

AGARD REPORT No.721

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Fatigue Rated Fastener Systems

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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.721
FATIGUE RATED FASTENER SYSTEMS

Edited by
H.H.van der Linden

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PREFACE

In recent years, the SMP has placed considerable emphasis on cooperative R & D programmes, especially where there are several variables to consider and where several identical tests must be made to evaluate the scatter in the results. Fatigue and corrosion tests lend themselves particularly well to this treatment, since one laboratory working on its own could spend a vast amount of time and money in deriving all the requisite data before any analysis of the results could be undertaken. By inviting the participation of several laboratories (even though these may be in separate countries), the work can proceed in parallel, thus reducing the total elapsed time. Moreover, each participant can reap the benefits of the whole programme for a small outlay.

Successful ventures in recent years include the Critically-Loaded Holes Programme and the Corrosion Fatigue Cooperative Testing Programme. This report presents the findings of the latest cooperative programme to be completed — an evaluation of Fatigue-Rated Fastener Systems.

Despite the advent of adhesives, composite materials, integrally-machined components and diffusion bonding, mechanical fasteners are still the most common means of joining parts together in the aerospace industry, and will remain so for many years to come. The designer needs to know which fastener systems are the most efficient, and this programme studied a number of systems from the fatigue point of view. In this context, 'system' means not only the fastener itself, but also the way in which the hole is prepared and the fit of the fastener in the hole.

The thanks of the Panel are due to the collaborating laboratories and especially to the Coordinator, Mr H.H. van der Linden, who was responsible not only for organising the programme but also for much of the analysis and the preparation of this report.

W.G. HEATH
Chairman, Working Group on
Fatigue-Rated Fastener Systems

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CONTENTS

	Page
PREFACE	iii
SUMMARY	1
1. INTRODUCTION	1
2. OBJECTIVES, METHODS AND MEANS	1
3. PROGRAMME OVERVIEW	2
3.1 No-load transfer joints	2
3.2 Low load transfer joints	2
3.3 High load transfer double shear joints	3
3.4 High load transfer single shear joints	3
3.4.1 Background of the single shear designs	3
3.4.2 Core programme	4
3.5 Assess to all details	4
4. TEST PROCEDURES	4
4.1 Measurement of load transfer and secondary bending	4
4.1.1 Secondary bending	4
4.1.2 Load transfer	4
4.2 Data recording	5
5. SPECTRA	5
5.1 The manoeuvre spectrum FALSTAFF	5
5.2 The standard load sequences for transport aircraft wings TWIST and MINI-TWIST	5
5.3 Constant amplitude loading	5
6. METHODS FOR ANALYSING THE FRFS PROGRAMME DATA	6
7. RESULTS OF THE FATIGUE RELATED FASTENER SYSTEMS TESTING PROGRAMME	6
7.1 Presentation of fatigue life data	6
7.2 Results of the measurements of secondary bending and load transfer	6
7.2.1 Reverse double dogbone specimen	7
7.2.2 Core programme single shear joints	7
7.2.3 Core programme double shear joints	7
7.3 Measured fit and surface roughness	7
7.4 Cost of fastener systems	7
7.5 Locations of primary fatigue crack origins	8
8. CORRELATION ANALYSIS	8
8.1 Correlation of fatigue lives of open hole specimen and no load transfer joints	8
8.2 Correlation of fatigue lives of no load and low load transfer joints	8
8.3 Low load transfer joints fatigue life analysis results	9
8.4 Comparison of UK and AGARD low load transfer joint design	18
8.5 Correlation of fatigue lives of double shear and low load transfer joints	10
8.6 Double shear joints fatigue life analysis results	10
8.6.1 Participants programmes	10
8.6.2 Core programme	10
8.7 Single shear joint fatigue life analysis results	10
8.7.1 Participants programmes	11
8.7.2 Core programme	11
8.8 Correlation of fatigue lives and cost of fastener systems	12
9. DISCUSSION	12
9.1 Determination of fatigue lives	12
9.2 Evaluation of the fastener system cost figures	12
9.3 Prime parameters in fastener system selection	13
9.4 Design data	13
9.5 Reference datum	13
9.6 Experimental methods	13
10. CONCLUSIONS	13

11. REFERENCES	Page
	14
TABLES	15
FIGURES	24
ANNEX 1: AGARD SMP WORKING GROUP ON FATIGUE RATED FASTENER SYSTEMS	46
ANNEX 2: FASTENER SYSTEMS	50
ANNEX 3: MEASUREMENT OF FIT AND SURFACE ROUGHNESS	52
ANNEX 4: DETERMINATION OF SECONDARY BENDING AND LOAD TRANSFER	54
ANNEX 5: RESULTS OF THE MEASUREMENTS OF SECONDARY BENDING AND LOAD TRANSFER	59
ANNEX 6: TABULAR PRESENTATION OF FATIGUE LIFE DATA	74

FATIGUE RATED FASTENER SYSTEMS
-AN AGARD COORDINATED TESTING PROGRAMME-

by
H.M. van der Linden
National Aerospace Laboratory NLR
Anthony Fokkerweg 2
1059 CM Amsterdam
The Netherlands

SUMMARY

This final technical report contains the description, test results, analysis and conclusions of a collaborative fatigue test programme which assessed the fatigue lives of a range of fastener systems using different joint test specimens. A range of high load transfer angle shear joint designs were evaluated and compared in an extensive core programme; secondary bending and load transfer were determined experimentally. Between seven and eight hundred specimens were fatigue tested by participants in seven countries. The fatigue tests were carried out mainly under FALSTAFF; some test series were done under MINI-TWIST and constant amplitude loading. The sheet materials used were from the 2000- and 7000- aluminium alloy series. The fasteners ranged from standard bolts to tapered fasteners, installed in holes which were drilled, broached, reamed or cold worked. The multiple linear regression analysis method and graphical methods were used to correlate results and to find trends among the variables. In addition the cost figures were related with the fatigue performance.

The AGARD coordinated Fatigue Rated Fastener Systems programme not only identified the prime parameters in fastener system selection but also quantitatively evaluated these.

Highlights of the data indicate that:

- secondary bending proved to be a prime parameter. At moderate to high values it tends to nullify the beneficial effect of fatigue enhancement fastener systems;
- at low to moderate secondary bending (or at the absence of it) the fit, clamping and cold work are prime parameters. At high load transfer and at high fatigue load levels the best results are obtained with cold worked holes plus high interference fit fasteners;
- double shear joints clearly show a fastener system rating;
- the hole quality as such is not a prime parameter. However, dimensioning to size to obtain a close tolerance fit results in holes with good fatigue quality;
- increasing costs of the fastener system might result in a better fatigue performance. Moderate to high secondary bending tends to nullify the extra costs of fatigue enhancement fastener systems. The conclusions of the report present a cost effectiveness rating of different fastener systems applied in double shear and low load transfer joint.

1. INTRODUCTION

The application of shear loaded fastener systems with known or advertised good fatigue performance is increasing considerably, both in new aircraft designs and in modifications of older ones. This increase in use is accompanied by an increase in research and development. The Structures and Materials Panel of the Advisory Group for Aerospace Research and Development (AGARD) recognised this and appointed working groups to carry out collaborative fatigue test programmes on fatigue rated fastener systems in aluminium alloy structural joints.

A first programme, the Critically Loaded Hole Technology Pilot Collaborative Test Programme (reference 1), was carried out in the period October 1976 up to October 1979 in which open hole and low load transfer joint specimens were fatigue tested under FALSTAFF flight-by-flight loading.

The results can be summarised as follows:

- consistent fatigue data can be generated in complex fatigue testing between the participants;
- interference fit fastener systems are relatively insensitive to effects of hole quality;
- valuable design data was generated on low load transfer joints.

After completion of the Critically Loaded Hole Technology Pilot Collaborative Test Programme a follow-on programme was defined in 1979: the Fatigue Rated Fastener Systems (FRFS) programme, coordinated by the author of the present paper.

The FRFS programme assessed the fatigue lives of a range of fastener systems using different joint test specimens. In addition the cost figures were related with the fatigue performance. A reference datum for the comparison of test results produced in different countries was established by means of "core" programmes. Results were analysed by the Air Force Flight Dynamics Laboratory (USA) and the National Aerospace Laboratory, NLR (The Netherlands). This AGARD Report describes the FRFS programme and presents the results and analysis.

2. OBJECTIVES, METHODS AND MEANS

The objectives of the cooperative programme were:

- to determine the fatigue lives for a range of fatigue rated fastener systems in different materials in combination with a selection of hole preparation techniques and installation parameters;
- to establish the cost figures of each fastener system in relation to its fatigue performance;
- to identify the prime parameters involved in fastener system selection;
- to generate design data for a number of fastener systems;
- to develop a reference datum for the comparison of test results produced in different countries using different specimen geometries;
- to develop experimental methods for fastener system fatigue rating.

Seven countries participated in the programme (table 1). As a first step each participant defined his own programme, which could be active, planned or desired. This definition specified plate material, thickness, surface treatment, interlayer sealant, final hole production tooling, fastener type, fastener fit, fatigue loading programme and load levels. The participant's programmes formed a total matrix of testing variables. Elements of the matrix, for instance load level and specimen geometry, were adjusted to give good overall problem coverage without unnecessary duplication. Further, a number of additional programmes, the "core" programmes, were defined to allow comparison of results produced in different countries using not completely identical specimen designs.

For clarity the FRFS programme was split up in four parts:

- No load transfer joints (NLT).
- Low load transfer joints (LLT).
- Double shear joints (DS).
- Single shear joints (SS).

with each part having its own basic and core programmes.

For all specimens of the FRFS programme fastener fit and sometimes hole surface roughness were measured during fastener installation.

The specimens of the FRFS programme were tested mainly under FALSTAFF (Fighter Aircraft Loading Standard For Fatigue evaluation) loading; some test series were carried out under the gust spectrum MINI-TWIST and under constant amplitude loading. No crack growth observations were made. Each fatigue test was reported on an special form.

Fatigue lives were evaluated in terms of:

- a fastener system, fit and hole quality;
- a installation cost figures;
- a joint geometry, i.e. load transfer and secondary bending;
- a plate material;
- a load spectrum.

A statistical analysis method and graphical methods were used to correlate results and to find trends among the variables.

Since there was a lack of a single shear standard specimen, a range of high load transfer single shear joint designs were evaluated and compared in an extensive core programme. The latter included fatigue testing of the single shear specimen together with a double shear equivalent design. All specimens were manufactured from one material.

Three different fastener systems (hole quality, fastener and fit) were selected and defined; the third fastener system was optional. Surface treatment, interlayer sealant, load levels and load spectrum were specified.

3. PROGRAMME OVERVIEW

As originally envisaged the FRFS programme consisted of separate programmes of testing directed to the requirements of individual laboratories and linked by additional core programmes; Annex 1 gives the original schedule. The FRFS programme overview, together with characteristic specimen examples, is presented in table 2. The four programme parts are described in the next subchapters.

3.1 No-load transfer joints

The no-load transfer specimen has a continuous dogbone member. The single fastener mounts a small non load carrying plate to the dogbone (figure 1a,b). Load transfer is close to zero and secondary bending is negligible. If testing of this joint type results in the same fastener system rating as for other types of joints, e.g. the low load transfer joint, then this simple and cheap design can be used for the evaluation of fastener systems.

The two basic programmes defined differed in intention and goal: Sweden would evaluate four fastener systems in one sheet material, while France would evaluate four sheet materials using one fastener system. Therefore a limited core programme was defined to allow comparison of the results of the two basic programmes. Table 3 overviews the programme originally defined. In addition to no-load transfer specimens Sweden also tested open hole ones (figure 1c).

3.2 Low load transfer joints

This part of the programme (table 4) may be considered as a supplemental one to the Critically Loaded Hole Technology Programme in that individual participants could investigate further the fatigue resistant fastener systems of particular relevance to them. The standard low load transfer reverse double dogbone is shown in figure 2. For 4.35 mm nominal diameter interference fit fasteners the load transfer at each fastener location is approximately 5% of the axial load. The joint is representative of lower wing skin panels attached to spars, for example. A core programme was defined to allow comparison of results obtained using the deviating UK design (figure 2c) with the results obtained by the other participants. Note that the UK design was already being tested when the FRFS programme began.

