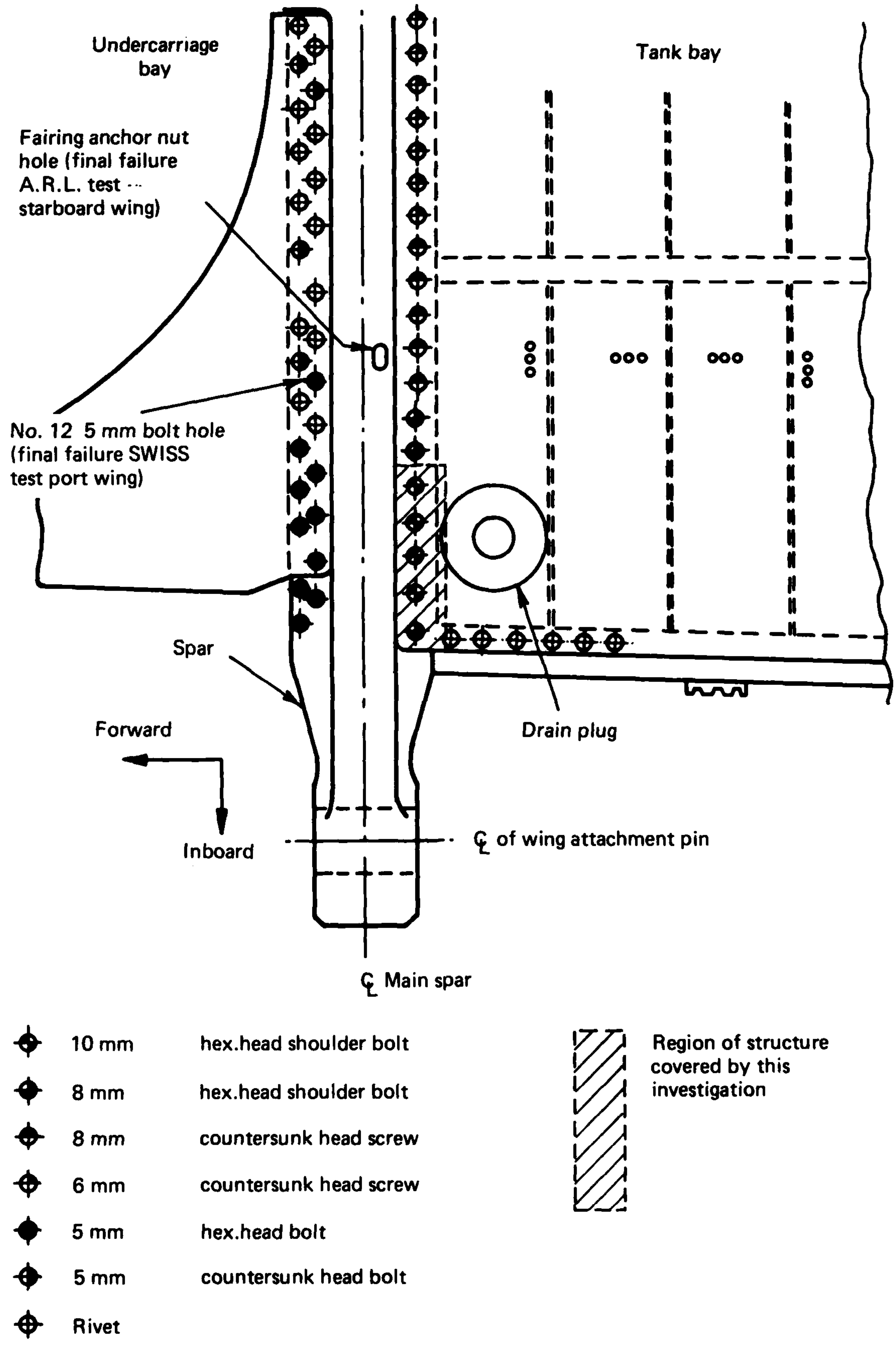
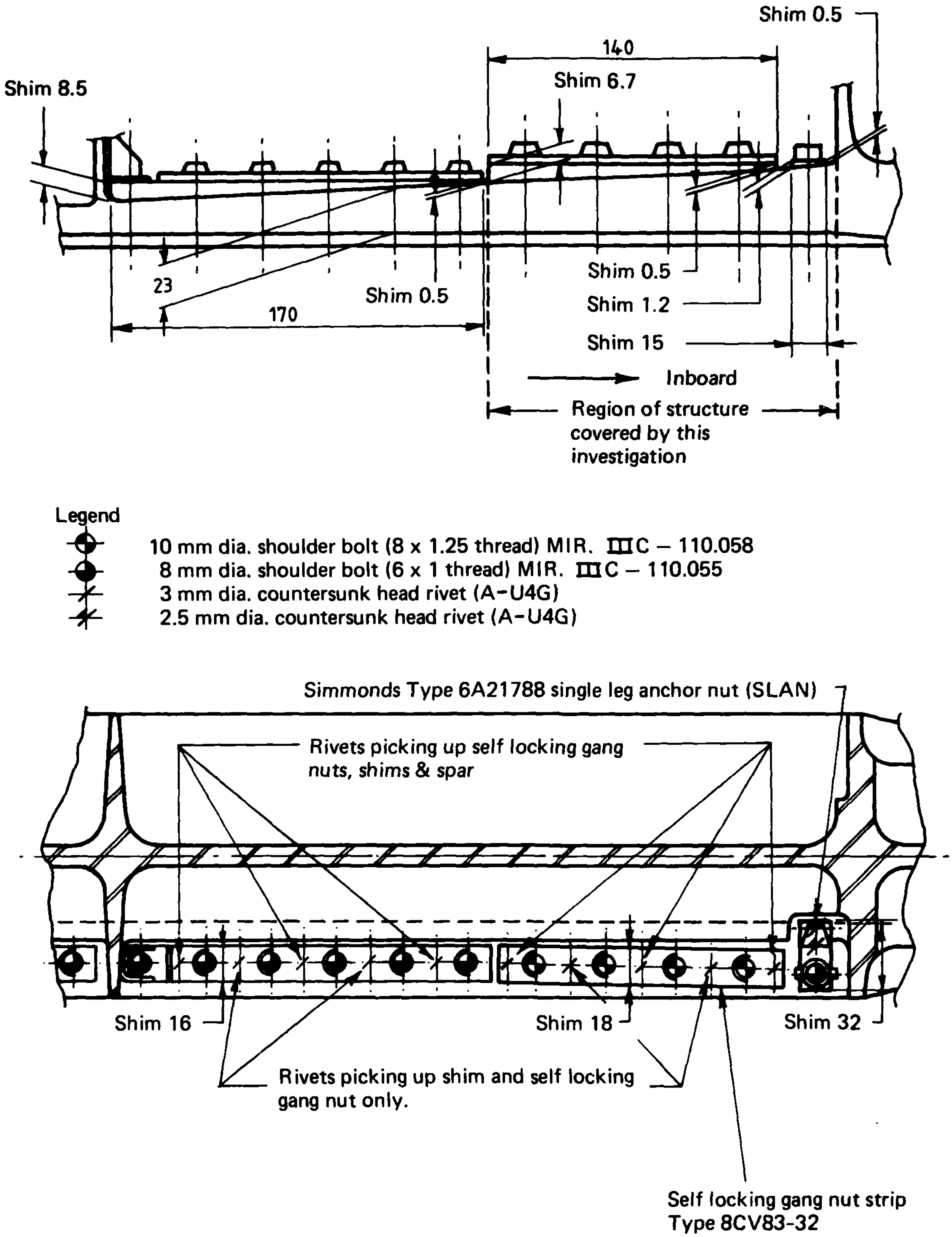


FIG. 2 MIRAGE PORT WING VIEWED FROM LOWER SURFACE



All dimensions in mm

Taken from AMD Manufacturing Drawing No. MIR.IIIE-113/2

FIG. 3 MAIN SPAR LOWER SURFACE, REAR FLANGE DETAIL.

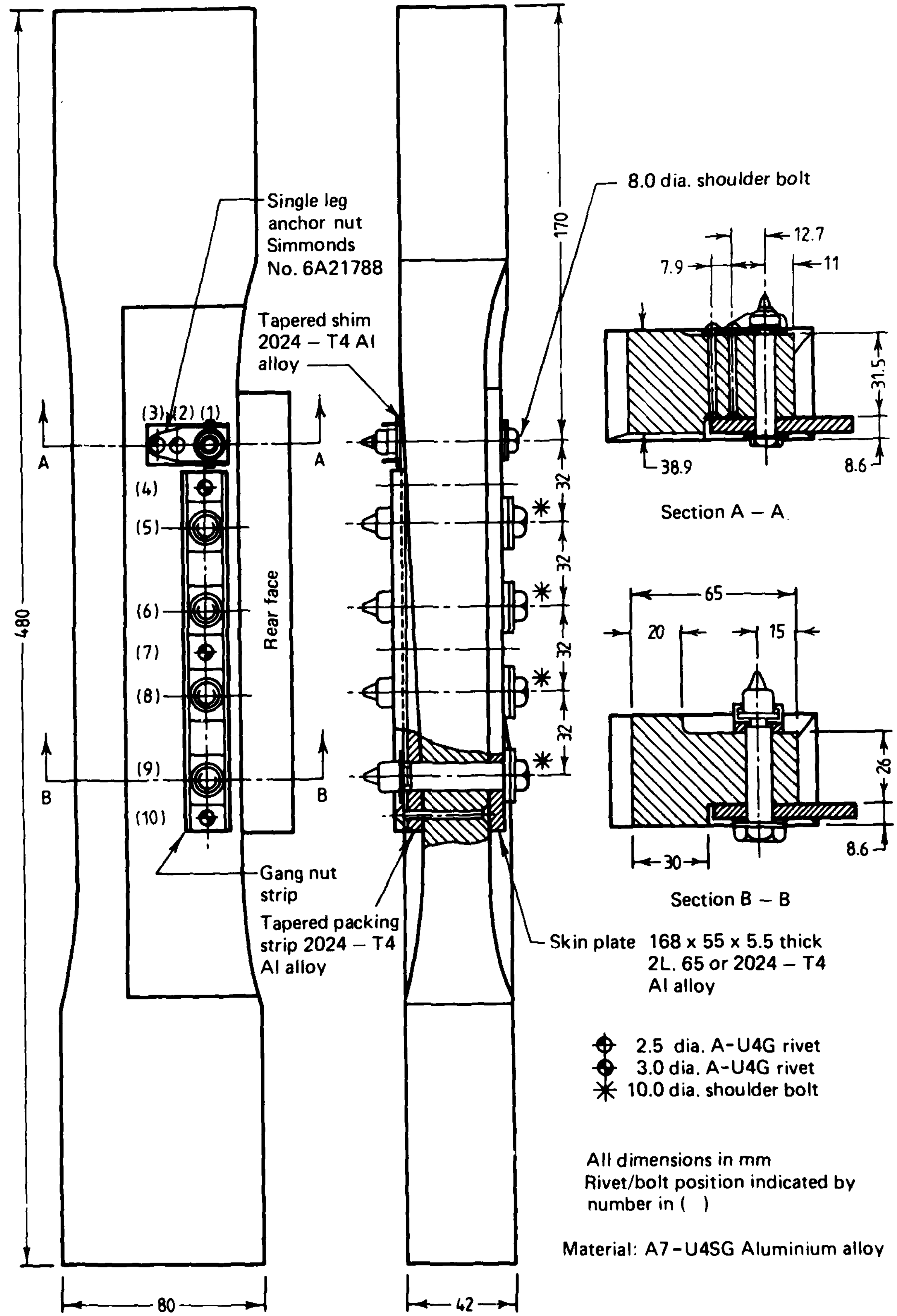


FIG. 4 MIRAGE SPAR LOWER REAR FLANGE FATIGUE SPECIMEN

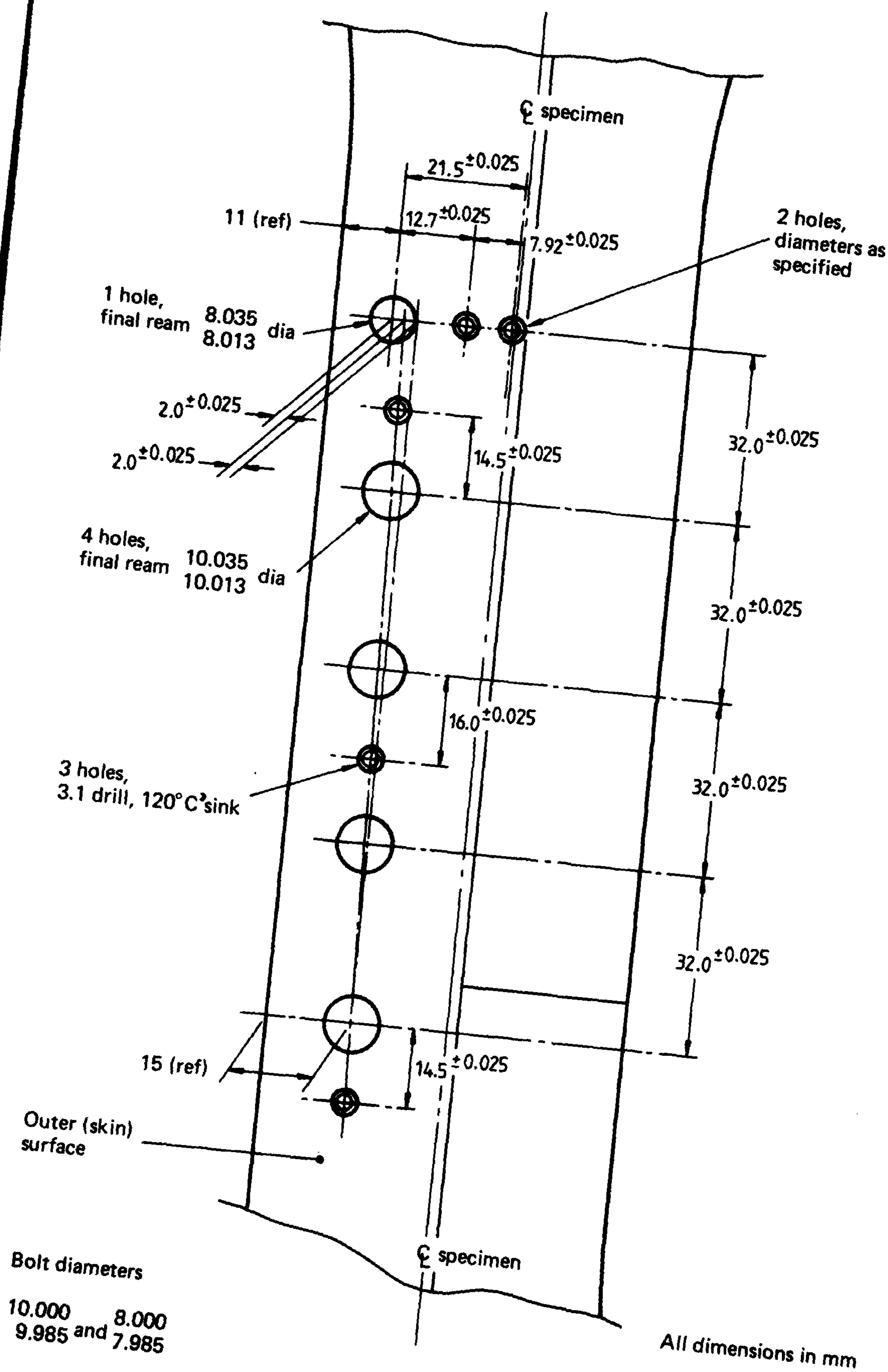


FIG. 5 RIVET AND BOLT HOLES AT TEST SECTION OF SPECIMEN

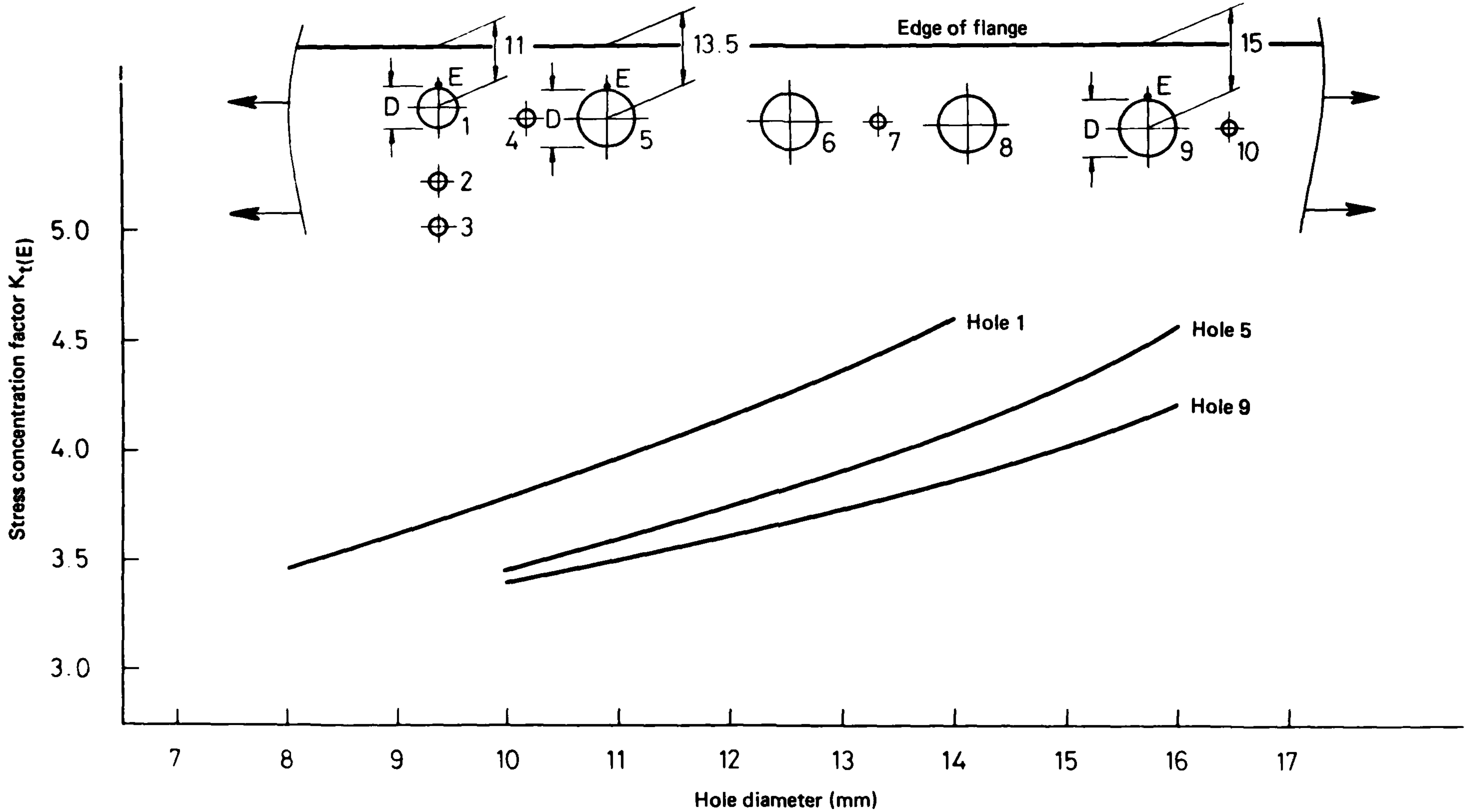


FIG. 6 STRESS CONCENTRATION FACTORS AT HOLES 1, 5 AND 9.

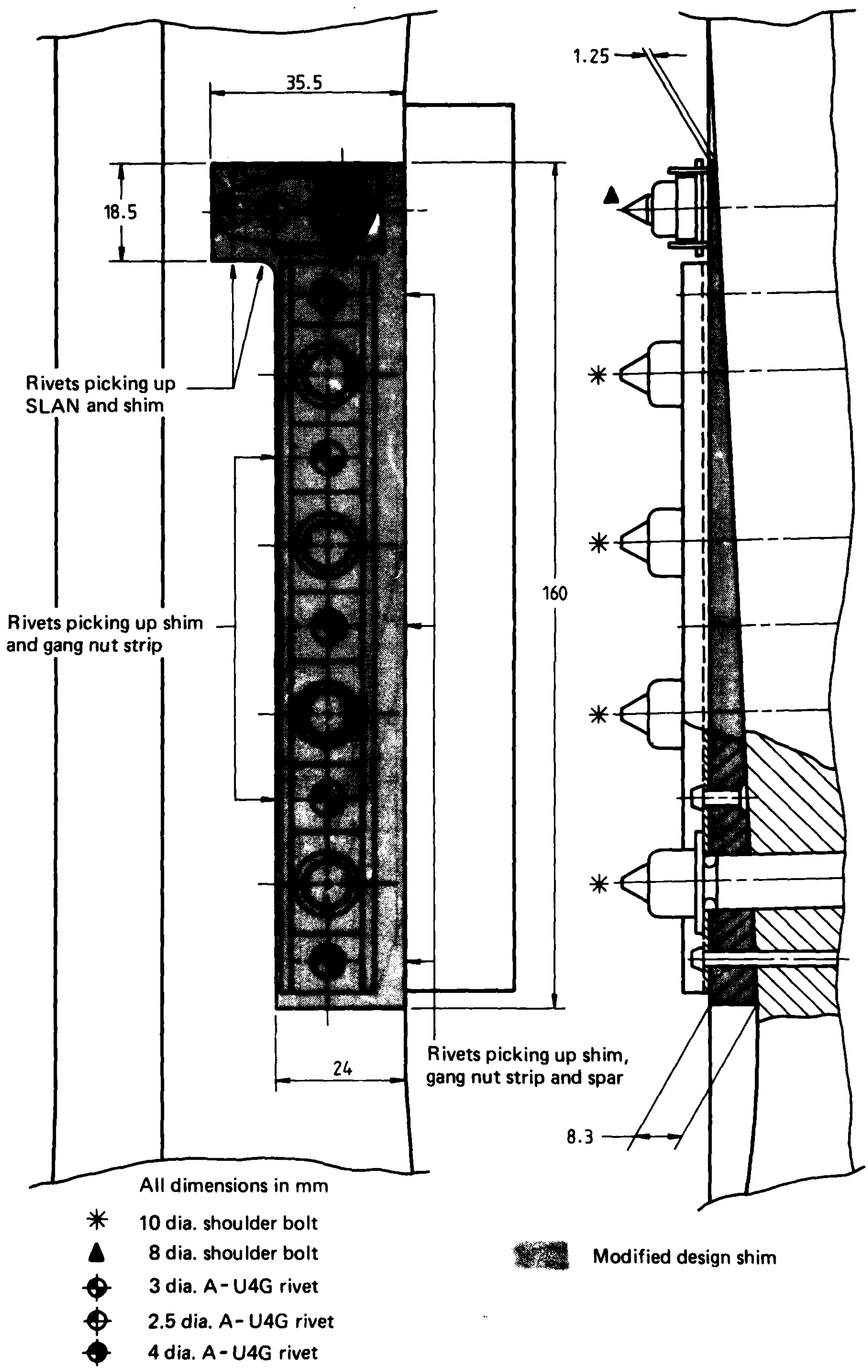


FIG. 7 MODIFIED GANG NUT STRIP/SLAN ASSEMBLY

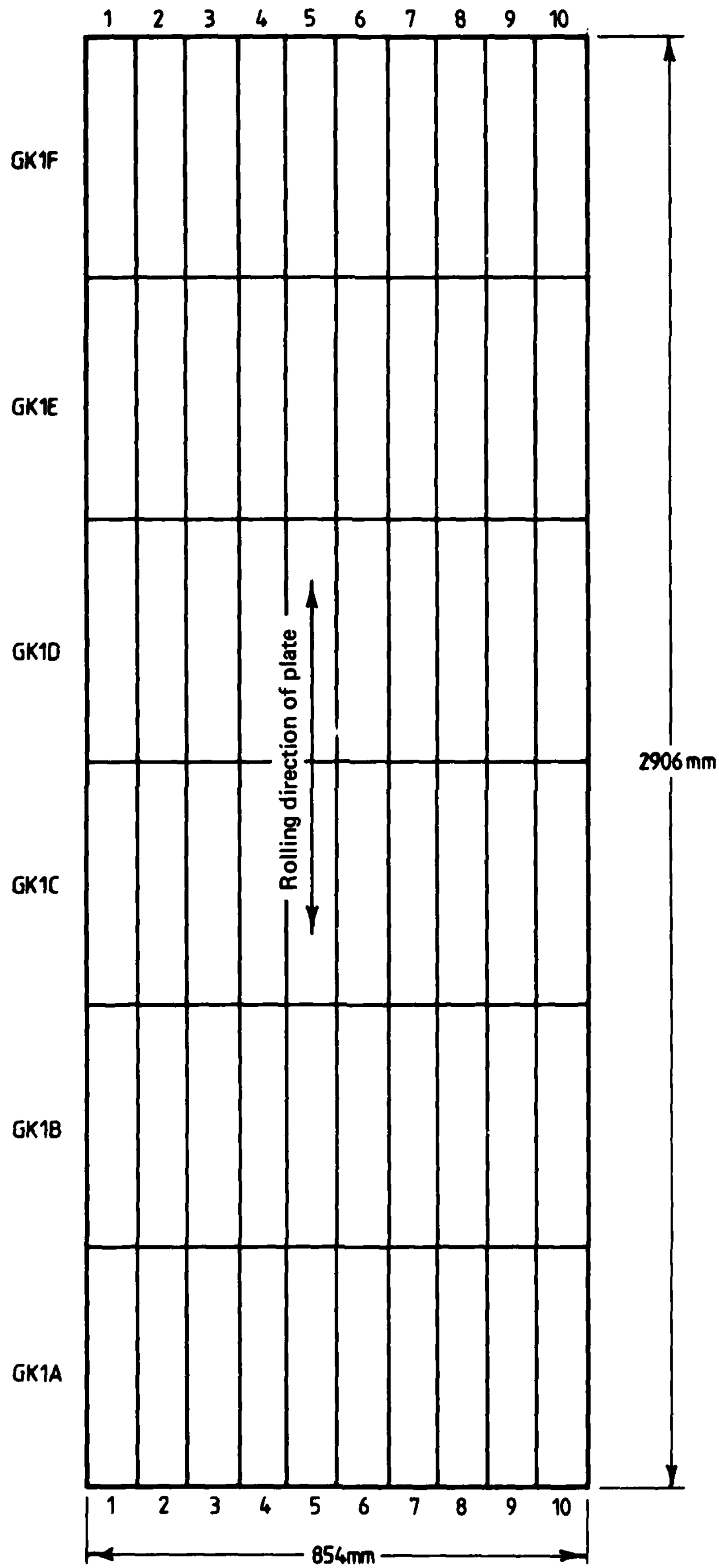


FIG. 8 FATIGUE SPECIMEN POSITIONS IN A7- U4SG PLATE (SERIAL NO. GK)