3.3 High load transfer double shear joints

Double shear joints have no secondary bending. Table 5 shows the test schedules. Since different specimen geometries (figure 3a,b,12), sheet materials and thicknesses, fastener systems and spectra were used it was felt necessary to define a core programme to evaluate and compare the different designs. Unfortunately, the double shear core programme was cut short during the course of the programme. The UK cancelled their contribution since no differences in fastener rating were observed comparing low load transfer and double shear specimen results. The Swedish programme and the Netherlands part of the double shear core programme could not be completed for economic reasons.

3.4 High load transfer single shear joints

Single shear joints are exposed to secondary bending caused by asymmetric eccentricities of the load carrying members. The amount of bending depends strongly on the joint geometry. It is generally recognised that differences in fastener systems tend to be overshadowed by excessive bending. Representation of a realistic bending situation by individual participants resulted in a number of different specimen geometries. These were evaluated under a range of variables directed to the requirements of individual participants (table 6).

3.4.1 Background of the single shear designs

Four designs will be described (figures 7 to 11):

- lap joint, a three row-type (F) and a two row-type (US);
- X-type joint (SW);
- Q joint (UK);
- $1\frac{1}{2}$ dogbone specimen.

Lap joints are used in an aircraft structure only if a double strap can not be applied. This type has a very high bending stress, which is in the order of the axial stress component. At least two fastener rows are present. In a two row lap joint the load transfer per row is 50 % of the total load. The load transfer decreases somewhat when three rows will be present. Due to the high bending and high load transfer this joint is the most fatigue critical one, i.e. it will give the shortest fatigue lives.

One might argue that this specimen is unrealistically severe because in the aircraft structure the bending is reduced by the support of other structural elements, e.g. stringers or ribs. Nevertheless, the fatigue data generated using the lap joints are used as one of the extreme data sets in between which a designer interpolates to obtain fatigue life estimates for his joint configuration. The US lap joint specimen (figure 8) is a standard one of MIL-STD-1312 (Method 2, 15 December 1977).

The $1\frac{1}{2}$ dogbone specimen might be considered as a standard one within the AGARD community: it is used in the corrosion fatigue testing programmes CFCTP (Corrosion Fatigue Cooperative Testing Programme) and FACT (Fatigue in Aircraft Corrosion Testing). The specimen simulates the load transfer and secondary bending characteristics of runouts of stiffeners attached to the outer skin, and was developed by the Laboratorium für Betriebsfestigkeit (LBF) in West Germany. The design goals were a load transfer of 40 % and a secondary bending ratio of 0.50 (figure 11).

However, an investigation (reference 2) suggested that in this type of specimen the load transferred was unrepresentatively low and dependent upon the type of fastener installed. Further, reference 3 shows a relatively low load transfer and indicates a fastener fit dependence.

The compression limit load is about - 10 kN, i.e. a specimen without anti-buckling guides will not buckle when compression loads do not exceed - 10 kN. The (bolted) grips and clamping-in procedure are well documented (reference 4).

In the UK an alternative specimen was designed (reference 5) that attempts to alleviate some of the problems associated with e.g. the $1\frac{1}{2}$ dogbone joint.

The alternative design, the Q joint (figure 10), is based on a single lap joint, but the addition of a further load carrying member controls bending by providing extra lateral stiffness. Further, the double shear connection at the second fastener row ensures that fatigue failures do occur at the single shear connection.

The advantage over the $1\frac{1}{2}$ dogbone lies in the fact that it is a 100 % load transfer joint. In the $1\frac{1}{2}$ dogbone the load can by-pass the fastener in a clearance condition before load is transferred in bearing.

In the Q joint the stiffer double shear connection might be expected to transfer more load than the single shear row; thus, a load transfer somewhat lower than 50 % is expected.

Initial testing (reference 5) suggested that the bending ratio is approximately 0.5; this ratio may decrease to a value nearer to 0.4 under dynamic loading conditions. A disadvantage is that the Q joint is more complicated and thus more expensive than the $1\frac{1}{2}$ dogbone.

The X type (figure 9) is a Swedish development. It is a two row joint because a known load transfer, independent of the type of fastener, may be obtained with a maximum of two rows. The design has splice plate areas equal to the base plate areas, implying a theoretical 50 % load transfer per row and independent of fastener stiffness. The splice plate centres of gravity coincide with the base plate centre of gravity, implying zero gross eccentricity and no major secondary bending. Compared to other splice plate configurations (reference 6) the X type had the most uniform load transfer distribution over the fasteners. Further, the splice plate stiffening effect is very local.

3.4.2 Core programme

Primary objective of the core programme was to evaluate and compare different designs as used in the participating institutes and companies. To obtain an impression of the influence of bending on the fatigue life, so called "double shear equivalent specimens" were derived from the single shear ones (figures 9, 11, 12) in which the asymmetric side sheet of the single shear design was replaced by two symmetrically placed side sheets each having half the thickness of the original one. The double shear feature excludes secondary bending.

However, load transfer might not have been completely identical in the two designs because of changed fastener fit and bending characteristics and the presence of two locations of frictional load transfer instead of one.

Table 7, which reviews the core programme, shows as an example, the $1\frac{1}{2}$ dogbone specimen and its double shear equivalent design.

All specimens in the core programme, namely all single and double shear designs, were manufactured from one material, i.e. the 5 mm thick 7050-T76 core programme material, which was furnished by the UK. Surface treatment, interlay sealant, load levels and load spectrum were specified (Annex 1). Two fastener systems were selected and specified (Annex 2):

- Fastener system A: a countersunk M1-Lok installed with clearance fit in a reamed hole (PRFS-A).
- Fastener system B: a countersunk M1-Lok installed with interference fit in a cold worked and reamed

hole (FRFS-B).

A third, optional, fastener system was defined because of completeness; this fastener system also had a countersink Hi-luk but it was installed with high interference in a reamed hole.

All core programme specimens then were fatigue tested to failure under FALSTAFF flight simulation loading. As in the other programmes, fit and surface roughness were measured during fastener installation (Annex 3). In addition to the fatigue tests, one specimen of each combination of specimen design and fastener system was instrumented with strain gauges to measure load transfer and secondary bending.

3.5 Assess to all details

The programme overview showed that various joint geometries were used to evaluate different materials, bolts, fastener systems, etc.

The tables refer to:

- e figures 1-12 for specimen configuration details;
- e table 8 for the mechanical properties of materials;
- e table 9 for the faying surface treatment details;
- e table 10 for the fastener systems.

It should be noted that the presentation of application and manufacturing instructions is beyond the scope of this report.

4. TEST PROCEDURES

The stress levels are given as gross area stress, unless otherwise indicated. Guidelines for testing have not been given since the Critically Loaded Hole Technology programme (reference 1) showed that:

- e the participating laboratories could apply spectrum loads satisfactorily;
- e there was the ability to generate consistent data in complex fatigue testing between the participants;
- e all the data generated at different laboratories were accepted by all participants.

4.1 Measurement of load transfer and secondary bending

Based upon the procedures of the LBF (FRG) and upon experience of SAAE-SCANIA and PFA (SW), RAE (UK) and the NLK (NL) standard procedures were developed (references 7, 8); these procedures are also given in Annex 4.

Each single shear joint was instrumented with a large number of strain gauges to determine the load transfer and secondary bending. Load transfer was also measured on the double shear equivalent specimens of the single shear core programme.

4.1.1 Secondary bending

Secondary bending is of interest at the fatigue critical cross section. Usually a crack started at a hole or at the faying surface close to a hole. The location of crack initiation was not accessible in most cases, so a neighbouring position was chosen for the measurement. The conventions adopted by the working group are given in figure 13. Jarfall (reference 9) showed that displacement of the strain gauge by 1/8 of a fastener diameter in the transverse direction changed the secondary bending by not more than 1 to 2 %; so the accuracy of positioning in transfer direction was not too critical. Positioning in the axial direction required a higher accuracy since the strain gradient was very steep; for a point at the same distance on the opposite side of the fastener the secondary bending was of the same order of magnitude but of reversed sign. Jarfall (reference 9) confirmed this using measurements on X type joints.

4.1.2 Load transfer

By definition the load transfer is the percentage of the total load transferred at a particular point of load transfer. The by-pass load (figure 13) was thus measured aft of each fastener row. Measurements by Eriksson and Magnusson (reference 10) showed that the strain distribution aft of the fastener row is not uniform; therefore, a row of strain gauges was bonded to allow integration over the member width. In order to minimize the number of strain gauges, strain gauges were bonded only at maxima and minima of the strain distribution.

Further, the gauges were located at equal distances (in the load direction) from points of load transfer. The distance between two fastener rows was usually 4 fastener diameters; thus the gauges were bonded at 2 diameter aft of the fastener row. Also strain gauges were bonded at both sides of the sheet to determine the axial strain (figure 13), which was used for the determination of the by-pass load.

4.2 Data recording

Individual data sheets were completed for each specimen:

- e the measurements of fit and surface roughness were recorded on the data sheet (Annex 3);
- e an example of the test data sheet, originating from the UK, is given in table 11;
- e the data sheet for reporting the load transfer and secondary bending measurements, see Annex 4.

5. SPECTRA

The fatigue tests were carried out mainly under FALSTAFF (Fighter Aircraft Loading Standard For Fatigue). A minority of the tests were done under the gust spectrum MINI-TWIST.

5.1 The manoeuvre spectrum FALSTAFF

FALSTAFF has been based on a large number of actual flight load-time histories pertaining to five different fighter aircraft types operated by three different Air Forces. The essential properties may be summarized as follows:

- a FALSTAFF represents a load sequence, defined by successive peaks and troughs, covering a "block" of 200 flights. This block size conforms with average European annual fighter utilisation.
- a The flights in FALSTAFF belong to three different groups of mission types: flight with repetitive patterns of severe manoeuvring (e.g. air-to-ground missions), flights with severe manoeuvring (e.g. air combat) and flights with only light to moderate manoeuvring (e.g. navigation mission).
- a The FALSTAFF sequence contains taxi load cycles. The majority of these taxi load cycles are associated with a crossing of zero-stress level.
- a The complete FALSTAFF sequence consists of 35966 numbers, ranging from 1 to 32. This complete sequence is contained in tabular form in reference 11. Moreover, this reference includes a complete FORTRAN listing of the program to generate FALSTAFF.
- a The "FALSTAFF load levels" ranging from 1 to 32 are Arbitrary Units. However, "zero"-stress level corresponds with FALSTAFF-level 7.5269. The smallest load variation ("omission level") considered is two FALSTAFF levels or approximately 8 per cent of the highest stress contained in FALSTAFF. The highest stress ("truncation level") considered is the one exceeded once per hundred flights.

Figure 14 and figure 15 show the load spectrum of FALSTAFF and some FALSTAFF flights respectively. The severity of the spectrum is usually identified by referencing the stress that a test specimen experiences at the highest load level in the spectrum. In this report the same convention is used.

5.2 The standard load sequences for transport aircraft wings TWIST and MINI-TWIST

The development of the standard TWIST (Transport Wing Standard) is fully described in reference 12. For testing purposes the spectrum has been approximated by the stepped function shown in figure 16. Stresses are expressed non-dimensionally by dividing them by the stress pertaining to undisturbed cruising flight, S_{mf} . There are ten gust load levels and one taxi load level. TWIST consists of blocks of 4000 different flights.

There are ten different flight types, ranging from storm (A) to calm (J) conditions. The frequency of occurrence of each flight type and of each load level within each type of flight is reported in table 12. The load sequence is completed by defining the sequence of application of the different flights and the sequence of loads within each flight. Basic properties of the defined sequences are:

- a The flights and loads for each flight are applied in a random sequence except that clustering of severe flights is not allowed.
- a The loads within each flight are applied in a random sequence of half-cycles such that a positive half-cycle is followed by a negative half-cycle of arbitrary magnitude.
- a Load sequences are generated individually for each flight. Thus flights of the same type generally have a different load sequence.

The positions of the severest flights in TWIST are: 1856 (type A); 2856 (type B); 301, 2936 and 1841 (type C).

The highest load to be included in the spectrum was chosen as the load that is exceeded approximately 10 times per aircraft life, or once per 4000 flights.

The main difference between TWIST and MINI-TWIST is that the latter contains considerably less load cycles of the smallest amplitude, resulting in approximately 15 load cycles per flight (table 12).

In the Fatigue Rated Fastener Systems programme a part of the tests were carried out under MINI-TWIST, which was truncated at level III; this version is designated as MINI-TWIST III.

The characteristic stress level is the mean stress level in flight, S_{mf} .

5.3 Constant amplitude loading

Some test series were also carried out under constant amplitude loading, having a stress ratio R (= minimum stress/maximum stress) of 0.1. The stress level indicated is the maximum stress.

6. METHODS FOR ANALYSING THE FRFS PROGRAMME DATA

A statistical analysis of the FRFS programme data has been carried out by Mr. J.M. Potter, Air Force Wright Aeronautical Laboratories, Dayton, Ohio, USA. It was assumed that each participant of the FRFS programme would use adequate statistical methodology within the portion of the programme for which they held responsibility.

The Northwest Analytical STATPAK software was used to perform the statistical analyses. The analysis methodology used was that of multiple linear regression. This methodology was chosen since it is useful where there exists more than one component affecting the performance of a product. In the FRFS programme the fatigue life is a product of several parameters (e.g. specimen design, stress, fastener type, material, interference, interface treatment, hole quality) whose interactions are not specifically defined. The FRFS programme compounds the problem by adding the variables of differing test organisations and manufacturing processes to result in a final report which has numerous intrinsic variations.

Multiple linear regression approaches assume that two or more variables are related to each other with an equation of the form given in equation 6.1.

$$Y = B_0 + B_1 \cdot X_1 + B_2 \cdot X_2 + B_3 \cdot X_3 + \dots + B_N \cdot X_N \quad (6.1)$$

where Y is the dependant variable and the X's are the independent variables and the B's are the coefficients which are calculated in the regression process. The STATPAK programme assumes that there is no significant interaction between the independent variables and that each variable contributes approximately equally to the regression.

As a completion of the statistical analysis the following correlations were made graphically:

- a open hole joints vs no load transfer joints;
- a no load transfer joints vs low load transfer joints;
- a low load transfer joints vs double shear joints;
- a secondary bending vs fatigue life;
- a load transfer vs fatigue life;
- a fatigue performance vs cost.

7. RESULTS OF THE FATIGUE RATED FASTENER SYSTEMS TESTING PROGRAMME

7.1 Presentation of fatigue life data

The complete set of fatigue life data for the FRFS programme is given in the tables 6-1 to 6-21 of Annex 6; the framed numbers are the log mean life figures.

The fatigue life data are plotted in figures 17 to 41 inclusive per participant and test schedule.

All stresses are gross area stresses, unless otherwise indicated.

7.2 Results of the measurements of secondary bending and load transfer

Secondary bending and load transfer have been determined on reverse double dogbone specimen, the single shear and double shear core programme specimens using standard instrumentation and procedures. Full details of the measurements are given in Annex 5, which also presents the secondary bending and load transfer as function of applied load. Table 13 summarizes the values of secondary bending and load transfer at the fatigue test stress levels.

- The following deviations from the standard procedures and instrumentation were observed:
- a the French type D double shear joint had broached instead of reamed holes; since the fit was within the specified range, this should not influence the results;
 - a the US type C2 lap joint was not instrumented according to the FRFS requirements: the secondary bending gauges were located too far from the fasteners. Therefore, a bending value was recorded which was too low. Further, contrary to its condition during the fatigue testing the specimen had no bending restraint during the measurements. No load transfer gauges were applied; the load transfer is estimated to be close to 50 % because the specimen is a two row joint;
 - a the double shear equivalent design of type C2 (USA) had side sheets which had twice the thickness as was specified. Moreover, the load transfer gauges were bonded only at the locations giving the lowest response, i.e. directly behind the fastener;
 - a the surface treatment of the French core programme specimen had only epoxy paint as surface treatment instead of primer + sealant;
 - a the Swedish I joints were provided with oversized holes.

7.2.1 Reverse double dogbone specimen

As an addition to the programme France instrumented and tested reverse double dogbone specimens, one not being made of 2024 and one of 7075, each containing two M1-loks mounted with high interference in reamed holes. Because this fastener system (and in particular the fit) were not the same as the core programme fastener systems (FRFS-A and -B) the results of the measurements cannot be compared directly with the results of the core programme measurements. Nevertheless, the results show interesting trends. There is a large difference in secondary bending and load transfer behaviour between the 2024- and 7075-alloy specimens. Secondary bending and load transfer are higher for the 2024-alloy specimen: the secondary bending ratio of .34 might be considered as a very high value for this joint type. It is noted here that the clamping procedure is crucial when using wedge type grips; exploratory tests at MIL showed that load transfer might even reverse if no special precautions were taken. It is essential to prevent relative motion of the two dogbones at the typical ends when clamping in. The solution used at MIL is given in figure 43. Germany used a pin loaded hole solution, figure 2b.

7.2.2 Core programme single shear joints

The effect of applied load on secondary bending is large for lap joint type specimen. A more moderate effect is observed on the Q type. The same classification applies to the effect of the fastener system on the secondary bending. A remarkably low bending is observed at the FRFS-A (clearance fit) 1½ dogbone specimen. The latter type shows more clearly the effect of the fastener system. In general the load transfer is less affected by the applied stress. Further, the influence of the fastener system on the load transfer variation is small for the lap joint and 1½ dogbone, and very small for the Q type joint. No secondary bending and load transfer measurements are available for X type joints with FRFS-A and -B. For reasons mentioned in 3.4.1 the load transfer is 50 % and is independent of the fit. The secondary bending ratio, determined in another programme, is about 0.80.

7.2.3 Core programme double shear joints

The C1 and D types show a negligible dependence of load transfer on the applied stress level. In both types the first fastener row, i.e. the first row where load is transferred from the base to the side sheets, has the highest load transfer, while the one or two fastener rows in the middle contribute only a little to the load transfer. The locations of highest load transfer correspond with the failure initiation sites. The change from a clearance fit to an interference fit results in an increase in end row load transfer and a decrease in load transfer in the middle fastener row(s). No load transfer measurements were made on type M₁, M₂ and N₁. The last is a two row joint i.e. it has a load transfer of 50 % whilst the load transfer of M₁, M₂ is estimated to be about 20 %.

7.3 Measured fit and surface roughness

The tables that present the fatigue life data, see Annex 6, give characteristic values of applied fit, either as an average value or as a range. The programme called for the measurement of fit and hole surface roughness. Some participants limited their efforts to the measurement of the diameter of a sample of the fastener and holes. The participants will report in detail on the measurements made. Hole surface roughness measurements were only made by two participants and are therefore not presented.

7.4 Cost of fastener systems

The cost of fastener systems consists of:

- equipment and tools;
- purchase cost, which depends on fastener type, fastener material and number of fasteners ordered;
- preparation of tooling, sealant etc.;
- installation:
 - positioning of tool
 - predrill
 - clamp
 - drill
 - deburr
 - inspection of hole
 - application of sealant/primer in hole
 - installation of fastener
 - inspection of fastener.

Table 13 reviews available information; cost are transposed into US dollars. The purchase cost per fastener drop sharply when the number of purchased pieces increases; for some fastener systems this is illustrated in figure 44. The relative cost of fastener systems can be compared using table 15. A comprehensive cost comparison can not be made because the total expenses should include not only the total direct costs such as fastener purchase cost and manhours for installation, but also writing off of equipment, cost of tooling, manhours for preparation, etc. The latter three cost elements can not be given as cost per fastener installation because the information necessary for this depends on the number of fasteners per component, total number of components etc. For illustration figures 45-46 detail the contribution of some cost elements that contribute to the total installation expenses. Evaluation of the costs of different fastener systems is very difficult.

First, the participants' data on the same fastener system deviate widely, as illustrated by the Taperlok system data. Nevertheless, this is the most time consuming fastener system. Special precautions should be taken to ensure that the structure is securely clamped together. Checking the hole for bearing area is a time consuming but essential operation. All operations must be closely controlled and carried out by skilled personnel. The cost of this taperlok fastener is high, but the cost of equipment and tools does not exceed that of standard fasteners. These costs are high for the equipment for cold work processes of which the split sleeve is the most time consuming. This is caused by the need to remove the sleeve and ream to size. It is noted that reaming and countersinking after the actual cold work process is not necessary any more in a new version of this cold work system.

7.5 Locations of primary fatigue crack origins

The programme description required the evaluation of fatigue lives in terms of fatigue crack initiation sites. Halfway through the programme all participants were requested to send fractured specimen halves to the NLR. It was the intention to examine and to determine the fatigue crack origins at a single source followed by the classification of the crack origins. However, this goal could not be achieved up to the moment the report was written. Fortunately, some participants identified and reported the primary fatigue crack origins themselves.

8. CORRELATION ANALYSIS

8.1 Correlation of fatigue lives of open hole specimen and no load transfer joints

Figure 17 presents the open hole specimen and NLT joint fatigue life data for the 2024 and 7010 alloys. Both specimen types do not end up with the same fatigue lives; the NLT joint gives the longer lives, except for the 7010 alloy in the lower stress level region. Further, the 7010 and 2024 alloy results, for each specimen type, are relatively close, but again with above exception. The results show that the presence of a transition fit fastener tends to give better fatigue lives compared to the open hole situation.

8.2 Correlation of fatigue lives of no load and low load transfer joints

Fatigue test data of both designs are available only for 2024 and 7050 specimens having an interference fit lockbolt fastener system (figure 47). The 7050 results are very promising; the slope is the same for both designs, while the low load transfer joints have a somewhat shorter fatigue life. The lives of the 2024 alloy specimen tested at the unrealistically high stress level are short. At the lower stress levels the slope is never the same for the two joints. But the general picture is, for both materials, that there is no significant difference in trends between the no load transfer and low load transfer joints. The statistical analysis indicates that a possibility exists that the no load transfer specimens could be substituted for the low load transfer joints to evaluate fastener systems. The likelihood of the same fastener retreating being observed in both specimen designs cannot be considered on the basis of the present results. It can only be concluded that the results point towards similar trends of the effect of stress level on the fatigue life.

8.3 Low load transfer joint fatigue life analysis results

The statistical analysis was limited to those specimens where the holes were not cold worked prior to fastener installation. A cold working independent variable would be possible but the data packages received did not contain the cold hole expansion measurements.

The data were analyzed with the only variables which had specific quantification associated with them; they were (1) fatigue life, (2) applied stress and (3) fastener interference. The effect of rasing compared with drilling of the fastener hole was analyzed separately in the case of the 7000 series aluminium specimens. The fastener interference was given as a positive number if there was interference between the pin and the hole; if there was clearance the interference was assumed to be zero for purposes of this analysis. In those cases where a range of interference was specified, the mean of the range was assumed. All material results were considered as a part of either a 2000 or a 7000 series aluminium pool.

The multiple linear regression analysis results are given in equations 8.1 and 8.2 for the reverse double dogbone 7000 and 2000 series aluminium alloy specimens, respectively.

$$N = 10^{\wedge} (5.734 - (0.006127) * Stress + (0.00364) * Interference) \quad (8.1)$$

$$N = 10^{\wedge} (7.075 - (0.013322) * Stress + (0.02210) * Interference) \quad (8.2)$$

where

N = fatigue life in flights (1ALSTAFF)
 Stress = maximum spectrum stress, MPa
 Interference = difference between fastener and hole size, μ m

The equations make sense in that the higher the stress, the shorter the fatigue life and the higher the interference the longer the life, as many investigations have confirmed qualitatively. The equations indicate that, for the range of data investigated, the 7000 series alloys have a longer fatigue life and have a steeper slope relative to the effect of stress than the 2000 series aluminium. At zero interference the crossover where the 7000 series becomes shorter lived is at a stress of 180.9 MPa and a life of 42250 flights.

A review of the data indicates an interesting trend in the effect of interference on fatigue performance. The coefficients of the 2000 series data are a factor of six greater than those of 7000 materials. It may be an unfair comparison since the majority of the 2000 coupons were manufactured within the range of 15 to 40 μ m interference with only the USA specimens at zero clearance (prior to rivetting) for two types of aluminium rivets which are themselves not considered to be high-performance, fatigue rated fasteners. The effect of interference calculated here is grossly overstated for the 2000 series aluminium coupons. The 7000 series data are considered to be more typical of interference fit fastened low load transfer specimens. The 7000 series data indicate that interference between fastener and hole results in a factor of approximately 50 percent increase in fatigue life for 30 μ m (0.002 inches) hole interference.