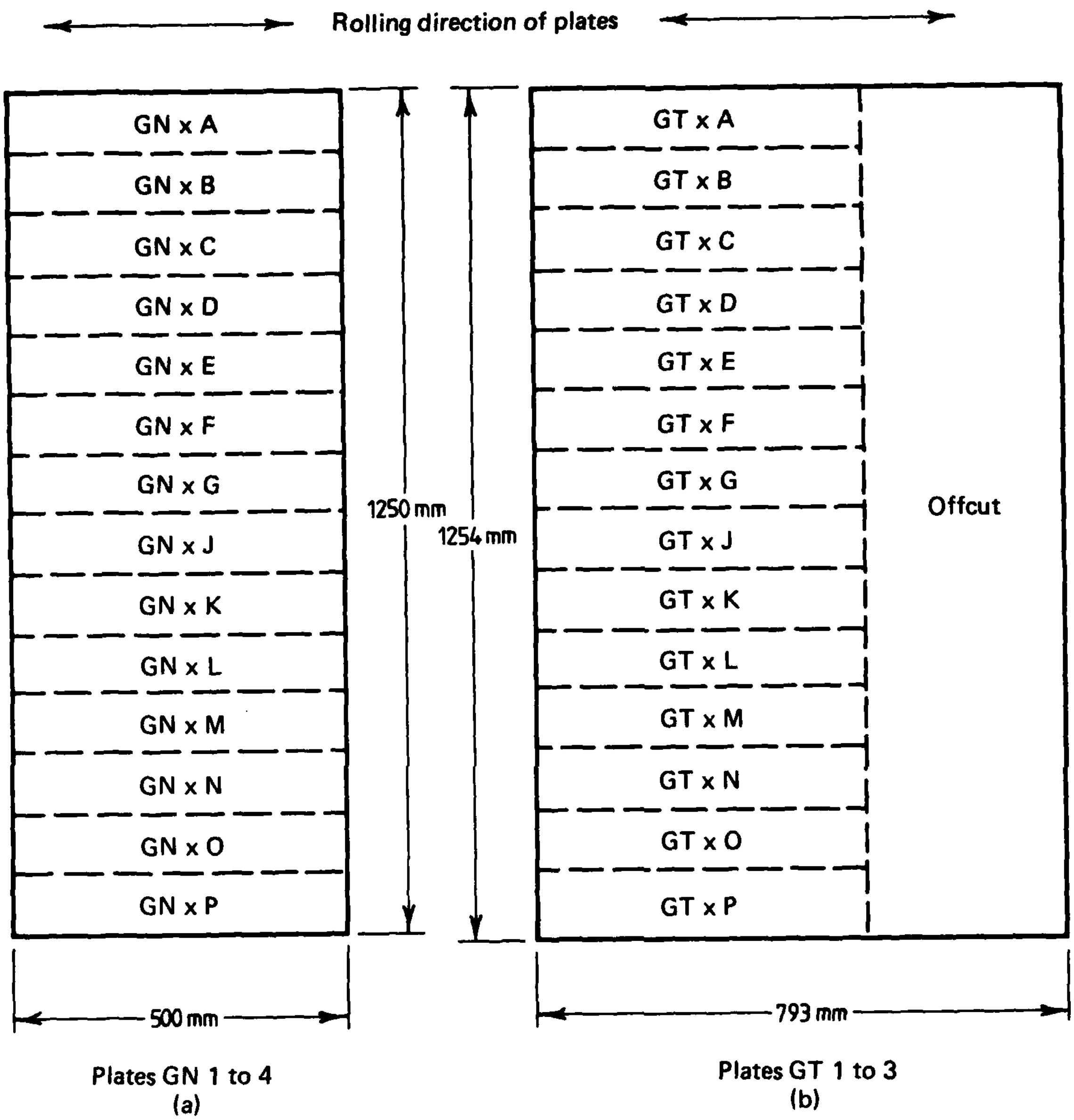


FIG. 9 FATIGUE SPECIMEN POSITIONS IN A7-U4SG PLATE SERIAL NOS. GN AND GT

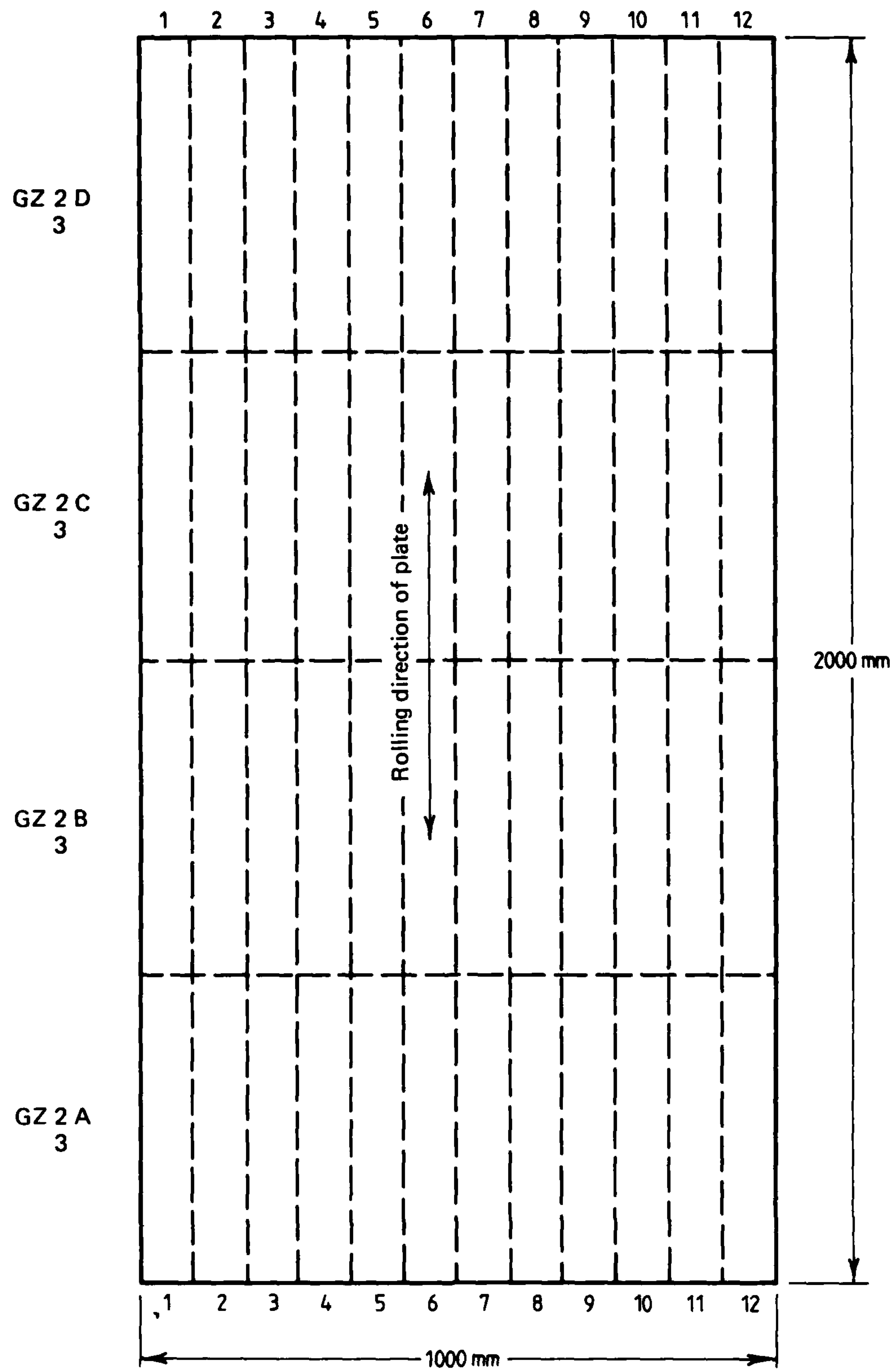


FIG. 10 FATIGUE SPECIMEN POSITIONS IN A7-U4SG PLATES SERIAL NOS. GZ2 AND GZ3

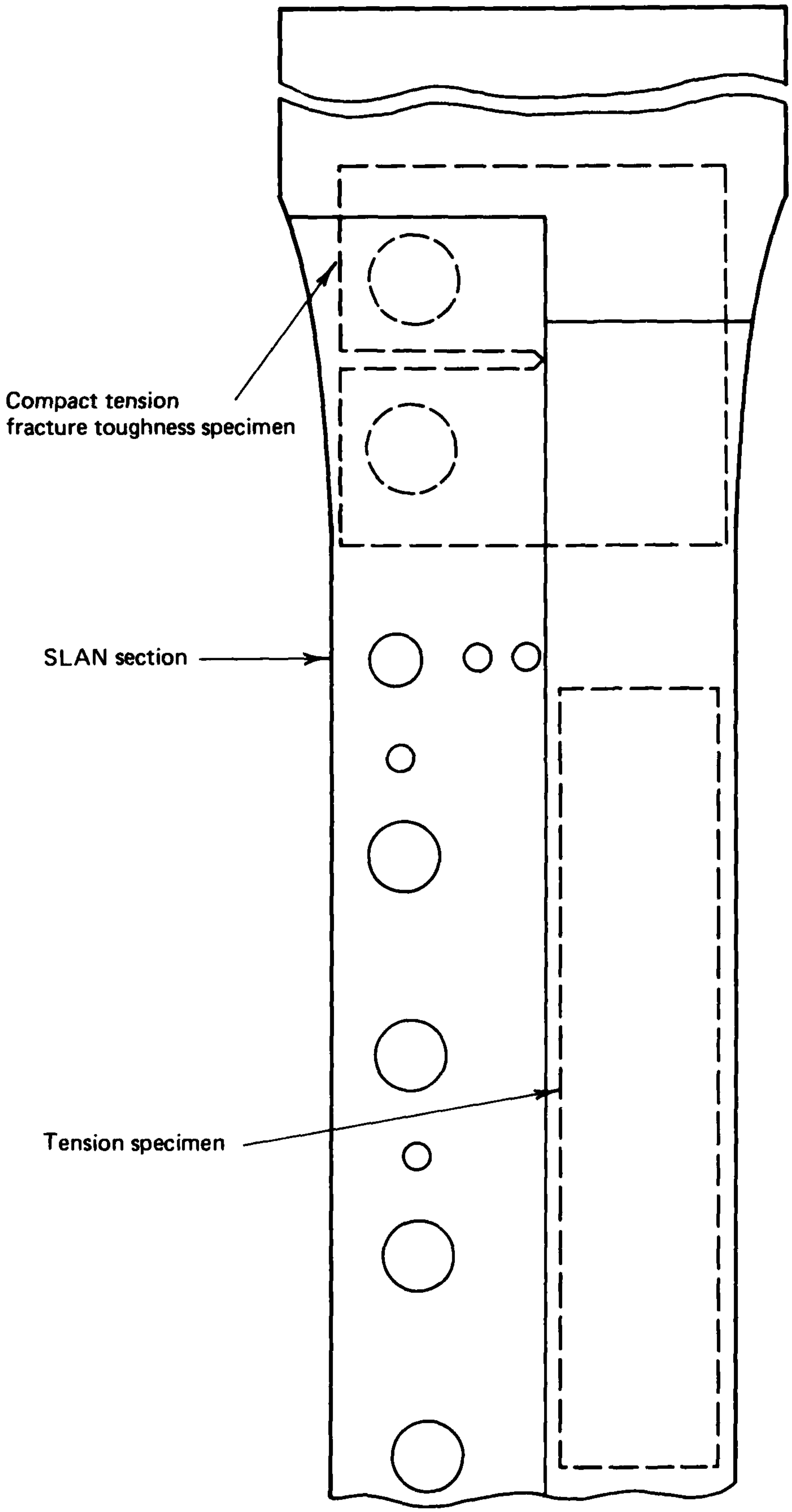


FIG. 11 LOCATIONS OF TENSION AND FRACTURE TOUGHNESS SPECIMENS

100 FLIGHTS (1989 CYCLES) REPRESENT 66.6 HOURS OF FLYING

FLIGHT A' →	10 CYCLES +3g/+1g	5 CYCLES +4g/+0.5g	2 CYCLES +5g/0g	1 CYCLE +6.5g/-1.5g	1 CYCLE +7.5g/-2.5g	1 CYCLE +6.5g/-1.5g	2 CYCLES +5g/0g	4 CYCLES +4g/+0.5g	10 CYCLES +3g/+1g
FLIGHT A →	10 CYCLES +3g/+1g	2 CYCLES +4g/+0.5g	2 CYCLES +5g/0g	2 CYCLES +6.5g/-1.5g	2 CYCLES +5g/0g	2 CYCLES +4g/+0.5g	5 CYCLES +3g/+1g		
FLIGHT B →	5 CYCLES +3g/+1g	5 CYCLES +4g/+0.5g	9 CYCLES +5g/0g	4 CYCLES +4g/+0.5g	5 CYCLES +3g/+1g				
FLIGHT C →	5 CYCLES +3g/+1g	1 CYCLE +4g/+0.5g	5 CYCLES +3g/+1g						

CYCLES OF +6.5g/-1.5g AND
+7.5g/-2.5g AT 1 Hz;
REMAINDER OF CYCLES AT 3 Hz

SEQUENCE OF FLIGHTS IN 100 FLIGHTS: 1 FLIGHT A', 18 FLIGHTS A, 36 FLIGHTS B AND 45 FLIGHTS C

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
B	C	C	B	C	C	C	A	C	C	B	B	A	C	C	C	B	A	C	B	B	B	A	C	C
51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
C	B	C	C	B	C	B	B	C	C	C	A	B	A	C	C	C	B	A	B	B	B	C	B	C

26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
C	A	A	C	C	B	B	B	C	B	A	B	C	C	B	A	A'	B	C	C	A	A	B	B	C
76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
C	A	B	C	B	A	B	C	C	B	A	A	B	C	C	B	C	C	B	B	C	B	C	A	C