The analyses fit the data as can be seen in figures 48 and 49 for the 7000 and 2000 series aluminium alloy materials, respectively. In the 7000 series data, the multiple linear regression curve at zero interference appears to fall in the middle of the data whereas the 2000 series regression line is at the lower limit of the data. The 2000 series regression line appears to go through the middle of the USA data which had squeezed rivets installed. As discussed in the previous paragraph, the USA data were used as zero clearance data in the analysis; it is noted that some interference will be present after rivet installation.

Since the other data are significantly offset to the right of the USA data, the regression indicated a strong effect of interference on fatigue life for the 2000 series specimens. The 7000 series data have a much smaller coefficient of interference.

The data from the 7000 series aluminium alloy specimens were analysed in an attempt to determine the effect of drilling versus reaming of the fastener holes. This analysis illustrates one way to avoid the problem of calculating where a parameter has no quantitative variable associated with it. In this case, the independent value '1' was assigned to those specimens which were reamed and the value '0' to those which were drilled. In order to suitably complete this analysis the French specimen series which had broached holes were removed from the data set. The result is given in equation:

$$N = 10 \wedge (5.5974 - (0.00575) * \text{Stress} + (0.00380) * \text{Interference} - (0.000812) * \text{Ream}) \quad (8.3)$$

This equation is somewhat different from that of Eq. 8.1 not only because an additional term has been added but also because ten (10) specimens were removed from the data set when the French specimens were deleted. Note that the coefficients of the mean, stress and interference variables were changed less than 10 percent from those given in Eq. 8.1. The coefficient to the "Ream" variable is given as -0.000812. Since the "Ream" variable is limited in value to either '0' or '1' the effect on the equation is minimal from this coefficient. A typical effect of the "Ream" variable would be to change the fatigue life less than one percent. This analytical result should not be taken to be a recommendation to discontinue reaming, though. Reaming is of importance in making a precise hole in which a fastener may be installed at a known interference. Thus, the effect of reaming may already be included in the analysis in another independent variable such as "interference".

Systems that stand out in figure 48 are the French broached hole specimens with Lockbolt fasteners and the Netherlands double margin drilled holes compared to their standard drilled counterparts. These data were not further investigated using the multiple linear regression since there was no way to quantify the hole quality parameters.

In figure 49, the Italian test specimens at 280 MPa stand out above the remainder of the 2000 series aluminium specimens. Here, again, the French broached hole specimens have lives at the high end of the pooled fatigue life data. The USA aluminium riveted specimens reside at the lower end of the fatigue life data.

The multiple linear regression analysis methodology has been shown to be useful in determining the impact of different test and manufacturing processes on the fatigue performance of the AGARD reverse double dogbone specimens. The greatest success has occurred when the parameter of interest can be quantitatively defined so that its impact on fatigue performance can be calculated.

The multiple linear regression analysis results quantify -for instance- the effect of interference, whilst no information is given of the scatter. To illustrate the latter the ranges of fit and corresponding fatigue lives were plotted (figures 50, 51), showing that scatter is certainly not negligible when selecting fastener systems.

The beneficial effect of interference is illustrated clearly by the German results. MBH/FW calculated the stress situation close to the fastener hole. Figure 52 shows that a fastener oversize of 15 μm (# 6.35 mm) results in a tangential stress of about 94 MPa. An increase in fit to 40 μm gives a tangential stress of 250 MPa. The net effect of the interference fit approach is to reduce the alternating component of the stress while increasing the maximum one. The determination of the optimum interference is difficult. The increase in fit from a medium to a high value with the Taperlok gives only a moderate improvement in life. An interference of one per cent of the fastener diameter, in this case, might be considered as an optimum value (reference 13). No significant differences in life are observed when comparing the titanium and steel fasteners. Further, the fatigue quality of the double margin drilled holes is certainly not worse than that of the reamed holes.

The Italian results suggest that, in low load transfer joints, the effect of cold working is spoiled by subsequent application of a clearance fit. Further, the effect of hole diameter is fairly small, giving longer lives for the 5 mm hole. The differences in the life are small when comparing protruding, countersink, and tension countersink Hi-Loks.

Disregarding the small differences in life improvement factors the same trends are found under FALLSTAFF and MINI-TWIST III loading. However, scatter is larger under MINI-TWIST III loading (France, the Netherlands).

The hand bucked rivets, in low load transfer joints, give longer lives than the machine squeezed ones. This is more pronounced for the 2024 rivets than for the 7050 rivets.

The numerous fastener systems evaluated in the UK are discussed in detail in 8.4.

8.4 Comparison of UK and AGARD low load transfer joint design

The fatigue test results for the low load transfer standard specimens are given in Annex 6 and are shown in figure 28 along with the results of the UK main programme. Whilst the clearance fit results are very similar it should be noted that the life improvement due to cold working is greater in the AGARD joint than in the UK joint. The X-ray diffraction measurements of Dietrich and Potter (reference 14) indicate that the compression region around a cold expanded hole extends to a size approximately that of the hole diameter in large plates. Since the UK design LIT specimens have such short edge margin, it is possible that as high an amount of cold working could not be developed resulting in the lower fatigue life seen here. It is noticeable from the UK fracture surface examinations that the cold worked specimens have different failure modes: the UK joint failing from a fretting origin away from the bore of the hole whilst the AGARD joint fails from origins at the bore of the hole. It could be argued that the UK joint is strongly affected by cold working, since the failure origin is moved completely away from the hole.

8.5 Correlation of fatigue lives of double shear and low transfer joints

Results from France and the UK show that the lives of the reverse double dogbones are -comparing the means- shorter than the lives of the high load transfer double shear joints (figures 53-56), but scatter-bands may overlap (partly). The Dutch results (figure 57) show the contrary: the low load transfer joint has better fatigue characteristics than the HLT double shear joint. Next the fastener system rating in both designs is compared.

From figure 53 it follows that the UK results have a drawback when comparing the double shear and low load transfer joints: the test stress level ranges differ. Without considering this it is observed that the low load transfer joint mean results are situated in two clusters, clearance fit fasteners versus cold-worked holes or interference fit fasteners. With the exception of the Huckcrimp system, used on low load transfer joints, significant life improvements were gained by using life enhancement systems. The reason why the Huckcrimp fails to increase the fatigue life over the Hi-lok system is because the improved clamping has little effect in low load transfer situations. In high load transfer joints clamping can significantly improve the fatigue performance by providing a load path which by-passes the fastener.

The high load transfer joint results show that life improvement mechanisms are obviously more effective where the potential for improvement is the greatest. Improved clamping will have an effect only when a large load is transferred by the fastener; frictional clamping then becomes significant. With higher load transfer and/or higher alternating stress, i.e. when the relative movement between fastener and joint material is large, the interference fit reaches its full potential, resulting in a delay in the onset of cracking.

Cold working also delays the onset of cracking and due to the compressive residual stress field also retards early crack growth.

Comparing the fatigue lives of the Huck-EXL and the Hi-tigue fasteners (figure 54), the UK results suggest that both joints are not equivalent with regard to the rating of the fastener systems considered.

8.6 Double shear joints fatigue life analysis results

8.6.1 Participant programmes

The French results show, figures 30 and 31, that the specimens made of the 7050 and the 7075 alloys have nominally equivalent under both spectra, except for the high MINI-TWIST III stress level. Under both spectra the 2024 specimens have an equal or better performance at the two lower stress levels whilst a worse performance is found at the highest stress level. This difference in behaviour of the two aluminium alloy series was also found in the low load transfer joints programmes.

The results of two double shear designs, having a load transfer of about 20 % and 50 %, confirm the often observed behaviour that "lower load transfer gives higher lives". The high load transfer joints also show that cold work, in combination with clearance fit, is superior to a medium interference fit and, except at the highest stress level, to a high interference fit. But the British results show that the (split sleeve) cold work results fall, at both stress levels, in between the results of the high interference system (Hi-tigue and Taperlok) in such a way that the scatter bands overlap. This overlapping of the scatter bands prevents the making of a straight forward comparison and ranking of the fastener systems. Nevertheless, the UK results further suggest that, certainly at high stress levels, cold work in combination with a medium to high interference, as with the Huck-EXL, might have very good fatigue characteristics. Noteworthy is the effect of clamping in clearance fit system: this might give life improvements, as compared to the Hi-lok system, comparable with those gained using e.g. the Acrea cold work and Hi-tigue high interference systems. One problem might be the relaxation of clamping during the life.

8.6.2 Core programme

Using the high load transfer (type D) double shear joint it is shown that FKPS-X (cold-work and medium interference) is superior to FKPS-A (clearance fit), whilst the French high interference system, in its turn, gives significantly longer lives than FKPS-X. This also points to the conclusion of 8.6.1 that cold work used to be combined with medium to high interference fit fasteners. The correlation with the load transfer values will be made in 8.7.2.

The first observation is that scatter in single shear joints fatigue lives tends to be smaller than in double shear joints. This is because the secondary bending focussed the peak stress at the outer surface of the joint. The single shear fasteners tilt in clearance fit holes, thus having a smaller bearing area than in double shear joints. This factor, together with the fact that single shear joints have only one mating surface for load transfer by frictional forces, also cause differences in load transfer between single and double shear joints.

Figure 35 shows that there is no single slope for the two 2000 series alloys in the life-stress plot; the same applies for the two 7000 series alloys. At higher stress levels the 2024 alloy gives longer lives than the 2024 alloy specimen, and the 7075 alloy gives shorter lives than the 7050 alloy specimen.

The investigation into rivet type, rivet material and sheet thickness (figure 37) shows that in the thicker material in particular the application of the 7050 rivet gives a large increase in life compared to the 2024 rivet; this is most striking for the Briles rivets. However, the 7050 Briles rivets show the same fatigue characteristics as the standard countersunk rivet whilst the 2024 Briles rivet is certainly not better than the 2024 countersunk one. This results suggest no superior behaviour for the Briles rivet under the simulated condition.

The few results on the comparison of the slight press fit Hi-lok and the interference fit Sleevebolt (figure 38) show no differences in fatigue life when used in 1/2 dogbone specimen. Moreover, the results of these fastener systems fall in the scatterband of FKPS-A and -X results, which almost coincide. Thus different fastener systems tend to give comparable lives in 1/2 dogbone specimens.

8.7.2 Core programme

As pointed out in 3.4.2 all specimens, i.e. all single shear and their double shear equivalent designs, were manufactured from one material and provided with one type of surface treatment. One half of the specimens were installed with fastener system A (FRFS-A), which has a countersunk Hi-lok installed with clearance fit in a reamed hole. The other half was installed with FRFS-B: a countersunk Hi-lok installed with interference fit in a split sleeve cold worked and reamed hole.

This section analyses the results from this and the double shear core programme. The multiple linear regression analysis was performed on the single shear data, except for the X joint data. The equation which best fits the data is given as:

$$N = 10^{\wedge} (5.874 - (0.006507) * \text{stress} - (0.00994) * \text{secondary bending} + (0.009874) * \text{load transfer}) \quad (8.4)$$

The coefficients of the secondary bending and load transfer are approximately 0.01, indicating that a 100 percent value of either secondary bending or load transfer will result in a change in life of a factor near ten. According to this equation, secondary bending results in a decrease in life and load transfer results in an increase. It is noted that the analysis treats the secondary bending and load transfer as independent variables, but they are not in actual joints.

It was thought that it may be possible to superimpose the secondary bending stress onto the applied stress. This was done for the single shear specimens by multiplying the applied stress by a factor of $(1 + \text{secondary bending}/100)$. The resultant relationship is:

$$N = 10^{\wedge} (5.3822 - (0.003699) * (\text{stress} * (1 + \text{secondary bending}/100)) + (0.002200) * \text{load transfer}) \quad (8.5)$$

This statistical correlation resulted in approximately the same coefficient of correlation as that of eq. 8.4 but the load transfer coefficient is significantly lower. Apparently the expansion of the stress scale with the addition of the secondary bending lets the load transfer take on a different level of importance within the multiple linear regression. The degree of correlation in the equation indicates that secondary bending is a primary component in the fatigue behaviour of single shear specimens.