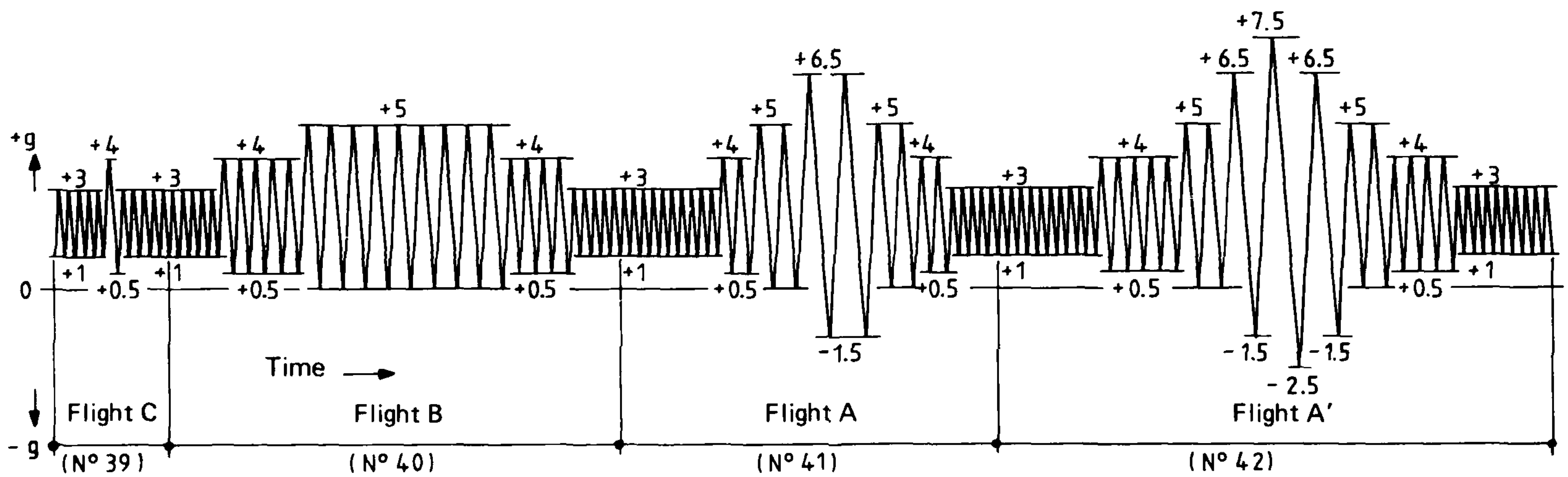


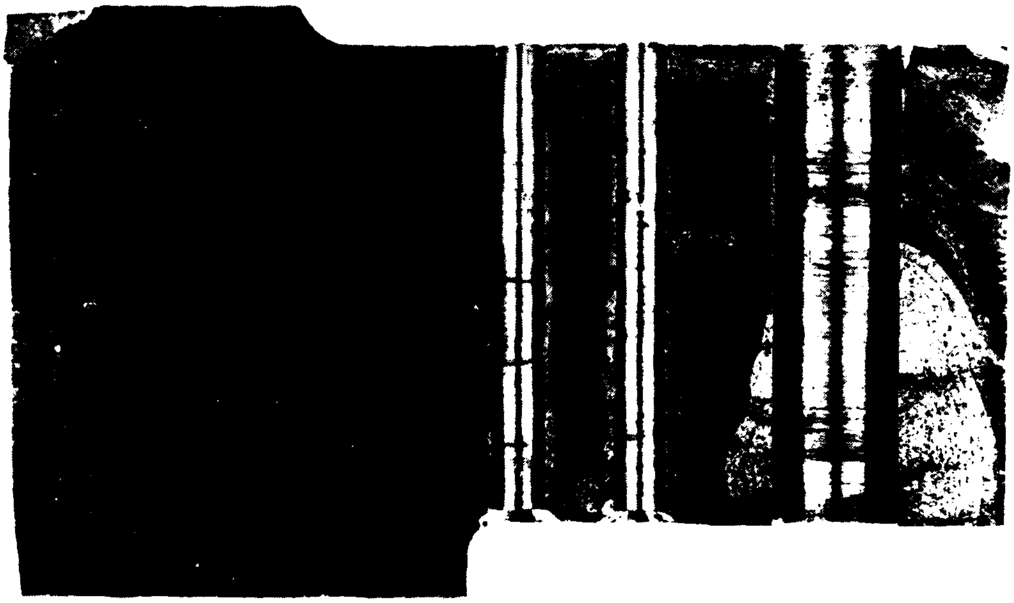
FIG. 12 FRENCH 100 FLIGHT MIRAGE III FLIGHT-BY-FLIGHT SEQUENCE

(i) GKIC6

(ii) GNIO

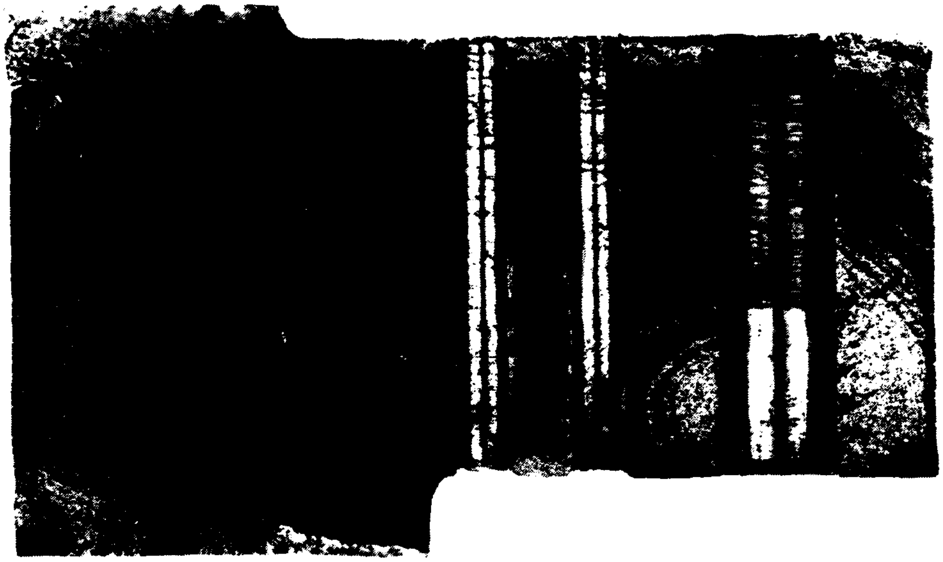
FIG. 13(a) PARALLEL SLAN RIVET HOLES CONTROL SPECIMENS WITH 2.5mm SLAN RIVETS

(i) GN2G

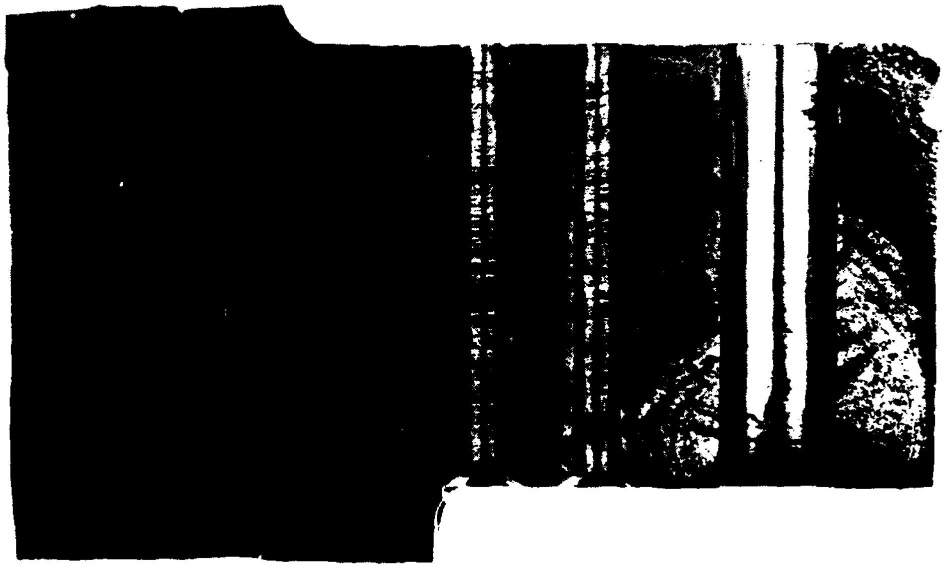


(ii) GN3A

FIG. 13(b) PARALLEL SLAN RIVET HOLES CONTROL SPECIMENS WITH 3.0mm SLAN RIVETS



(i) GK1D9



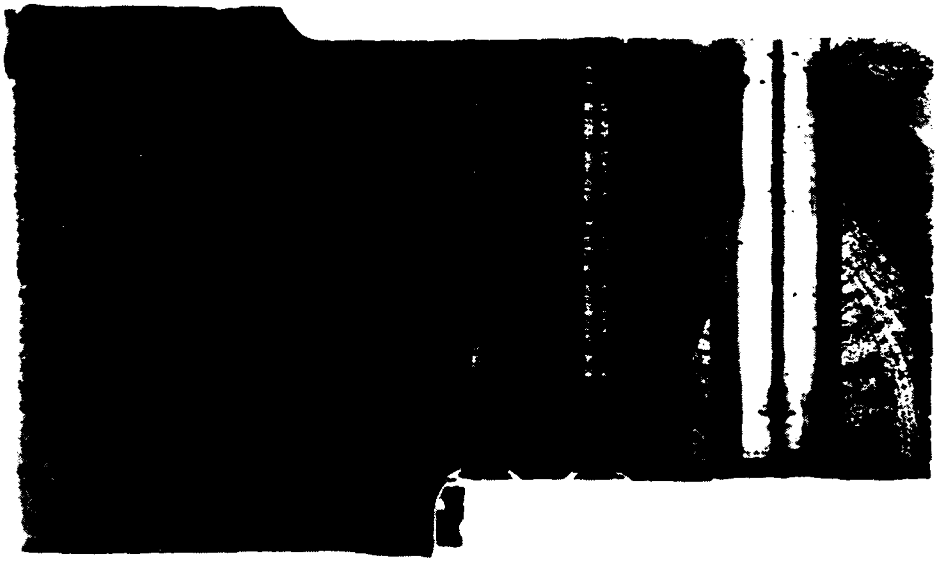
(ii) GZ3A10

FIG. 13(c) PARALLEL SLAN RIVET HOLES CONTROL SPECIMENS WITH 0.125 INCH SLAN RIVETS

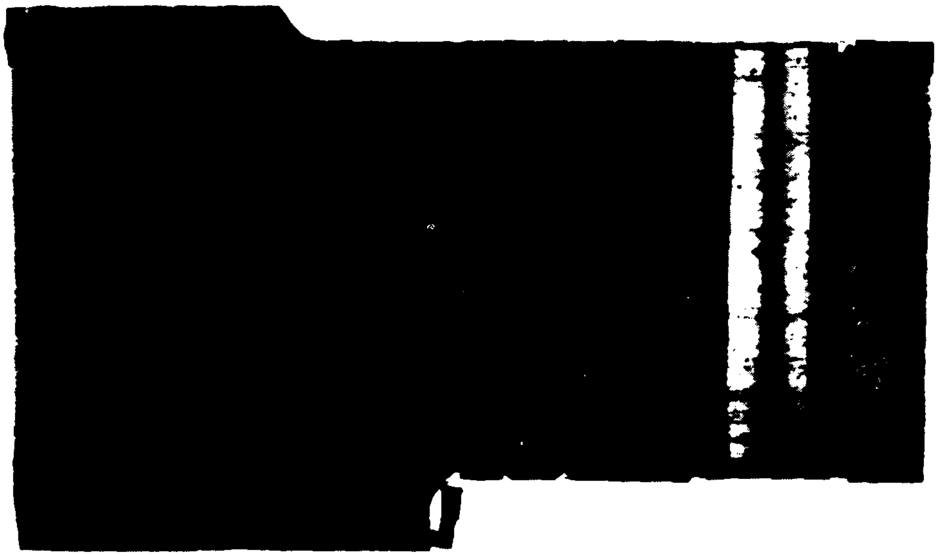
(i) GK1B6 Hole (1) 11mm diameter

(ii) GK1B10 Hole (1) 12mm diameter

FIG. 14(a) SPECIMENS WITH HOLE (1) REAMED OVERSIZE AND WITH 2.5mm SLAN RIVETS



(i) GT2E Hole (1) 9mm diameter



(ii) GT2N Hole (1) 11mm diameter

FIG. 14(b) SPECIMENS WITH HOLE (1) REAMED OVERSIZE AND WITH 0.125 INCH SLAN RIVETS

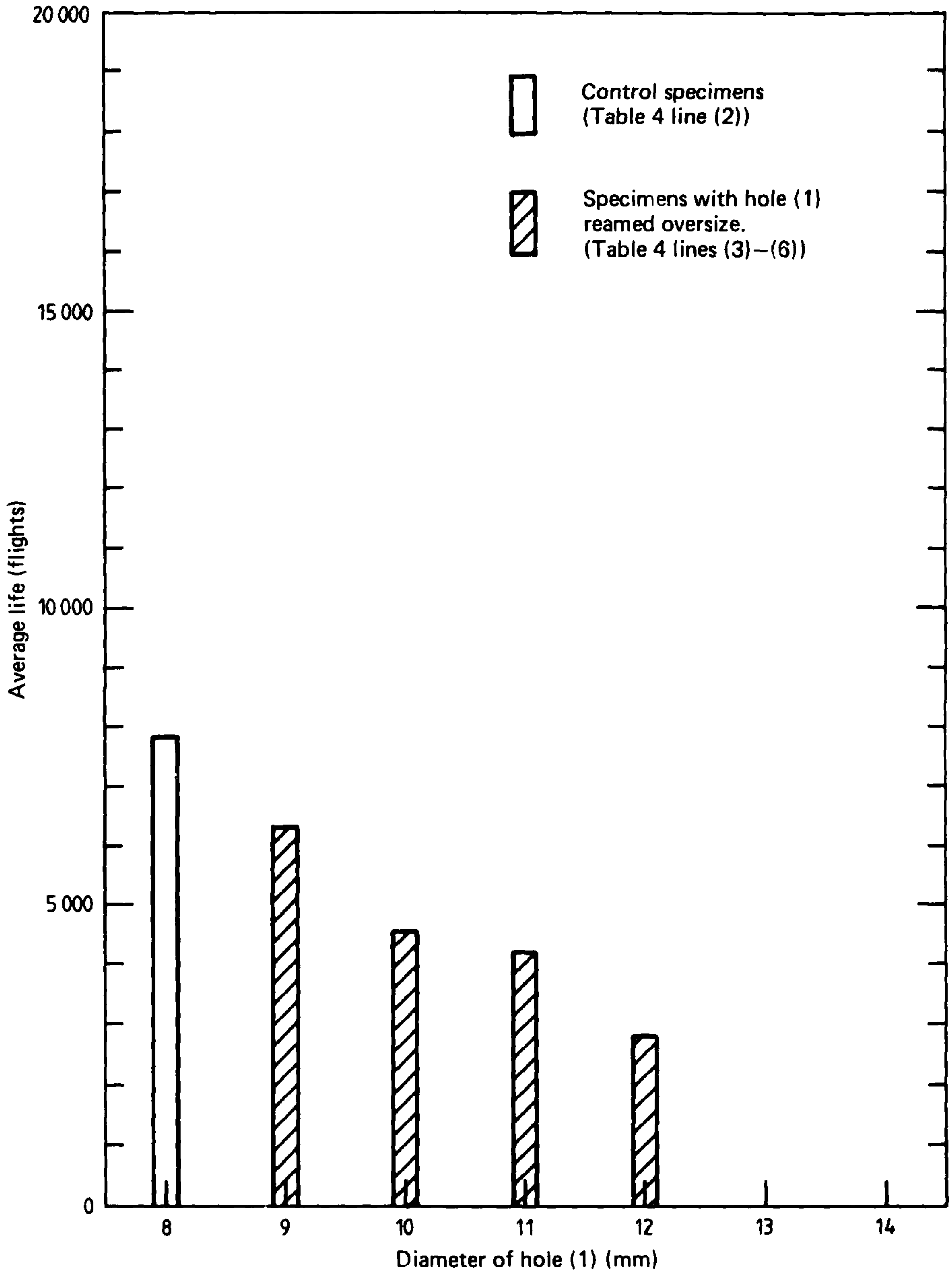
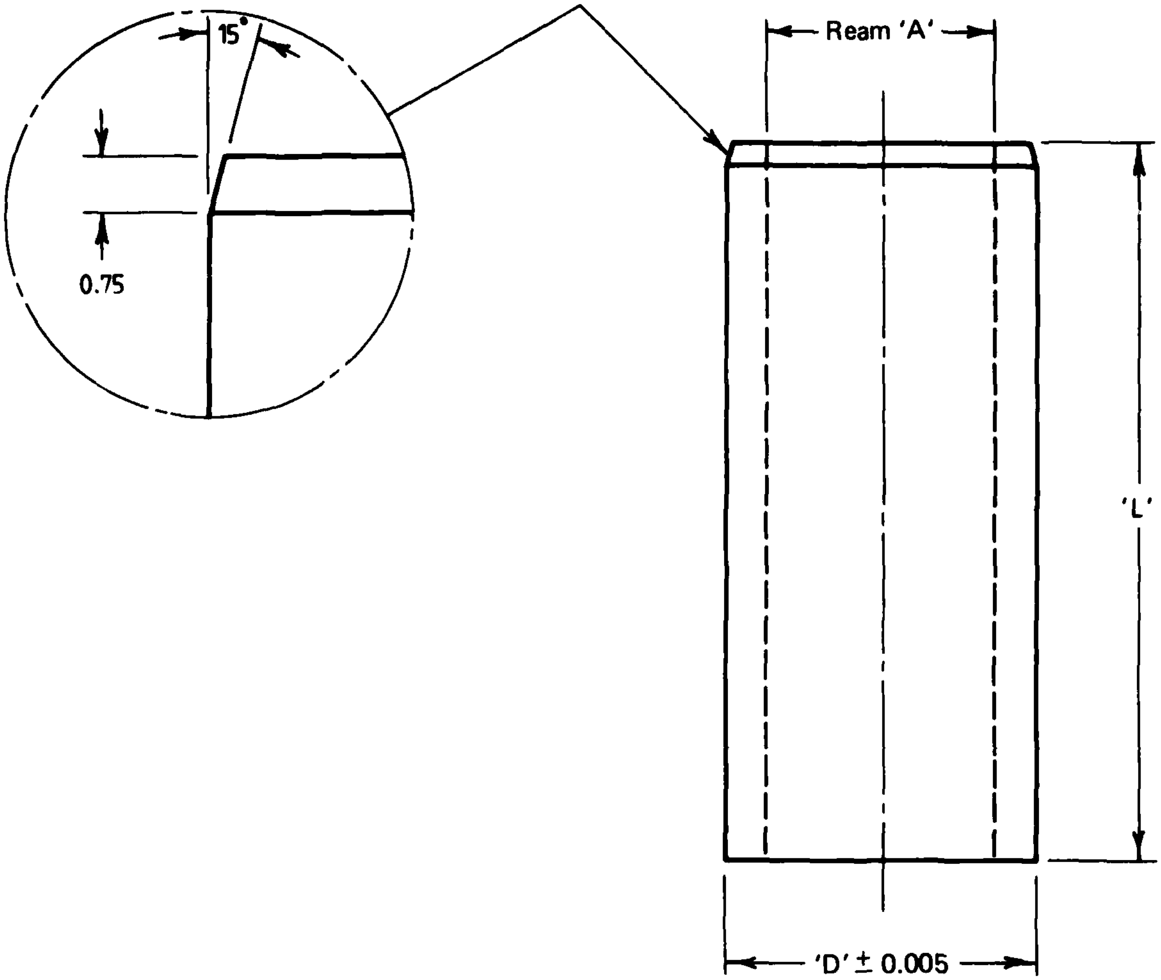


FIG. 15 COMPARISON OF LIVES OF CONTROL SPECIMENS TO LIVES OF SPECIMENS WITH HOLE (1) REAMED OVERSIZE.