Figure 58 presents the fatigue test results of the core programme single shear, double shear equivalent and double shear designs. This figure also gives a regression line using equation 8.4, as an example.

The differences in life for single shear specimens with FRFS-A and with FRFS-B are small; in general, FRFS-B gives only a small improvement in life. There are three exceptions: the X joint, where there is a significant difference between the fatigue lives obtained with FRFS-A and FRFS-B (the FRFS-A series had slightly oversized holes, the FRFS-B series had very much oversized holes resulting in an average of 9 μ m clearance instead of 25 μ m interference), the Q joint, where there is no significant difference between the two fastener systems, thus illustrating that the increase in bending when going from FRFS-A to FRFS-B is in balance with the decrease in load transfer (table 13) and the C2 lap joint where the deviating correlation between fatigue life and stress level might be influenced by the bending restraint, preventing rotation and thus high secondary bending of the specimen at low loads and allowing rotation and thus high secondary bending ($SS \gg 1.00$) at the high stress level. The bending restraint was not used during the secondary bending and load transfer measurements. Consequently, the secondary bending value should not be used in the evaluation of the fatigue test results.

The small differences in fatigue lives under FRFS-A and -B allow a combined plot of fatigue life versus secondary bending to be made (figure 59). Excluding the C2 lap joint result, for reasons mentioned previously, a correlation is found between secondary bending, fatigue life and stress level; when increasing the stress level a reduction in life is found, but this reduction in life becomes more pronounced with increasing secondary bending. In conclusion, the beneficial effect of fatigue rated fastener systems is overshadowed by secondary bending of single shear joints. Load transfer plays a secondary role in this.

The double shear core programme results (figure 58) show, contrary to the single shear designs, a large life improvement when applying FRFS-B. It is noted that the results of the 1/4 dogbone double shear specimens with FRFS-B are an underestimation since two tests were stopped at about 100,000 flights and a third test was stopped due to test machine malfunctioning. This programme part also shows that the statement "the higher the load transfer, the shorter the fatigue life" could not be confirmed for all joints. It might be that small differences in the fit disturb the rating of joints on the basis of load transfer.

Comparison of the fatigue lives of single shear specimens and their double shear equivalent designs is only possible with the type C lap joint and the 1/4 dogbone specimen. The first type has such shorter lives for the single shear design. It is noted that the FRFS-A double shear equivalent specimen has a lower load transfer than its single shear counterpart. The double shear equivalent design of the 1/4 dogbone has longer lives only for FRFS-B. Fastener system A in the double shear equivalent design shows a somewhat smaller fatigue life than the 1/4 dogbone results; this is caused by the increase in load transfer in combination with a moderate fastener system quality when changing from a single shear to a double shear joint. It is noted that the French core programme specimens had only epoxy paint as interlayer surface treatment.

8.8 Correlation of fatigue lives and cost of fastener systems

For reasons mentioned in 7.4 only the total direct costs, i.e. the fastener purchase cost (based on 25000 pieces) and the manhours for hole manufacturing and fastener installation, can be evaluated in more detail. The cost/life plots (figure 60, a) show envelopes, the cost scale of which is affected strongly by the Taperlok system. If this system is omitted a general trend of better fatigue performance with increasing cost is observed in the high load transfer data. Exceptions to this trend are the Huck-EXL, which is more cost effective, and the Acra sleeve cold-working, which is somewhat less cost effective.

These conclusions relate to specific installation requirements, e.g. fit specimen design, etc. The cost correlation with low load transfer joint result is given in figure 62. For reasons given in 7.4 the results of different participants should not be correlated. Again, the cost effectiveness of some fatigue enhancement fastener system is difficult to deduce.

9. DISCUSSION

As mentioned in chapter 2 the report the primary objectives of the FRFS programme were:

1. to determine the fatigue lives for a range of fatigue rated fastener systems in different materials in combination with hole preparation techniques and installation parameters;
2. to establish the cost figures of the fastener system in relation to the fatigue performance;
3. to identify the prime parameters involved in fastener system selection;
4. to generate design data for a number of fastener systems;
5. to develop a reference datum for the comparison of test results produced in different countries using different specimen geometries;
6. to develop experimental methods for fastener system fatigue rating.

Each of the objectives will be discussed.

9.1 Determination of the fatigue lives

Between seven- and eight hundred specimens were fatigue tested in the framework of this programme. A minor part of the programme dealt with riveted lap joints. The fasteners ranged from standard bolt to tapered fasteners installed in holes, which were drilled, reamed or coldworked. The effect of the fit of the fastener system, being a primary installation parameter, was evaluated in detail. The shear materials used were from the 2000- and 7000-aluminium alloy series; the surface treatment, i.e. anodise, primer, sealant, etc. was applied per the participant's standard. The majority of the tests were carried out under FALSTAFF loading. In short: the first objective of the programme has been achieved.

9.2 Evaluation of the fastener system cost figures

The analysis (section 8.8) showed that the cost data of different participants could not be compared directly. However, the very detailed data of some participants give a clear insight into the cost elements of the different installation operations. The cold-working process results in longer installation times as compared to the "ordinary" fastener systems; in particular "post cold work" steps contribute to the extra time required, but it is understood that new developments will eliminate the reaming-to-size operation. The relatively long installation time of the Taperlok is the most striking observation. A general trend was observed when comparing the total direct installation costs with the fatigue lives obtained: increasing costs might result in a better fatigue performance. This was more marked where the potential for improvement is greatest i.e. the high load transfer double shear joints. Since moderate to high secondary bending tends to nullify the beneficial effect of fatigue enhancement fastener systems it seems not worthwhile to spend the extra costs of these systems. A better insight into the cost effectiveness for high load transfer double shear and low load transfer joints is obtained by comparing the ratio of total direct cost and the number of flights to failure for the various fastener systems. The figures 62 and 63 present these ratios for the fastener systems evaluated by the UK. The comparison of the ratios of the high load transfer double shear joint suggests that the Huck-EXL system is the most cost effective system of the ones evaluated. Moderately cost effective are the Huckcrimp and the Split Sleeve cold work systems and -to a somewhat lesser extent- the Hi-tigue system. The Acra cold work and especially the Taperlok system are highly cost ineffective; the latter applies also for the Hi-luk installed in clearance fit in combination with high load levels. The low load transfer joint results (figure 63) show that again the Huck-EXL is the most cost effective system. But, contrary to the double shear joint results, the Hi-tigue system is only a little less cost effective; the Huckcrimp system is as cost ineffective as the Taperlok system. Care should be taken when trying to establish the potential cost benefits or penalties in practical situations. It can be concluded that the second objective proved to be difficult to fulfil entirely. Nevertheless, the combination of cost and fatigue data given, together with above evaluation, will prove useful in the fastener system selection process.

9.3 Prime parameters in fastener system selection

The results of the correlation analyses suggest that the selection of the prime parameters should be achieved by joint geometry classification. Parameters describing the joint geometry are the secondary bending, load transfer and their dependence on the applied load.

These parameters are material dependent in low load transfer joints. For other joint types the effect of the material on the secondary bending, etc. was not established.

Load transfer plays a secondary rôle in the fatigue performance of simple shear joints. In the double shear (core) programme, differences in fastener system, in terms of life improvement, are clearly shown. Thus, load transfer is not as dominant as is the secondary bending in simple shear joints. Further, the fatigue life rating of the different designs does not correspond with the load transfer values measured in the core programme. This might be caused by the differences in interlay surface treatment (French specimen) and differences in fit as applied by the different participants. Considering other data it is concluded that fastener installation parameters (fit, clamping, cold work) and load transfer are also important parameters. It is suggested that hole manufacturing to size and fastener installation should be done at a single source for this kind of core programme.

Thus, fastener interference is a prime parameter, except when applied in single shear joints. However, no optimum value can be given. Results suggest that the interference should be at least 1 % of the fastener diameter. But with high load transfer in combination with high fatigue stress levels the cold work plus high interference is the prime parameter.

Last but not least: the cost of the fastener system, of course, is also a prime parameter. In conclusion: the FRFS programme not only identified the prime parameters in fastener system selection but also qualitatively evaluated them.

9.4 Design data

The large number of specimens tested and the numerous variables included in the programme yielded in a large amount of variable design data. It will be clear that the programme did not cover all variables, simply because the total programme was built around the various participant's individual choice of programme.

9.5 Reference datum

The core programme allowed a comparison of different joint geometries from various participants. Not only the fatigue tests, but in particular the determination of secondary bending, load transfer and fit contributed largely to the understanding of the behaviour of complex joints. The information obtained might serve as a good reference datum for comparison of test results to be produced in future. Moreover, the core programme results are a first step towards the definition of standard specimen for the evaluation of fatigue rated fastener systems, which will be a new ACARD SMP activity.

9.6 Experimental methods

Each participant used his own experimental techniques. The report focused on the clamping procedures of "clamping sensitive" joints as the reverse double dogbone and 1½ dogbone. Clamping sensitivity may occur when a joint does not transfer all loads from one base sheet to one other base sheet.

Experimental methods were developed with regard only to the measurement of secondary bending and load transfer. However, the pre-loading procedure should be specified exactly. The following preloading is proposed:

- 0 load → 100 % FALSTAFF → Min. load FALSTAFF → 0
- 5000 cycles: 0 load → 50 % FALSTAFF → 0
- 0 load → 100 % FALSTAFF → Min. load FALSTAFF → 0
- 5000 cycles: 0 load → 50 % FALSTAFF → 0
- 0 load → 100 % FALSTAFF → Min. load FALSTAFF → 0; at the 100 % FALSTAFF the measurements should be made.

Further, the form to record standard test information was not used widely in the programme. This is in contrast with the success of the form to record the measured fit. The procedures to measure the fit worked well.

10. CONCLUSIONS

The ACARD coordinated Fatigue Rated Fastener Systems programme has demonstrated that:

- (1) Secondary bending proved to be a prime parameter. At moderate to high values it tends to nullify the beneficial effect of fatigue enhancement fastener systems; the fastener installation parameters (fit, clamping and cold work) are no prime parameters in that situation.
- (2) Single shear joints are the most severely loaded joints with regard to fatigue.
- (3) When secondary bending is present the load transfer plays a secondary rôle.
- (4) At low to moderate secondary bending or at the absence of it the fit, clamping and cold work are prime parameters. At high load transfer and at high fatigue load levels the best results are obtained with cold worked holes plus high interference fit fasteners.
- (5) Double shear joints clearly show a fastener system rating under realistic fatigue loading; the life improvement mechanisms are more marked in these joints than in low load transfer/low secondary bending joints.
- (6) The low load transfer joints and the high load transfer double shear joint are not equivalent with regard to the fastener system rating and cost effectiveness.
- (7) Results suggest that the effect of stress level is the same for no load and low load transfer joints; the low load transfer joint has somewhat shorter lives.
- (8) The hole quality as such is not a prime parameter. However, dimensioning to size to obtain a close tolerance fit results in holes with good fatigue quality.

- (9) Increasing costs of the fastener system might result in a better fatigue performance, but
- moderate to high secondary bending tends to nullify the extra costs of fatigue enhancement fastener systems;
 - both in high load transfer double shear and in low load transfer joints the Huck-EXL system is the most cost effective and the Taperlok the most cost ineffective of the systems evaluated. The Huck-crimp system is moderately cost effective for the double shear joints and as cost effective as the Taperlok system in low load transfer joints; while the opposite applies for the Acree cold work system.
- The Split Sleeve cold work system is moderately cost effective for both types of joints, but it is understood that new developments will eliminate the time consuming, and thus costly, reaming to size operation. The clearance fit Hi-lok system is cost ineffective particularly at high load transfer in combination with high fatigue load levels;
- care should be taken when trying to establish the potential cost benefits or penalties in practical situations.
- (10) Valuable results and a large amount of design data were generated in international cooperation by combining participants programmes and adding core programmes.
- (11) The results of the core programmes provide an excellent basis for the comparison of test results produced using different specimens.
- (12) The core programme results are a first step towards the definition of standard specimens; the low load transfer core programme showed that the use of standard or reference specimen results in easily comparable fatigue test data.
- (13) Standardized fatigue test spectra are indispensable.
- (14) Fatigue tests on fastened joints should be accompanied by the determination of secondary bending and load transfer on each combination of specimen type, material and fastener system.
- (15) The requirements and standard instrumentation for the determination of secondary bending and load transfer need only to be adjusted -as proposed- with regard to the pre-loading procedure.
- (16) The diameters of each hole and fastener should be measured in fatigue test programmes, which evaluate bolted joints. The procedures adopted in this programme worked well.

11. REFERENCES

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TABLE 1
Participants of the Fatigue Rated Fastener System programme

COUNTRY	CODE	PARTICIPANTS	
FRANCE	F	Centre d'Essais Aeronautique de Toulouse-CEAT	J.P. Herteman
GERMANY	FRG	Verainigte Flugtechnische Werke VFW-MBB	K. Hoffar
ITALY	I	University of Pisa	G. Cevallini
THE NETHERLANDS	NL	National Aerospace Laboratory-NLR	H.W. van der Linden
SWEDEN	S	SAAB-SCANIA	L. Jarfall
UNITED KINGDOM	UK	Royal Aircraft Establishment	R. Cook
UNITED STATES OF AMERICA	USA	Air Force Materials Laboratory	R.B. Urzi
		Air Force Flight Dynamics Laboratory	J.M. Potter

TABLE 2
Fatigue Rated Fastener System programme parts

JOINT DESIGNS AND EXAMPLE	PARTICIPANTS PROGRAMMES	CORE PROGRAMMES
NO LOAD TRANSFER 	F S	F S
LOW LOAD TRANSFER  RDO	F FRG I NL UK USA	UK
H.L.T. DOUBLE SHEAR 	F S NL UK	F S NL
H.L.T. SINGLE SHEAR  1 1/2 DOGBONE	F S NL USA	F S NL UK USA

.... : for codes see table 1

TABLE 3
No load transfer joint programme

		PARTICIPANT			CORE PROGRAMME
		F		S	
MATERIAL	2024-T3 2024-T351 2214-T651 7475-T7351 7050-T7651	• • • •	•	•	•
FAYING SURFACE	ANODIZING, PAINT AND SEALANT BARE	•		•	•
HOLE QUALITY	BROACH REAM	•	•	•	• •
FASTENER	LOCKBOLT, CSK BOLT, CSK, HEX. RIVET, CSK, UN.	•	•	• •	•
FIT	TRANSITION INTERFERENCE	•	•	•	• •
SPECTEUN	FALSTAFF	•	•	•	•

TABLE 4
Low load transfer joint programme

[illegible]

TABLE 5
Double shear joint programme

DESIGN		PARTICIPANTS									
		F	NL				S		UK		
		III	II	II		II	II	II	II	II	II
MATERIAL	2024-T351	•	•	•	•	•	•	•			
	7050-T7651	•									
	7175-T7351	•									
	7010-T7651								•	•	•
FAYING SURFACE	ANODIZE etc.	•	•	•	•	•			•	•	•
	PRIMER	•	•	•	•	•			•	•	•
HOLE QUALITY	DM DRILL		•	•	•						
	REAM		•	•	•		•	•	•	•	
	BROACH	•									•
FASTENER	COLD WORK										
	HI-LOK	•	•	•	•	•			•	•	•
	TAPERLOK										
	HI-TIGUE								•	•	
	HUCK CRIMP								•	•	
FIT	HUCK-EXL						•	•			
	RIVET								•	•	
SPECTRUM	BOLT										
	CLEARANCE	•	•	•	•	•	•	•	•	•	•
	TRANSITION										
SPECTRUM	INTERFERENCE	•	•	•	•	•	•	•	•	•	•
	FALSTAFF	•	•	•	•	•	•	•	•	•	•
SPECTRUM	MINI-TWIST	•	•	•	•	•	•	•	•	•	•
	CONST. AMPL.	•	•	•	•	•	•	•	•	•	•
		•	•	•	•	•	•	•	•	•	•

TABLE 6
Single shear joint programme

DESIGN		PARTICIPANT			
		US	F	US	S
		II	III	II	II
MATERIAL	2024-T3	•	•	•	•
	2214-T3		•		
	7075-T76		•	•	
	7475-T7351		•		
FAYING SURFACE	CLAD	•			
	ANODIZE etc.		•	•	
HOLE QUALITY	PRIMER		•	•	
	SEALANT		•	•	
FASTENER	TOPCOAT			•	
	DRILL	•		•	
FIT	REAM				•
	BROACH		•		•
SPECTRUM	HI-LOK		•	•	
	LOCKBOLT	•		•	
	RIVET			•	
SPECTRUM	SLEEVBOLT				•
	BOLT				•
SPECTRUM	CLEARANCE				•
	TRANSITION	•	•	•	•
SPECTRUM	INTERFERENCE	•	•	•	•
	FALSTAFF	•	•	•	•

TABLE 7
Core programme on single shear joints

MEASUREMENT OF SECONDARY
BENDING AND LOAD TRANSFER

FATIGUE TESTS ON SINGLE
SHEAR JOINTS AND THEIR
DOUBLE SHEAR EQUIVALENT
DESIGNS:



ALL SPECIMENS:

- o MATERIAL ALUMINIUM
7080-T76, $t = 6 \text{ mm}$
- o INTERFAY: EPOXY PRIMER
AND PR-1431-G SEALANT
- o TWO FASTENER SYSTEMS



FASTENER SYSTEM CODE	HOLE QUALITY	FASTEN- ER	FIT CLEARANCE -INTERFERENCE
A	REAM		20^{+10}
B	3 rd % COLD WORK AND REAM	HI-LOK HL-18-6-7 CSK $\phi 8.35 \text{ mm}$	-25^{+10}
C OPTIONAL	REAM		-80^{+10}

TABLE 8
Mechanical properties of materials

SEQUENCE NUMBER	PARTICIPANT	ALLOY	HEAT TREATMENT	STARTING THICKNESS - FINAL THICKNESS (mm)	DIRECTION	TENSILE YIELD STRESS (MPa)	ULTIMATE STRESS (MPa)	ELONGATION %	YOUNG'S MODULUS (MPa)	REMARKS	MANUFACTURER
1	FRANCE	2024	T351	4.5 -	L	345	482	20.8			CECEDUR
2		2024	T351	12 -	T	372	486	19			ALCOA
3		2024	T351	50 -	T	358	482	14.3			CECEDUR
4		2214	T651	50 -	R	311	423	5.8			CECEDUR
					T	481	510	10			CECEDUR
					S	444	508	5.1			ALCOA
5		7050	T7051	5	T	565	582	12		AGARD MATERIAL 1)	ALCOA
6		7050	T7051	19 -	L	492	543	11			ALCOA
					T	491	543	12			CECEDUR
7		7075	T7351	18 -	T	425	437	12			CECEDUR
8		7475	T7351	55 -	L	444	510	8.8			CECEDUR
					T	443	508	11.7			CECEDUR
					S	417	504	7.8			CECEDUR
9	FED. REP.	2024	T3	5	L	151.7	470.8	20.7	68243		CECEDUR
10	GERMANY	7050	T70	5	L	518.0	570.0	15.1	68671	AGARD MATERIAL 1)	ALCOA
11	ITALY	2024	T351	5							ALCOA
12	THE NETHERLANDS	2024	T3							AGARD MATERIAL 1)	ALCOA
13		7050	T70								ALCOA
14	UK	7010	T1001	19 -	L	430	530	8		AGARD MATERIAL 1)	AL
15		7050	T70	5						AGARD MATERIAL 1)	AL
16	USA	2024	T3	3.2						CLAD	
17		2024	T351	1.4						CLAD	
				2.3						CLAD	
18	CHN	7050	T70	5						AGARD MATERIAL 1)	ALCOA
19	FRANCE	7075	T70	3.2						AGARD MATERIAL 1)	ALCOA
20	RUSSIA	2024	T3	5	L	368	486	19.5	73200		ALCOA
21		7010	T70051	124-6	L	431	498	12.0	70700		ALCOA
22		7050	T70	5	L	532	566	15.0	76000	AGARD MATERIAL	ALCOA

and information 1

TABLE 9
Faying surface treatment

SEQUENCE NUMBER	PARTICIPANT	ANODIZING LAYER	PRIMER	ISOPREP	SEALANT	PAINTING INSTALLATION
1	FRANCE	-	SPRAY PRIMER 70-50 ANV	SPRAY 70-50 ANV	-	WET
2		-	SPRAY PRIMER 100-50 ANV	SPRAY 70-50 ANV	-	WET
3		SPN	PRIMER	-	PR1001-2	WET
4		ALUMINUM 1000	PRIMER	-	PR1002	WET
5	GERMANY	ANODIZING	SPIN COATING PRIMER	-	PR1004C	WET WITH PR1000
6		ANODIZING	SPIN COATING PRIMER	-	PR1004C	WET, for 1000-50 only
7	ITALY	ANODIZING	PRIMER	-	PR1003C	WET WITH PR1001
8	THE NETHERLANDS	-	PRIMER	-	PR1001C type 1	WET
9		CHEMICAL ALN	ANODIZING PRIMER 70-50	-	PR1004C	WET
10		-	SPRAY PRIMER	-	PR1001C	WET
11	UNITED KINGDOM	ALUMINUM	SPRAY PRIMER	-	PR1004C PR1002 AA	WET WITH PR1002 AA
12	USA	-	-	-	-	-
13		CHEMICAL	SPRAY PRIMER	FOR COMPOSITE PAINT	-	-
14	CHN	-	SPRAY PRIMER	-	PR1001C	PR1001 A + B
15	CHN	-	SPRAY PRIMER	-	PR1001C	WET