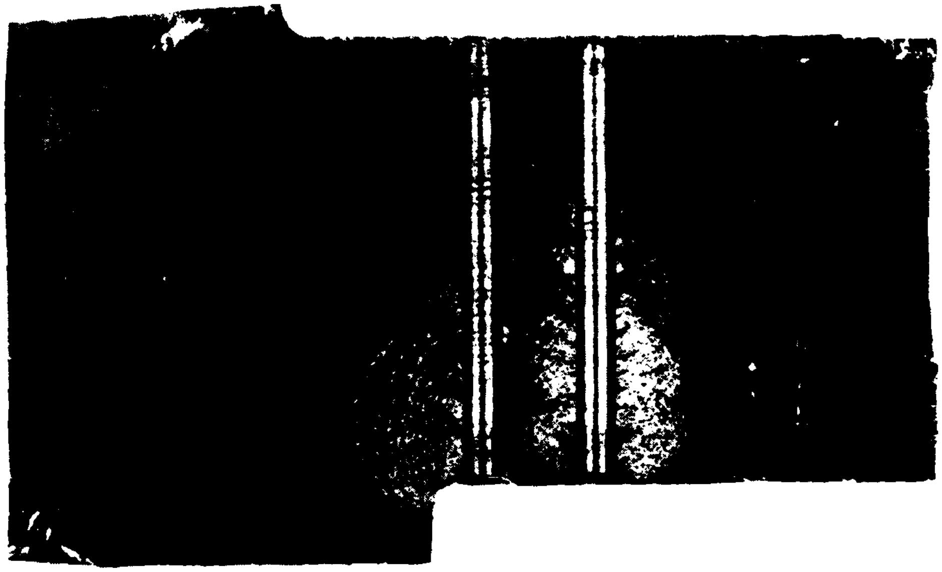


Hole Location	'A' + 0.035 + 0.013	'L'	'D'
1	6.35 6.5 8.0 8.6	31.75	hole dia. + 0.3%
5, 6, 8, 9	10.0 10.6	31	hole dia. + 0.3%

Notes

1. Diameter 'D' interference 0.25 to 0.35% on hole size
2. Material to be as specified
3. External surfaces to be ground finish
4. All dimensions in mm

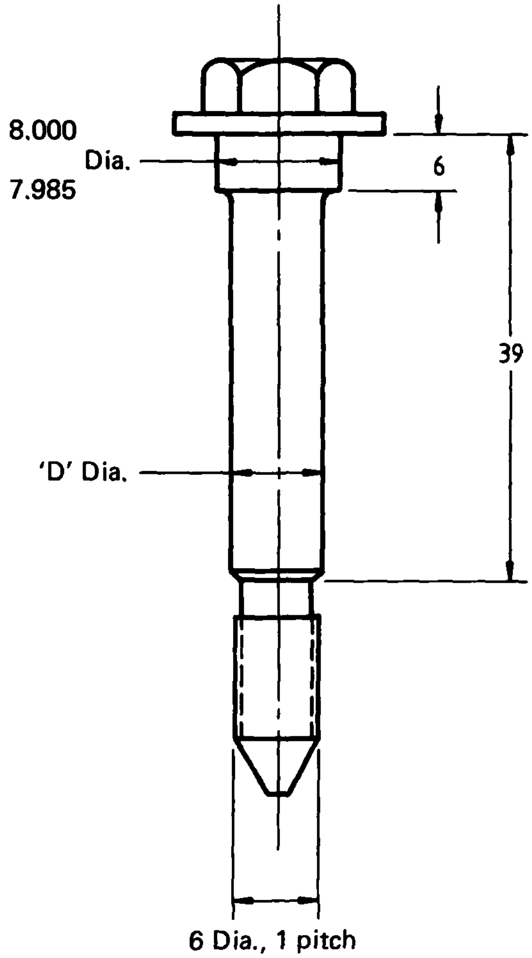
FIG. 16 STEEL BUSHES



(i) GK1C8 11mm bush in hole (1).

(ii) GK1E4 13mm bush in hole (1).

FIG. 17 SPECIMENS WITH 4130 STEEL INTERFERENCE - FIT BUSHES AND 2.5mm SLAN RIVETS

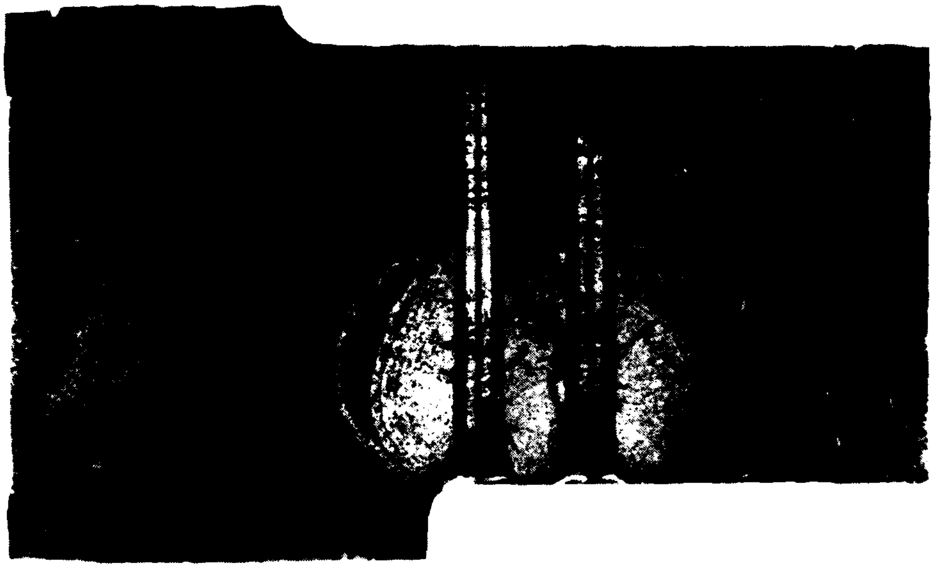


Notes

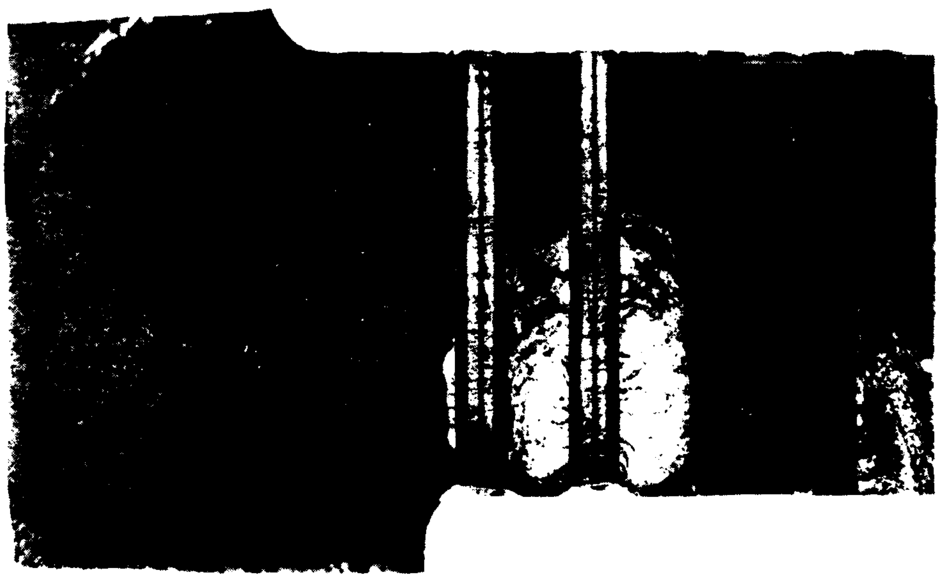
1. All dimensions in mm
2. Stepped bolt is modified 8 mm machine screw, part number MIR.IIIC–110.055
3. Diameter 'D' either 6.350 $^{+0.000}_{-0.015}$

   or 6.500 $^{+0.000}_{-0.015}$ as specified.

FIG. 18 STEPPED UNDERSIZE BOLTS



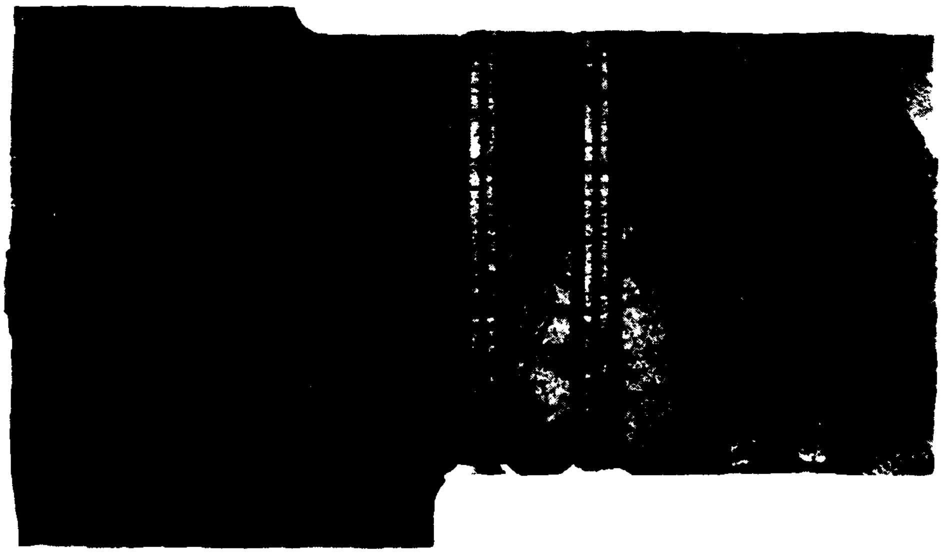
(i) GZ2 B1 9mm bush in hole (1)



(ii) GZ2 A7 11mm bush in hole (1)

FIG. 19 SPECIMENS WITH 4130 STEEL INTERFERENCE – FIT BUSHES AND 0.125 INCH SLAN RIVETS

(i) GZ3 D2 1mm bush in hole (1)



(ii) GZ2 A11 13mm bush in hole (1)

FIG. 20 SPECIMENS WITH TYPE 304 STAINLESS STEEL INTERFERENCE – FIT BUSHES AND 0.125 INCH SLAN RIVETS

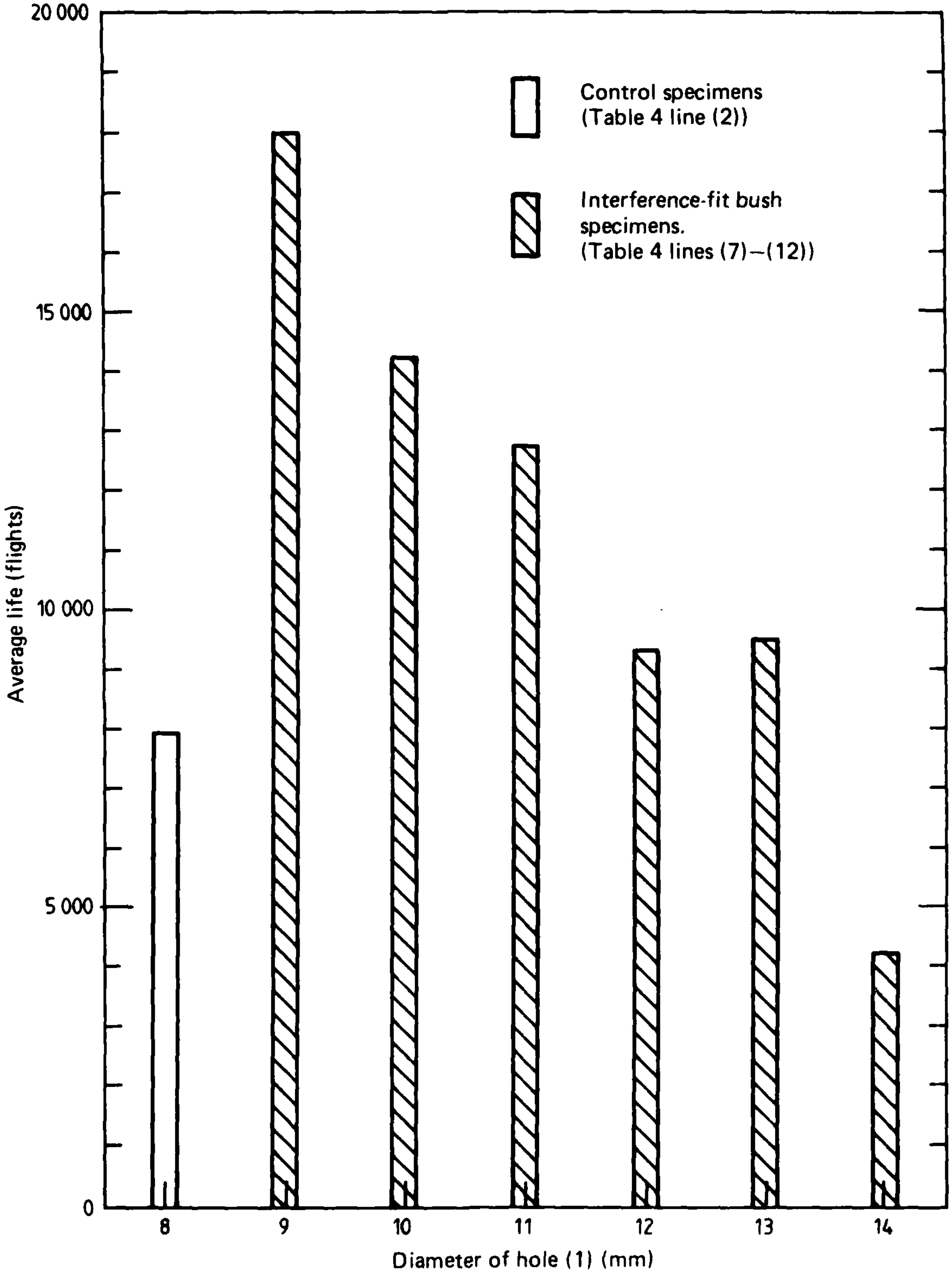


FIG. 21 COMPARISON OF LIVES OF CONTROL SPECIMENS TO LIVES OF SPECIMENS WITH INTERFERENCE-FIT BUSHES

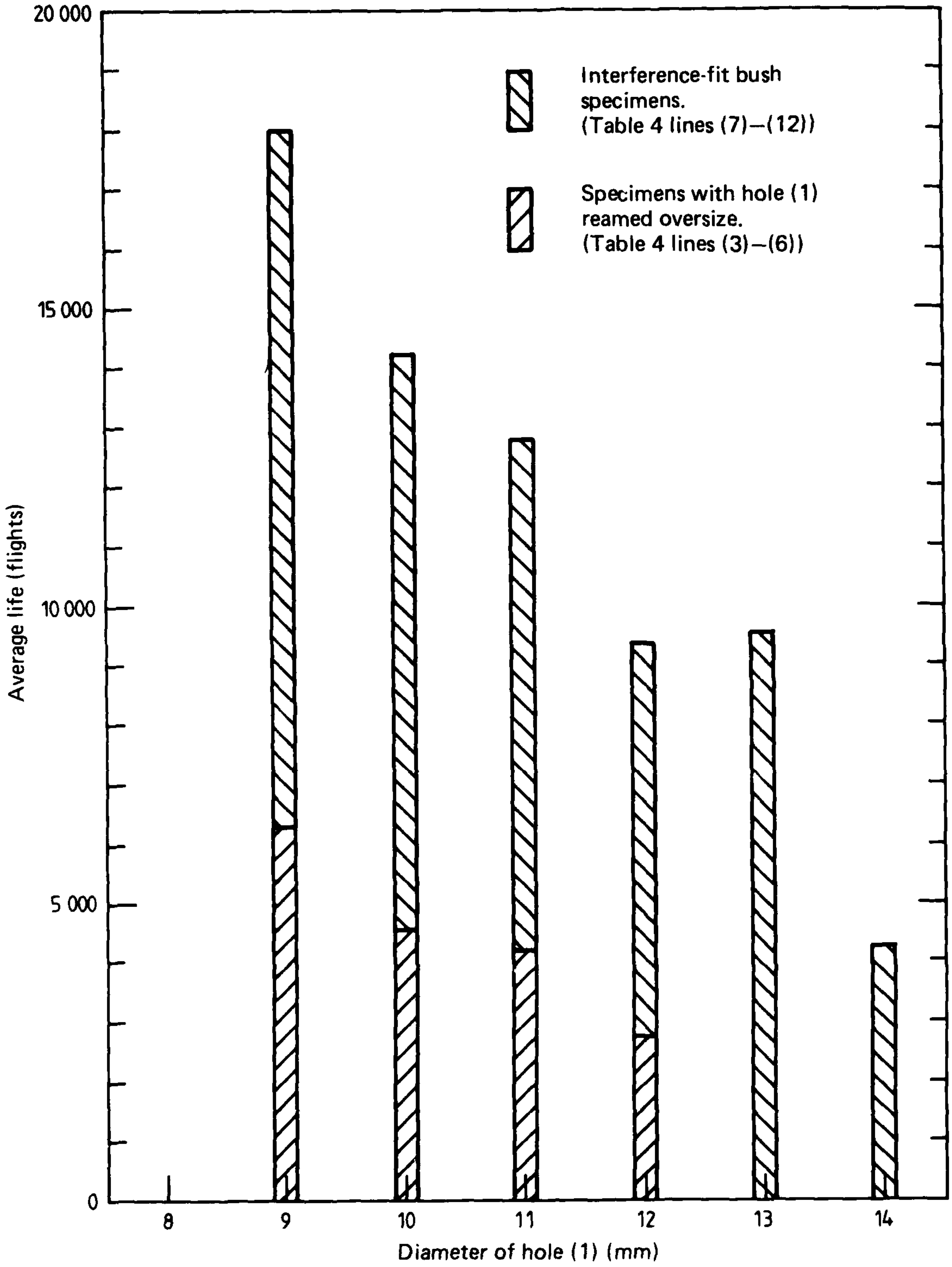


FIG. 22 COMPARISON OF LIVES OF SPECIMENS WITH INTERFERENCE–FIT BUSHES TO LIVES OF SPECIMENS WITH HOLE (1) REAMED OVERSIZE

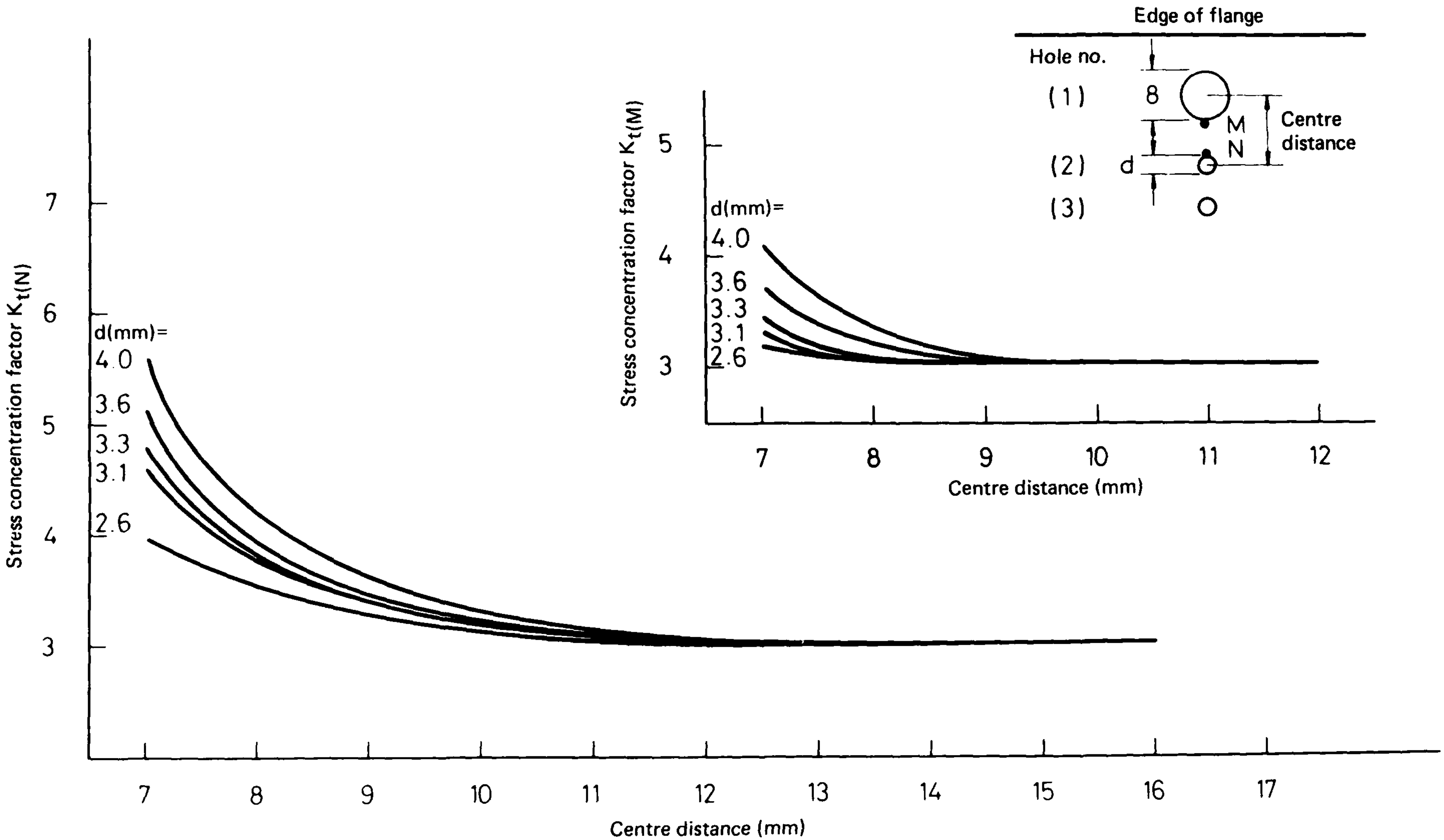


FIG. 23(a) STRESS CONCENTRATION FACTORS AT HOLES (1) AND (2) (FOR HOLE (1) DIAMETER OF 8mm) AS A FUNCTION OF THE RIVET HOLE DIAMETER AND DISTANCE BETWEEN THE HOLES

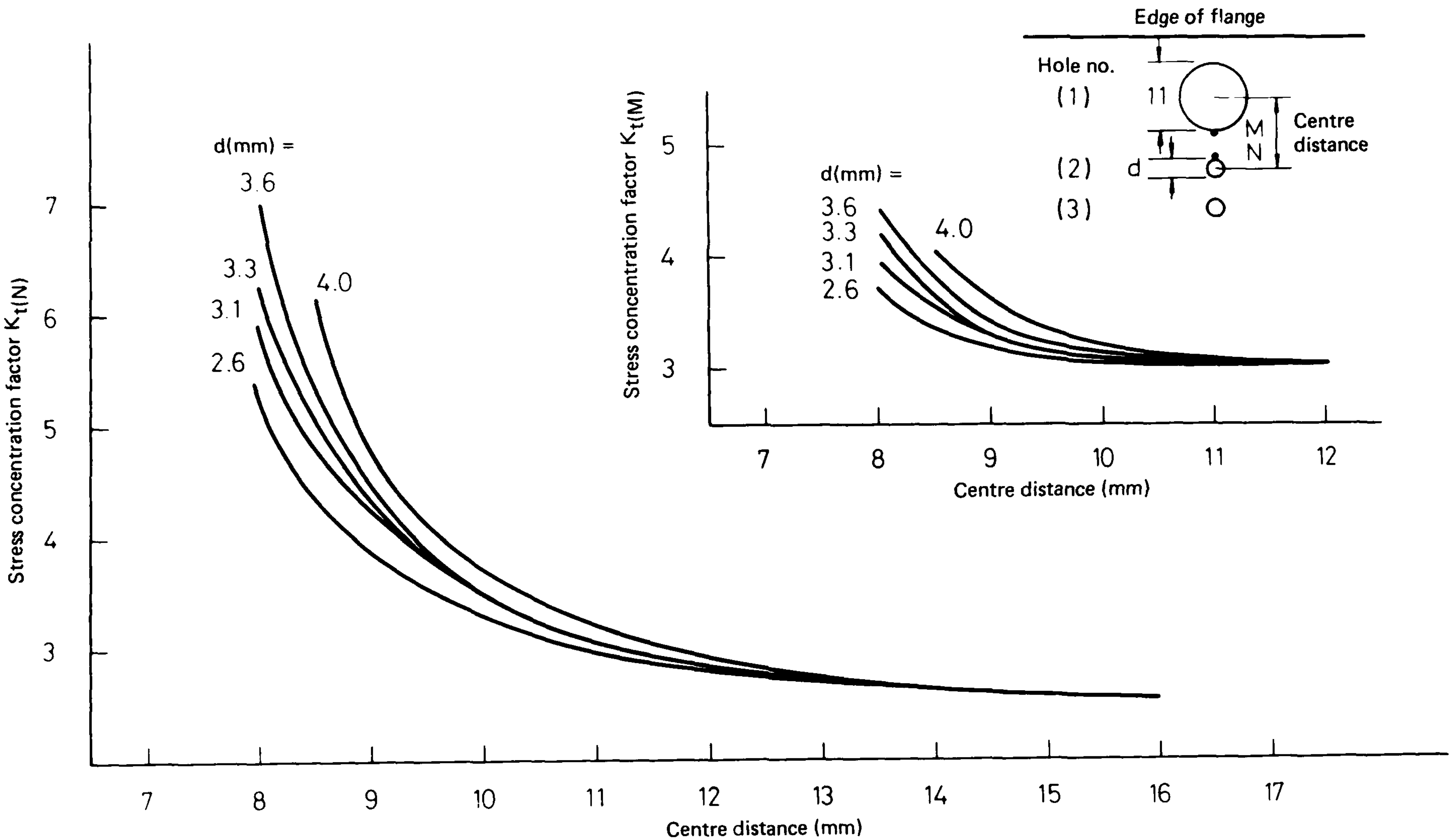


FIG. 23 (b) STRESS CONCENTRATION FACTORS AT HOLES (1) AND (2) (FOR HOLE (1) DIAMETER OF 11mm) AS A FUNCTION OF THE RIVET HOLE DIAMETER AND DISTANCE BETWEEN THE HOLES

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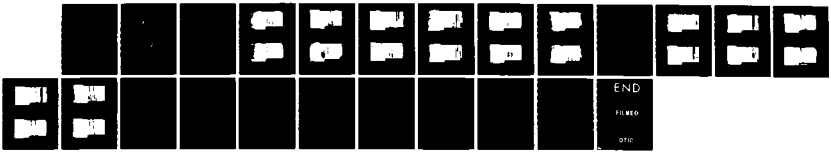
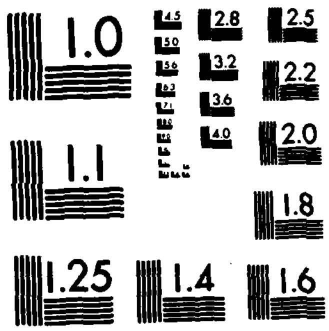



1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

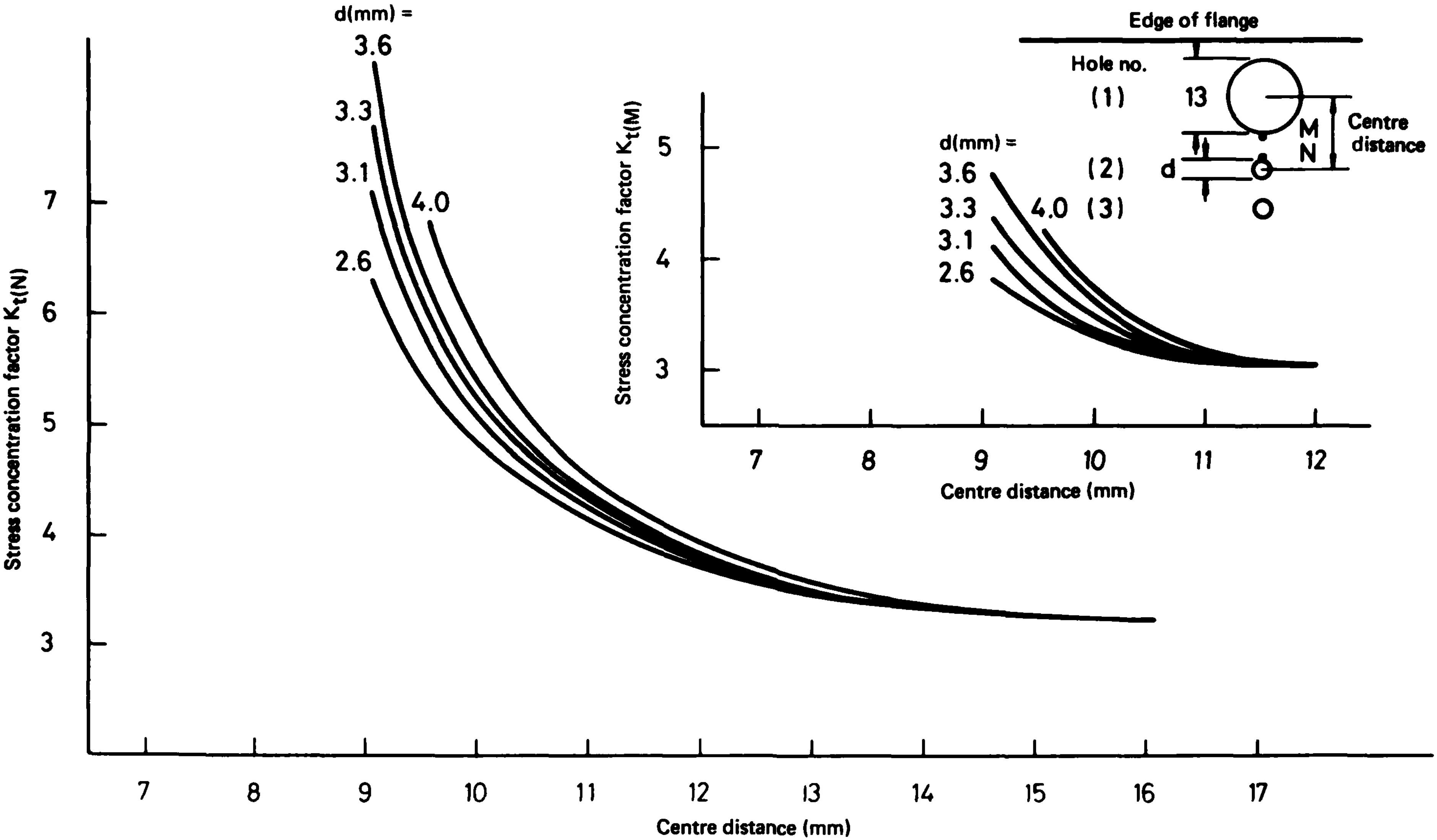
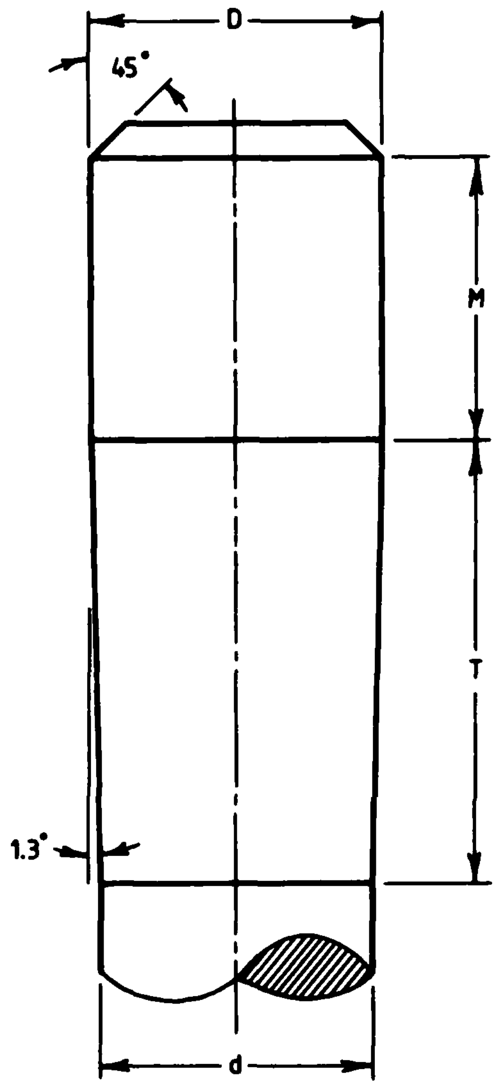