TABLE 10
Fastener systems

SEQUENCE NUMBER	PARTICIPANT	HOLE PRODUCTION STEPS	FASTENER	PIT (um)
1	FRANCE	BEAM TO Ø 6.15 HOLE	NI-LOK Ø 6.35, Steel, CSK	CLEARANCE 10-30
2		BROACH TO Ø 6.15 HOLE	NI-LOK Ø 6.35, Ti, CSK	CLEARANCE 10-30
3		BEAM (Ø 5.11-5.97) - COLD WORKING 1 X - BEAM TO Ø 5.5	NI-LOK Ø 6.35, Steel, CSK	INTERFERENCE 15-25
4		BEAM (Ø 5.71-5.97) - COLD WORKING 1 Y - BEAM TO Ø 6.15	NI-LOK Ø 6.35, Ti, CSK	INTERFERENCE 15-25
5		BROACH TO Ø 6 HOLE	LOCKBOLT SL Ø 6, TRAV, CSK	INTERFERENCE 16-32
6		BEAM TO Ø 6.31 HOLE	NI-LOK Ø 6.35, TRAV, Ball nose	INTERFERENCE 80
7	P.B. CERNANT	BEAM TO Ø 6.30 (N7)	NI-LOK NI10VP-8-7, COLLAR NI70-8	INTERFERENCE 17
8		DOUBLE MARGIN DRILL TO Ø 6.26 (N11)	DITTO	INTERFERENCE 16
9		BEAM TO Ø 6.30 (N7)	DITTO	INTERFERENCE 22
10		DOUBLE MARGIN DRILL TO Ø 6.26 (N11)	DITTO	INTERFERENCE 40
11		BEAM TO Ø 6.14 AND 6.30 (N7)	DITTO	CLEARANCE 12
12		BEAM TO Ø 6.29 (N7)	LOCKBOLT BALP P-T 8-07, COLLAR 6 LC-C 8	INTERFERENCE 15
13		DOUBLE MARGIN DRILL TO Ø 6.26 (N11)	DITTO	INTERFERENCE 21
14		DITTO	LOCKBOLT CPL 5 SP-07 08-7, COLLAR 1 SCI-C-6	INTERFERENCE 42
15	ITALY	TAPLOCK BEAMER (TFL 2000 BR 3-4)	TAPLOCK TLM 200-4-4, COLLAR TLM 1010-4	INTERFERENCE 17
16		DRILL Ø 6.5 (MANUAL) - BEAM Ø 9.00 - see table 155	NI-LOK Ø 5, Ti, CSK, SHEAR TYPE, LN 29797-05	INTERFERENCE 13-45
17		DRILL Ø 5.1 (MANUAL) - BEAM Ø 6.00 - see table 156	NI-LOK Ø 6, Ti, CSK, SHEAR TYPE, LN 29797-06	INTERFERENCE 13-45
18		DRILL Ø 5.5 (MANUAL) - BEAM Ø 6.00 - see table 170	NI-LOK Ø 6, Ti, CSK, TENSILE TYPE, PAN 3215-06	INTERFERENCE 13-45
19		DRILL Ø 5.5 (MANUAL) - BEAM Ø 6.00 - see table 170	NI-LOK, Ø 6, Ti, PROTRUDING, SHEAR TYPE, LN 29796-06	INTERFERENCE 13-45
20		DRILL Ø 7.5 (MANUAL) - BEAM Ø 9.00 - see table 158	NI-LOK, Ø 8, Ti, CSK, SHEAR TYPE, LN 29797-08	INTERFERENCE 16-51
21		DRILL Ø 5.25-5.134 - SPLIT SLEEVE COLD WORK 3.51-4.81 X - BEAM Ø 6.00 - see table 1066	STO. BOLT, Ø 6, Ti, CSK, LN 29924-06	CLEARANCE 10-40
22		BEAM - see 17 -	NI-LOK, Ø 6, Ti, CSK, NI2111-06-11	INTERFERENCE 13-45
23		COLD WORK, BEAM - see 21 -	SIMILAR TO LN 29797	INTERFERENCE 15-45
24	TNE	DOUBLE MARGIN DRILL Ø .7445" - see table 5 -	STO. BOLT, Ø 6, Ti, CSK, LN 29924-06	INTERFERENCE 15-45
25	NETHERLANDS	STANDARD DRILL Ø 6.4 - see table 6 -	NI-LOK NI10VP-8-7, PROT., Ø 6.35	TRANSITION 21-26
26		DOUBLE MARGIN DRILL - see table 1 -	DITTO	CLEARANCE 63-255
27		BEAM - see table 7 -	NI-LOK NI 15-N-7, CSK, Ø 6.35	INTERFERENCE 70-40
28		COLD WORK 5.86 X - BEAM - see table 7 -	DITTO	INTERFERENCE 60-100
29	UK	DRILL-BEAM TO Ø .7500"-.7100" (N5)-CSK-DEBURS	DITTO	CLEARANCE 8-23
30		DRILL-TAPER BEAMER	NI-LOK 8-FAST NUT (60-80 160 16)	
31		DRILL-BEAM TO Ø .7445"-.7400" (N5)-CSK-DEBURS	TAPERLOCK	
32		DRILL-BEAM TO Ø .7500"-.7500" (N5)-CSK-DEBURS	NI-TIGHE 8-FAST NUT (90-100 160 16)	
33		DRILL/CSK TO Ø .730"-.741" USING MUCK CONSIDERED CUTTER-DRIVEN-MUCK HANDREX COLD WORK TO Ø .744"-.749"	HUCKING-NUT (60 16 16)	
34		DRILL-BEAM TO Ø .715"-.710" (N5)-CSK-DEBURS LIGHTLY-REPLY SLEEVES COLD WORK-BEAM TO Ø .740"-.749" CSK DEBURS	MUCK KIL, COLLAR WITH MUCK SHALING TOOL	
35		DRILL-BEAM TO Ø .755"-.760" (N5)-CSK-DEBURS-INSERT COLD WORKING MUCK SLEEVES NUT	NI-LOK 8-FAST NUT (60-80 16 16)	
36			NI-LOK 8-FAST NUT (60-80 16 16)	
37			25-31: TUCKER VALVE CONFIRMED AFTER 1 HOUR OF INITIAL FASTENING AND IMMEDIATELY PRIOR TO TESTING	
38	USA	STANDARD DRILL-DEBURS	SOLID RIVET (MS 20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	1050-1
39		STANDARD DRILL-DEBURS For MIL-STD-883C, Table 2.1.2 (a), 2001	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	2024
40		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
41		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
42		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
43		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
44		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
45		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
46		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
47		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
48		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
49		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
50		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
51		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
52		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
53		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
54		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
55		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
56		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
57		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
58		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
59		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
60		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
61		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
62		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
63		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
64		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
65		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
66		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
67		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
68		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
69		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
70		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
71		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
72		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
73		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
74		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
75		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
76		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
77		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
78		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
79		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
80		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
81		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
82		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
83		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
84		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
85		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
86		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
87		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
88		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
89		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
90		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
91		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
92		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
93		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
94		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
95		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
96		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
97		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
98		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
99		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	
100		DITTO	RIVET Ø 1/16" (MS20470) 2024-T3 (D6), 7070-T73 (B), MACHINED	

DIMENSIONS IN mm

TABLE 11
Standard test information to be recorded

FATIGUE TEST

(a) General Data

Date and location of testing
Manufacturer/model of fatigue test machine
Test temperature (°C)
Relative humidity (%).

(b) Specimen Data

Material specifications
Type of specimen, including interlayer compounds, etc.
Specimen identification
Type of surface (machining history and treatment)
Fastener system: fastener type
dry/wet installed
fit
hole preparation technique
Installation costs of the fastener system.

(c) Test Data

Type of loading
Mean cyclic frequency
Frequency of maximum load excursion (for standard spectrum loading)
Characteristic stress levels (mean, or peak stress for standard spectrum loading)
Cyclic waveform
Number of cycles or flights to failure
Fracture surface observations including initiation sites.

TABLE 12
Definition of flight types and number of load cycles within each flight for TWIST and MINI-TWIST
(if different, figures between brackets refer to MINI-TWIST; otherwise MINI-TWIST equal to TWIST)

Flight type	Number of flights in one block of 4000 flights	Number of gust loads (full cycles) at the 10 amplitude levels										Total number of cycles per flight
		I	II	III	IV	V	VI	VII	VIII	IX	X	
A	1	1	1	1	4	8	16	64	112	391	900 (0)	1500 (600)
B	1	1	1	1	2	5	11	39	78	388 (385)	899 (0)	1400 (520)
C	1	1	1	1	1	2	7	22	61	277 (286)	878 (0)	1250 (380)
D	4				1	1	2	14	44	208	680 (0)	950 (270)
E						1	1	8	24	185 (168)	503 (0)	800 (200)
F	80						1	3	19	115 (107)	312 (0)	650 (150)
G	181							1	7	70 (721)	412 (0)	490 (80)
H	420								1	16	233 (23)	250 (80)
I	1090									1	89 (4)	70 (5)
J	2711										25 (2)	25 (2)
Total number of cycles per block of 4000 flights		1	2	5	18	52	152	800	4170	34800	35865 (18422)	
Cumulative number of load cycles per block of 4000 flights		1	3	8	26	78	230	1030	5200	10000	39863 (58422)	

TABLE 13
Secondary bending and load transfer of single shear core programme
specimens at fatigue test stress levels

SINGLE SHEAR CORE PROGRAMME SPECIMEN	STRESS LEVEL (MPa)	FRFS-A		FRFS-B	
		SB	LT (%)	SB	LT (%)
TYPE C 	150	1.32	54	1.52	41
	200	1.23	54	1.42	43
TYPE Q 	210	.42	47	.53	43
	263	.44	49	.53	43
TYPE C2 	150	-	[1.08] ①	-	50
	200	-	[.07] ②	-	50
1 1/2 DOGBONE 	200	.04	25.4	.21	22.7
	250	.09	25.8	.22	23.0
X JOINT 	150	.80	50		③

SINGLE SHEAR CORE PROGRAMME SPECIMEN	STRESS LEVEL (MPa)	FRFS-A	FRFS-B
		LT (%)	LT (%)
TYPE J1 DS-JOINT 	150	45.8	42.0
	200	46.0	43.8
	250	46.7	44.4
TYPE D DS-JOINT 	200	33.8	41.8
	250	33.9	41.7
1 1/2 DS DOGBONE 	200	35	41
	250	35	40
DOUBLE SHEAR OF TYPE C2 	150	-	[47] ②
	200	-	[50] ④
TYPE M1 & M2 	NOMINAL VALUE LT = 20 % ③		
TYPE H1 	NOMINAL VALUE LT = 50 % ③		

① without bending restraints

② instrumentation not in accordance with requirements

③ nominal value, not measured with FRFS-A, -B; measured in:

8 mm plate: SB = 0.83

4 mm plate (150 MPa): SB = 0.73 LT = 47

(50 MPa) LT = 50

④ side sheets t instead t/2

TABLE 14
Cost of fastener systems

PARTICIPANT	FASTENER SYSTEM	COST OF EQUIPMENT AND TOOLS (\$)	①	PREPARING TIME	②	TOTAL COST PER 1000 FASTENER INSTALLATIONS (\$) (7)
			COST PER FASTENER (\$)		INSTALLATION TIME PER FASTENER (min) * predrill up to installation	
GERMANY	HI-LOK + DM	-	1.36	1.14 min. (1)	1.16	1723
	(CP) LOCKBOLT + DM	-	0.48	.62 min. (1)	1.08	818
	TAPERLOK	-	1.44	2.39 min. (1)	3.18	2436
ITALY	T1 HI-LOK CSK SHEAR	-	1.00		1.54	1483
	T1 HI-LOK PROTR. SHEAR	-	-		1.51	1473
	T1 HI-LOK CSK TENSION	-	-		1.60	1526
	CW+TI HI-LOK CSK SHEAR	-	25000		2.64	1827
	CW+TI STD. BOLT CSK	-	0.64 (2)		2.78	1811
THE NETHERLANDS	HI-LOK/STD. OR DM DRILL	-	1.12 per	1.56 h (4)	5.21 (5)	2126
	HI-LOK/REAM	-	1.12 25000	1.80 h (4)	3.52 (5)	2239
	HI-LOK/CW + REAM	-	1.42 (3)	2.28 h (4)	4.29 (5)	2764
UNITED KINGDOM	HI-LOK/PLANE HOLE	1019	1.51		5.2	1483
	TAPERLOK	1080	3.48		26.0	11627
	HUCK-EXL	540	.67		7.0	2863
	HI-TIGUE	1046	1.17 per		5.5	3433
	HUCKCRIMP	587	.73 5000		7.0	2923
	HI-LOK + CW	4271	1.58 (5)		10.3	4807
USA	HI-LOK + ACRES CW	2098	1.89 (3)		8.3	4491
	HI-LOK SLEEVBOLT				54 (6) 60 (6)	- -

NOTES: (1) includes preparation of tooling, sealant and of inspection
(2) without cost of sleeve
(3) inclusive cost of sleeve
(4) indicated time is per test series
(5) inclusive sealant and primer application
(6) includes hole and fastener inspection
(7) assumed: 1 manhour = \$ 18.8

TABLE 15
Relative cost of fastener system

PARTICIPANT	FASTENER SYSTEM	RELATIVE COST OF EQUIPMENT AND TOOLS	RELATIVE COST PER FASTENER	RELATIVE PREPARING TIME	RELATIVE INSTALLATION TIME PER FASTENER	RELATIVE TOTAL COST PER FASTENER INSTALLATION
GERMANY	HI-LOK + DM	-	100	100	100	100
	(CP)-LOCKBOLT + DM	-	35	54	93	47
	TAPERLOK	-	106	210	274	141
ITALY	T1 HI-LOK CSK SHEAR	-	100	-	100	100
	T1 HI-LOK PROTR. SHEAR	-	-	-	98	99
	T1 HI-LOK CSK TENSION	-	-	-	109	103
	CW+TI HI-LOK CSK SHEAR	-	-	-	171	123
	CW+TI STD BOLT CSK	-	64	-	181	122
THE NETHERLANDS	HI-LOK/STD. OR DM DRILL	-	100	100	100	100
	HI-LOK/REAM	-	100	115	111	105
	HI-LOK/CW + REAM	-	127	146	134	130
UNITED KINGDOM	HI-LOK/PLANE HOLE	100	100	-	100	100
	TAPERLOK	106	230	-	500	691
	HUCK-EXL	53	45	-	135	170
	HI-TIGUE	103	113	-	106	204
	HUCKCRIMP	58	48	-	135	174
	HI-LOK + CW	419	104	-	198	286
USA	HI-LOK + ACRES CW	206	125	-	160	267
	HI-LOK SLEEVBOLT	-	-	-	100 111	- -