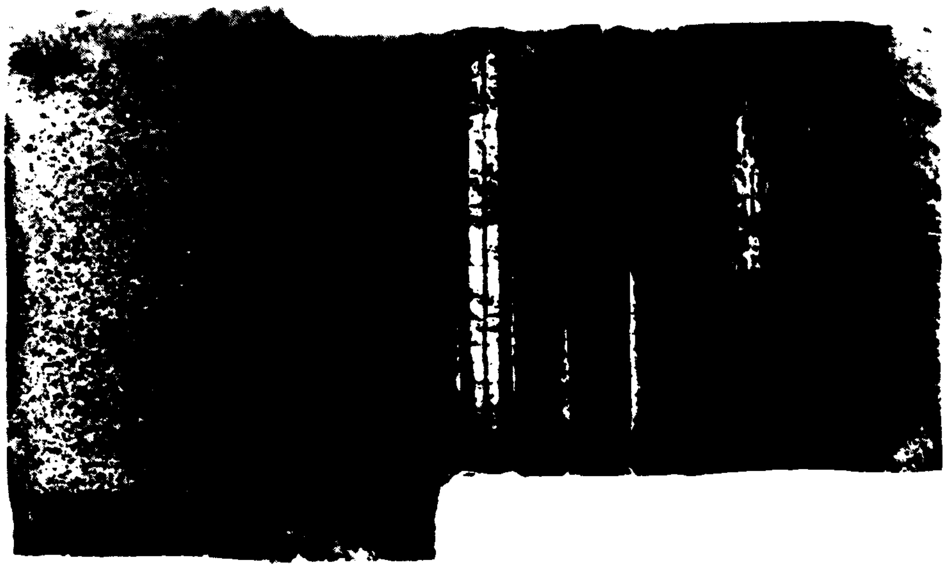
FIG. 23(c) STRESS CONCENTRATION FACTORS AT HOLES (1) AND (2) (FOR HOLE (1) DIAMETER OF 13mm) AS A FUNCTION OF THE RIVET HOLE DIAMETER AND DISTANCE BETWEEN THE HOLES



	mm	mm
Maximum diameter (D)	4.044 4.034	3.707 3.697
Stem diameter (d)	3.81	3.60 h7
Parallel length (M)	3.96	3.0
Lead-in taper (T)	6.4	2.4
Starting hole diameter	3.920 3.912	3.632 3.620
Final hole diameter	3.978 3.965	3.65
Nominal cold expansion	3.4 – 2.9%	2.4 – 1.8%

FIG. 24 ARL RIVET HOLE COLD-EXPANDING MANDRELS

(i) GK1 D4 13mm diameter bush in hole (1). Hole (2) reamed to 4mm diameter and 4mm 2117 rivet fitted



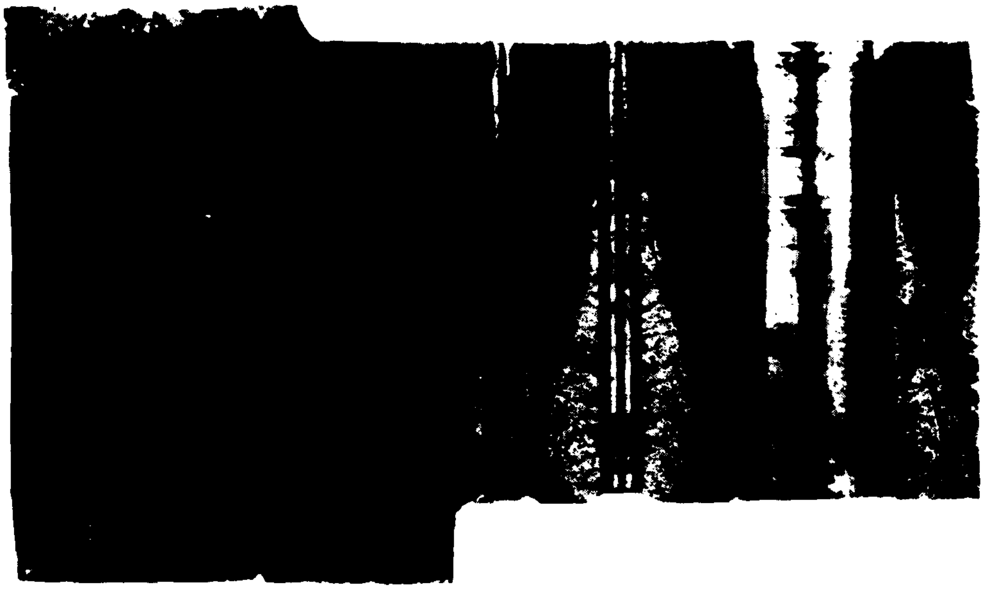
(ii) GK1 E5 13mm diameter bush in hole (1). Hole (2) cold expanded to 4mm diameter and 4mm 2117 rivet fitted

FIG. 25 SPECIMENS WITH 4130 STEEL INTERFERENCE – FIT BUSHES AND REWORKED SLAN RIVET HOLES

(i) GK1 F2 11mm diameter bush in hole (1).
Hole (2) reamed to 4mm diameter
and left open.

(ii) GK1 D7 11mm diameter bush in hole (1).
Hole (2) cold expanded to 4mm
diameter and 4mm 2117 rivet
fitted.

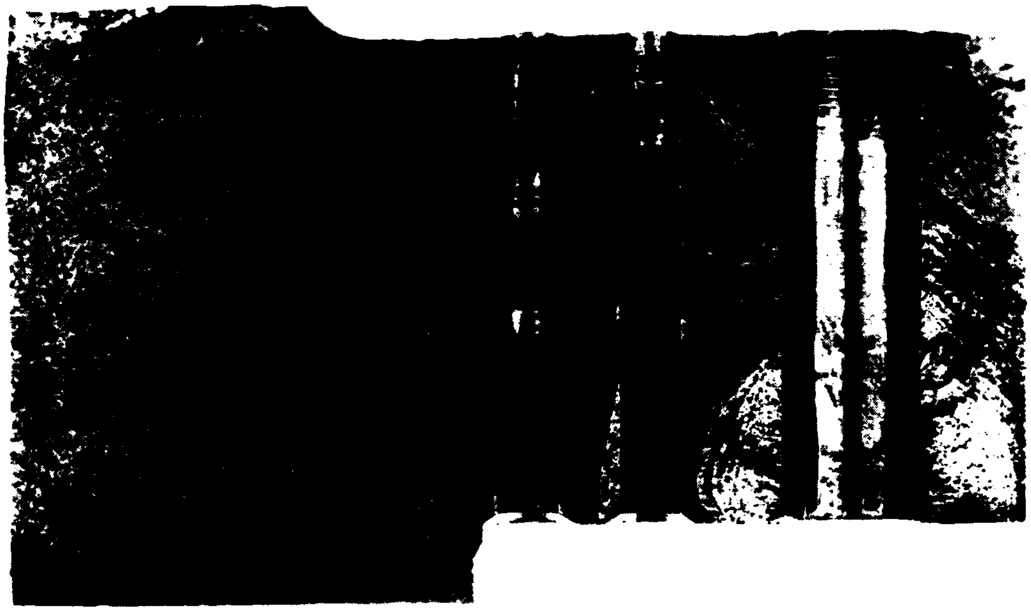
FIG. 26 SPECIMENS WITH 4130 STEEL INTERFERENCE – FIT BUSHES, REWORKED SLAN RIVET HOLES AND MODIFIED GANGNUT/SLAN ASSEMBLY.



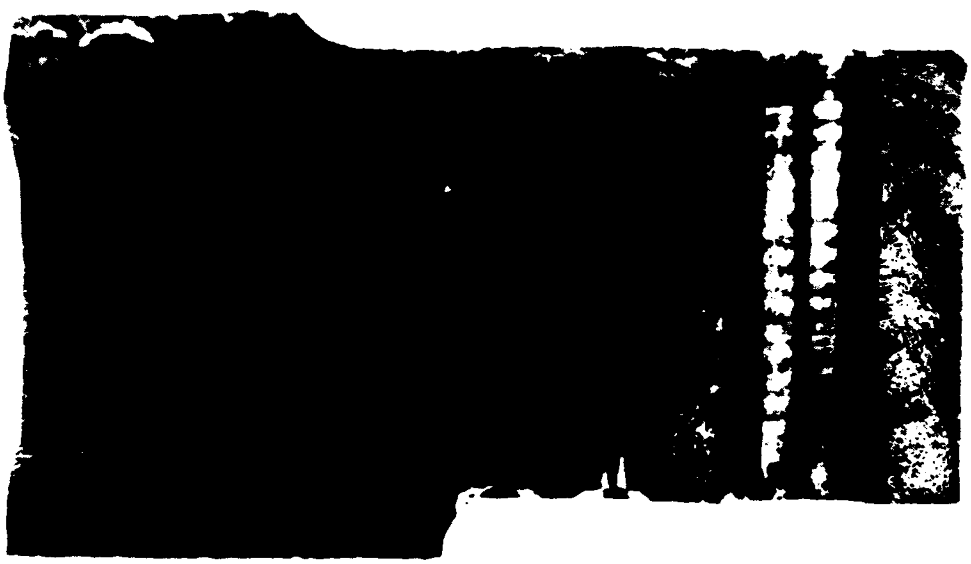
(i) GK1 C7 Hole (1) diameter 11.1mm.

(ii) GK1 B5 Hole (1) diameter 11.1mm.
0.3% interference bush in
hole (1).

FIG. 27 SPECIMENS WITH BOLT HOLES COLD-EXPANDED BY BOEING PROCESS; 2.5mm SLAN RIVETS



(i) GN 2N Hole (1) cold expanded to 8.6mm.
Holes (2) and (3) cold expanded to
3.66mm and left open.



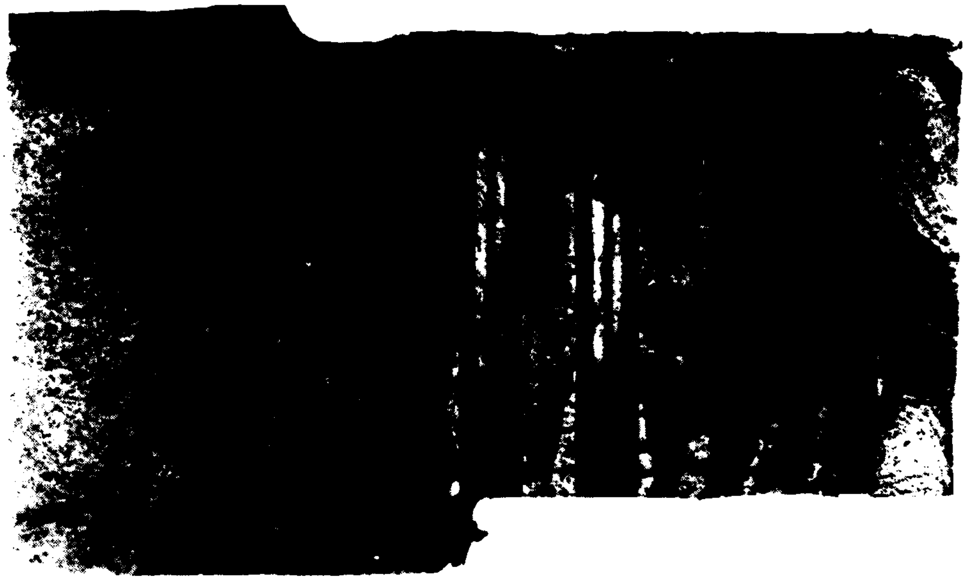
(ii) GN 1G Hole (1) cold expanded to 10.3mm.
Holes (2) and (3) cold expanded to
3.66mm and left open.

FIG. 28 SPECIMENS WITH BOLT HOLES COLD-EXPANDED BY BOEING PROCESS; ALL RIVET HOLES REWORKED AND MODIFIED GANGNUT/SLAN ASSEMBLY USED.

(i) GK1D1 13mm diameter bush in hole (1)

(ii) GK1F6 11.3mm diameter bush in hole (1)

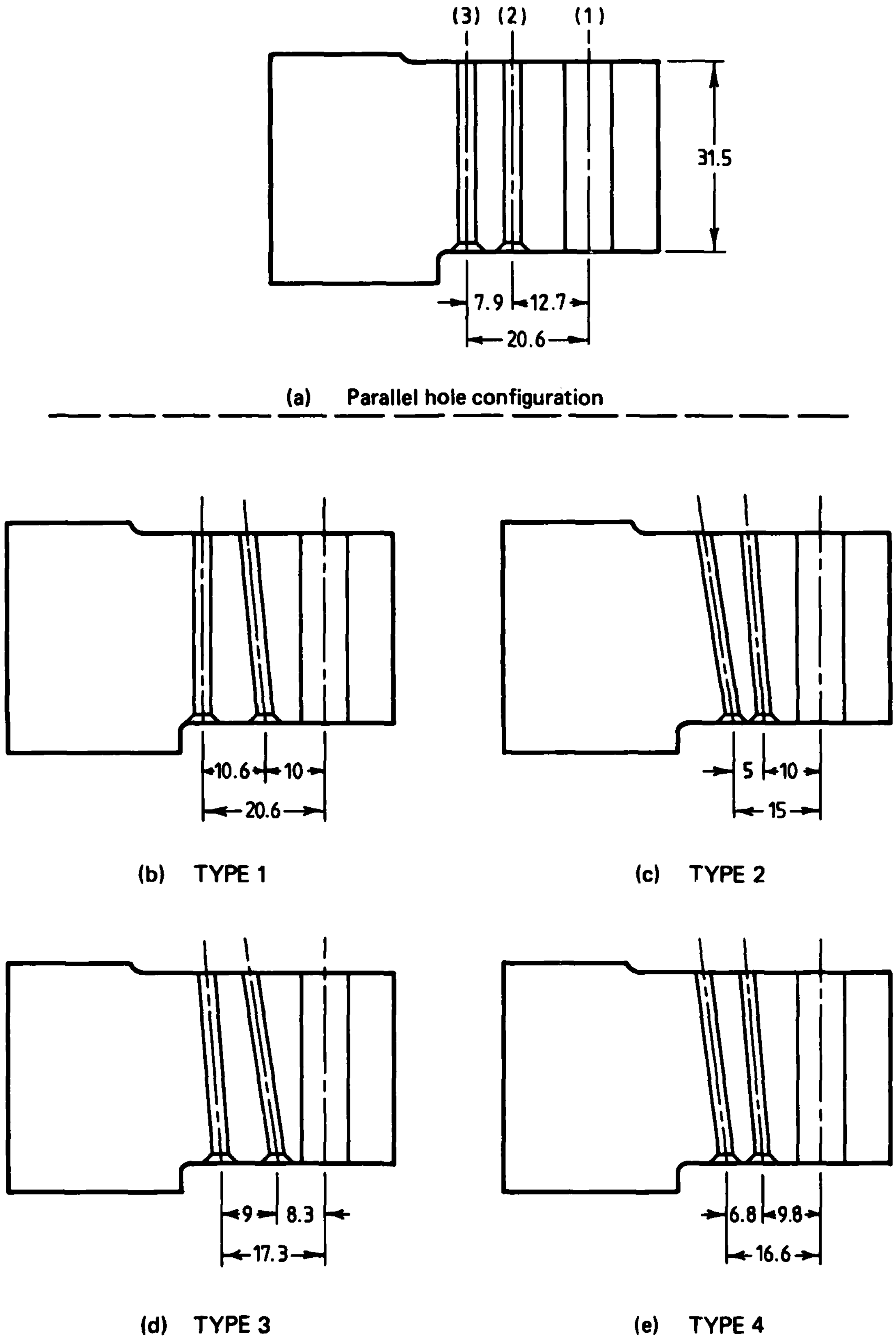
FIG. 29 PART FATIGUED SPECIMENS REFURBISHED USING 4130 STEEL INTERFERENCE-FIT BUSHES AND THE MODIFIED GANGNUT/SLAN ASSEMBLY. SLAN RIVETS NOT DISTURBED.



(i) GZ3 B9 11mm diameter bush in hole (1)

(ii) GZ3 D5 13mm diameter bush in hole (1)

FIG. 30 PART FATIGUED SPECIMENS REFURBISHED UNDER FACTORY CONDITIONS USING TYPE 304 STAINLESS STEEL BUSHES.



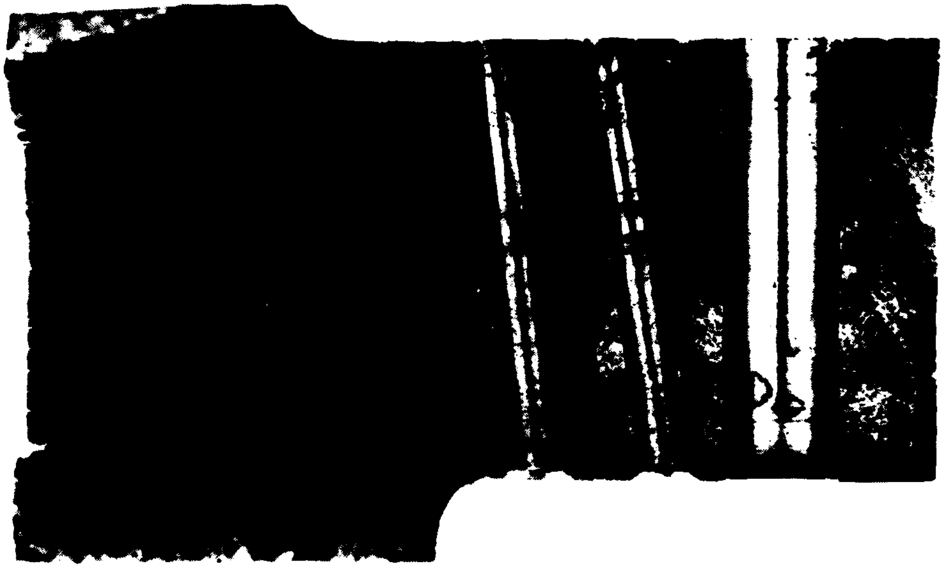
Inclined hole configurations

FIG. 31 SLAN SECTIONS

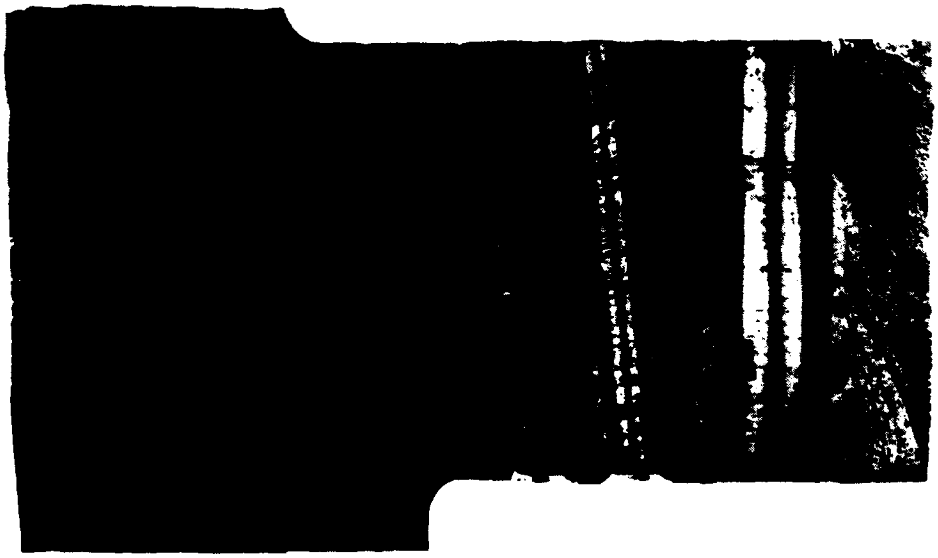
(i) GK1 E6 TYPE 1 specimen

(ii) GN 1M TYPE 2 specimen

FIG. 32(a) INCLINED SLAN RIVET HOLES CONTROL SPECIMENS

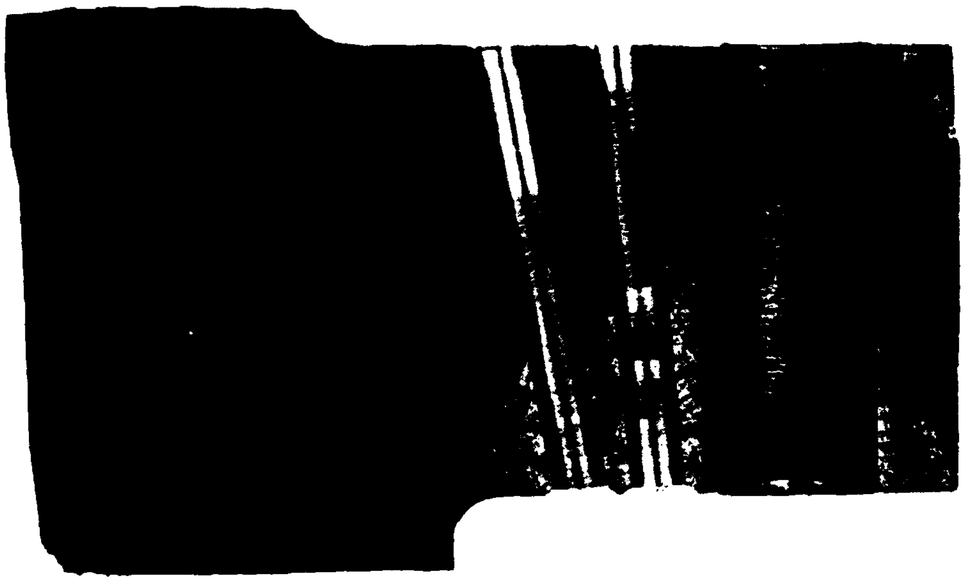


(i) GN 2K TYPE 3 specimen



(ii) GZ2 A6 TYPE 4 specimen

FIG. 32(b) INCLINED SLAN RIVET HOLES CONTROL SPECIMENS



(i) GNIJ 11mm bush in hole (1).
Holes (2) and (3) reamed to
3.62mm and left empty.

(ii) GT2A 11mm bush in hole (1).
Holes (2) and (3) cold expanded to 3.66mm
and left empty.

FIG. 33 TYPE 2 INCLINED SLAN RIVET HOLES SPECIMENS – REFURBISHED

(i) GNIN Hole (1) reamed to 8.6mm diameter. Holes (2) and (3) cold expanded to 3.66mm and left empty.

(ii) GZ3 B8 8.6mm bush in hole (1). Holes (2) and (3) reamed to 3.66mm diameter and left empty

FIG. 34 TYPE 3 INCLINED SLAN RIVET HOLES SPECIMENS – REFURBISHED

(i) GZ3 A9 9mm bush in hole (1). Holes (2) and (3) reamed to 4mm diameter and left empty.

(ii) GZ3 C5 11mm bush in hole (1). Holes (2) and (3) reamed to 4mm diameter and left empty.

FIG. 35 TYPE 4 INCLINED SLAN RIVET HOLES SPECIMENS – REFURBISHED

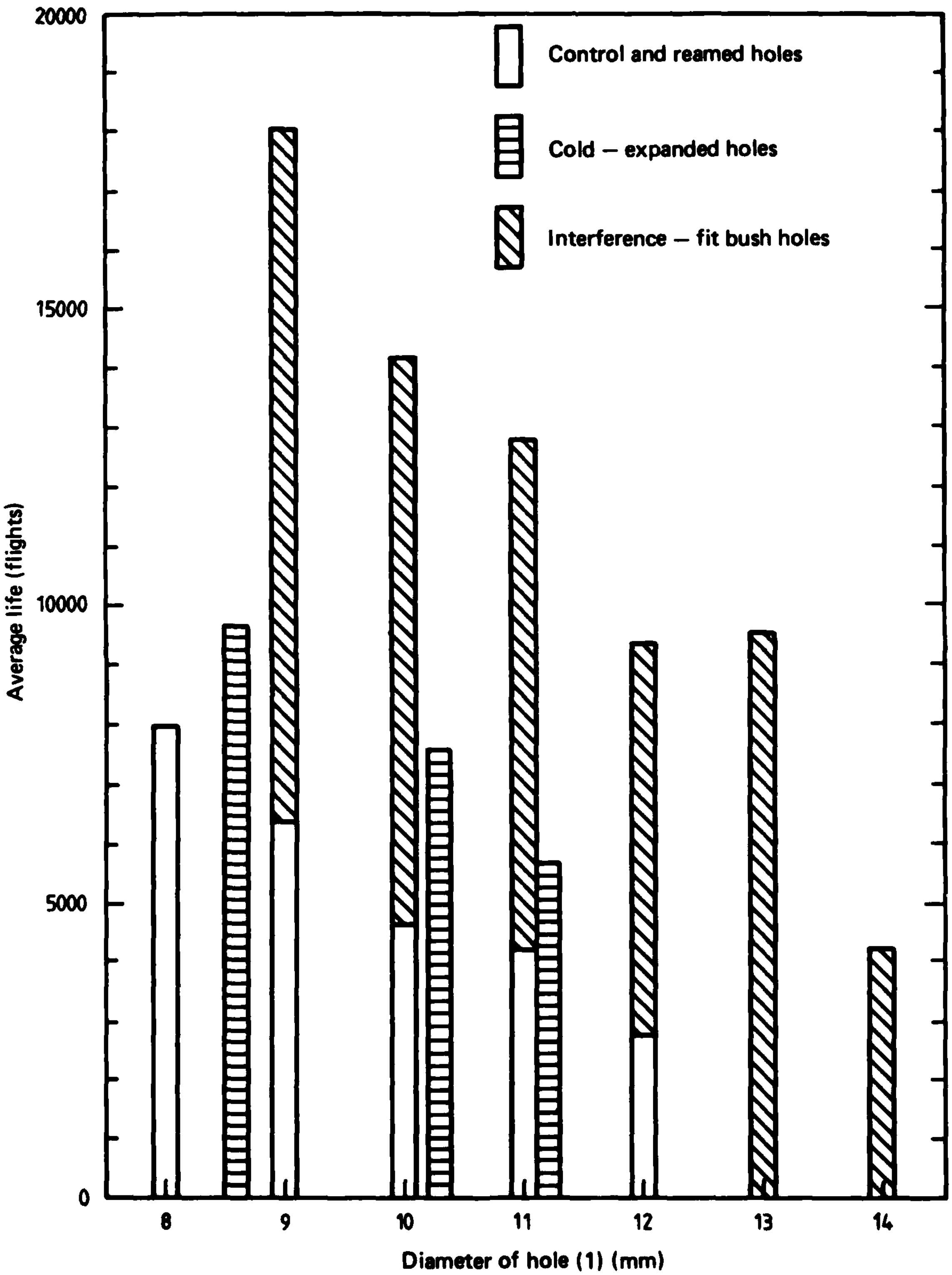


FIG. 36 EFFECTIVENESS OF BOLT HOLE REFURBISHMENT TECHNIQUES

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AR-003-004	ARL-STRUC-R-398	January 1984	DST 79/130

4. Title	5. Security	6. No. Pages	7. No. Refs
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Bolted joints	Interference fitting	11030
Holes (openings)	Bushings	
Cold working	Aluminum alloys	
Aircraft structures	Mirage aircraft	

16. Abstract

An increased life-of-type requirement for Mirage IIIO aircraft operated by the Royal Australian Air Force (RAAF) was associated with a specific need to develop a refurbishment technique for extending the lives of fatigue-cracked wing main spars. This led to a comprehensive series of flight-by-flight fatigue tests on specimens of a geometry and thickness (32 mm) closely representing the inboard lower rear flange section of the spar.

Of the various options investigated, the most promising was the use of interference-fit steel bushes in bolt holes—either alone or in combination with a modified anchor-nut sub-assembly which eliminated the need for some rivets in the spar flange. Specimens with oversize reamed holes utilizing oversized sleeved bolts performed poorly, while cold-expansion of the critical bolt hole using the Boeing split-sleeve process was unsatisfactory because of small hole-to-spar edge distances and the proximity of small rivet holes.

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16. Abstract (Contd)

This investigation has shown that acceptable extensions of fatigue life for wing main spars of the Mirage IIIO are possible by the use of combinations of standard bolts and 0·3% interference-fit steel bushes (of 1·5 mm wall thickness) in the critical bolt holes, with the provisos that pre-existing fatigue cracks are completely removed and that (after reworking) bolt hole/rivet hole separation distances are adequate. In some circumstances acceptable increases in life may be obtained by reducing the outside diameter of the bush and utilizing stepped undersize bolts.

The installation of interference-fit stainless steel bushes (which provide some potential for through-the-bush crack detection) has been adopted as the basic procedure for extending the fatigue lives of the wing main spars of the RAAF Mirage IIIO fleet.

17. Imprint

Aeronautical Research Laboratories, Melbourne

18. Document Series and Number	19. Cost Code	20. Type of Report and Period Covered
Structures Report 398	251020	–

21. Computer Programs Used

22. Establishment File Ref(s)

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