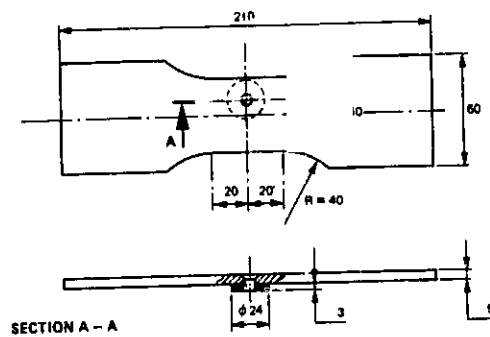


Fig. 1a No load transfer specimen - French design "B"

(F)
DIMENSIONS IN mm

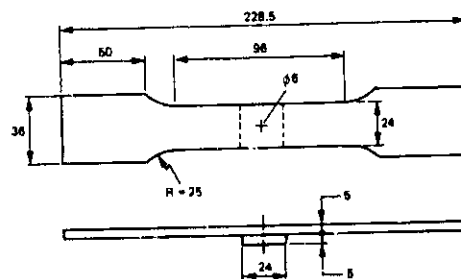


Fig. 1b No load transfer specimen - Sweden

(S)
DIMENSIONS IN mm

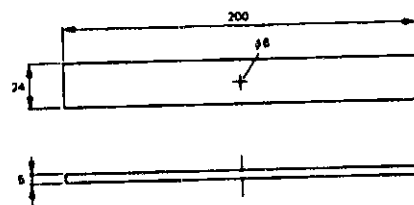


Fig. 1c No load transfer open hole specimen - Sweden

(S)
DIMENSIONS IN mm

Fig. 2a AGARD low load transfer reverse double dogbone specimen

CLAMPING AREA

RE

DIMENSIONS IN mm

Fig. 2b AGARD low load transfer reverse double dogbone specimen
(specimen configuration of FRG)

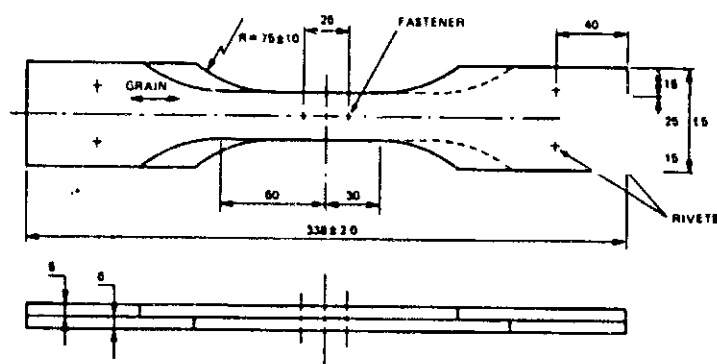


Fig. 2c UK low load transfer reverse double dogbone specimen

UK

DIMENSIONS IN mm

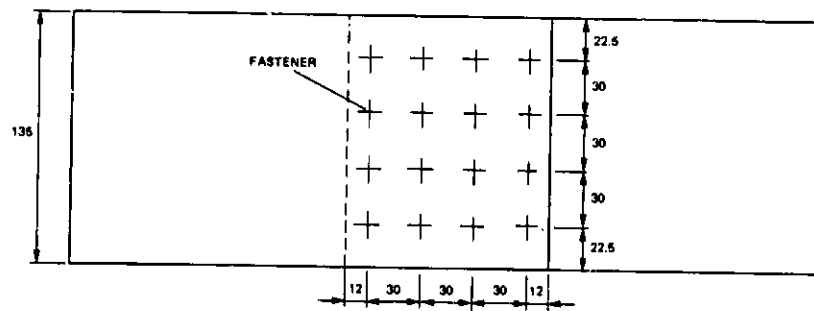


Fig. 3 High load transfer double shear joint, type D - France

F

DIMENSIONS IN mm

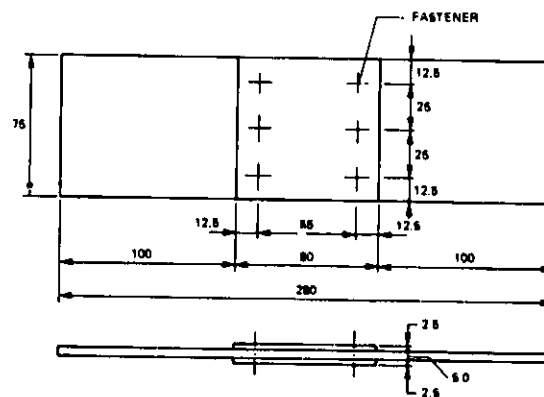


Fig. 4a Medium load transfer double shear joint, type M1 - the Netherlands

NL

DIMENSIONS IN mm

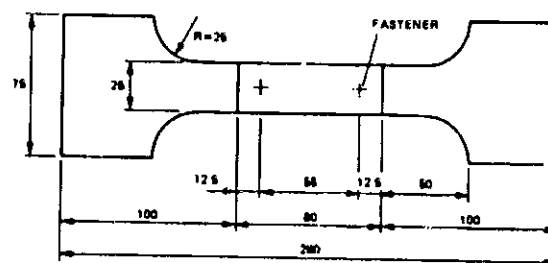


Fig. 4b Medium load transfer double shear joint, type M2 - the Netherlands

NL

DIMENSIONS IN mm

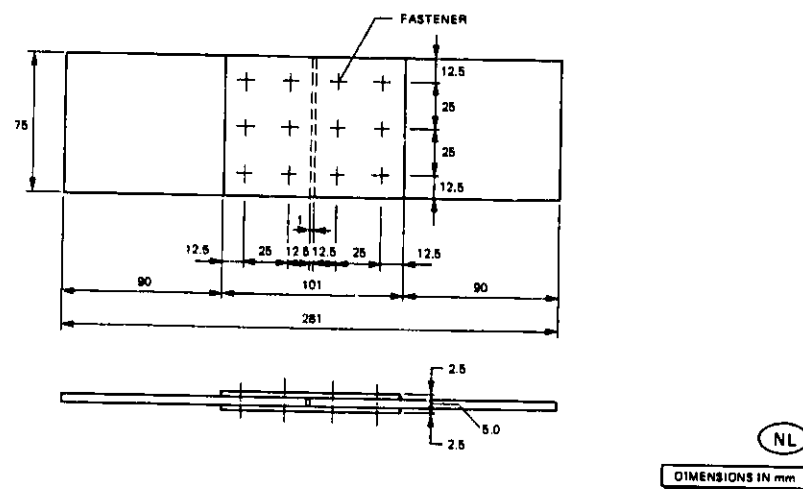


Fig. 5 High load transfer double shear joint, type H1 - the Netherlands

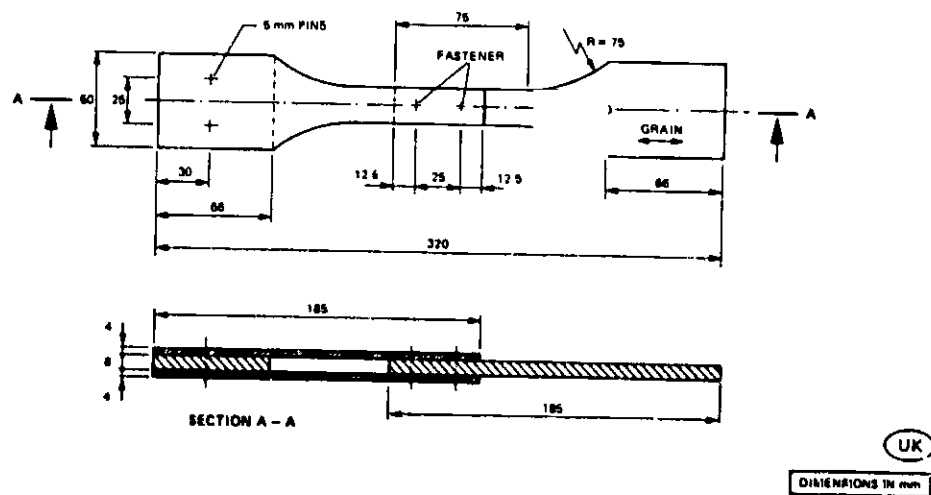
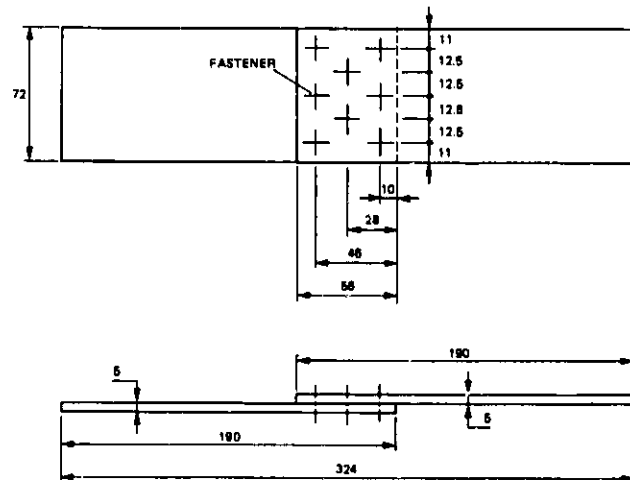


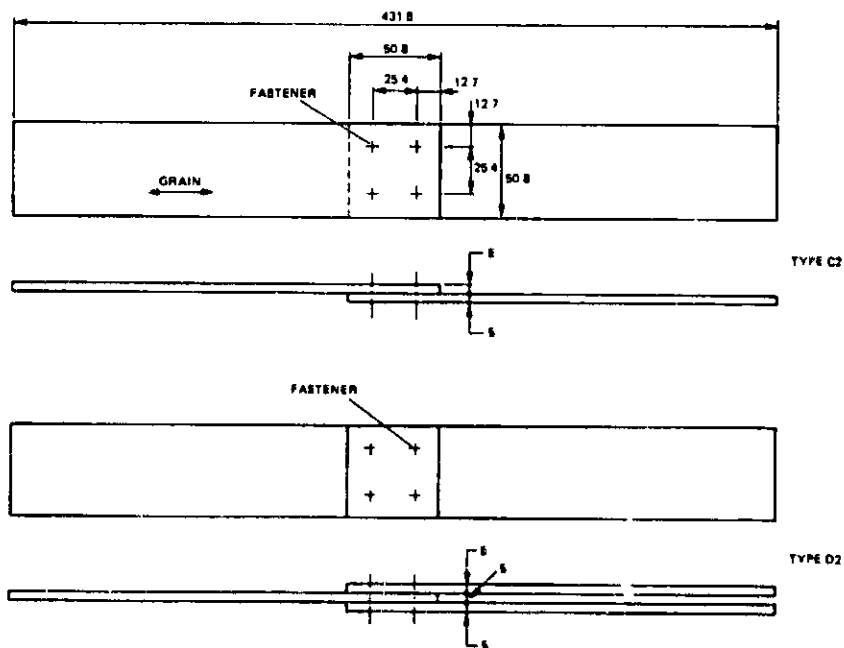
Fig. 6 High load transfer double shear joint, type H2 - United Kingdom



F

DIMENSIONS IN mm

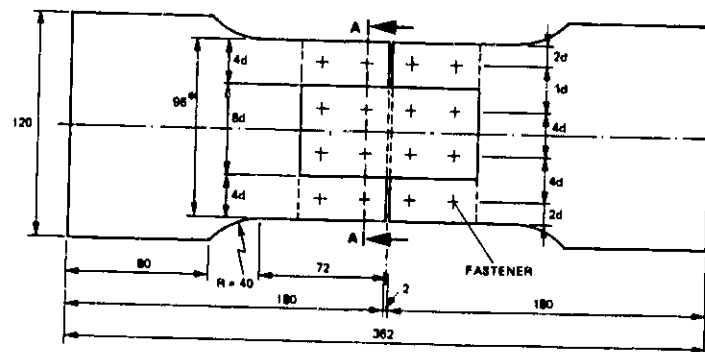
Fig. 7 High load transfer single shear joint, type C - France



USA

DIMENSIONS IN mm

Fig. 8 High load transfer lap joint specimen, type C2, and its double shear equivalent, type D2 - USA



TYPE 1

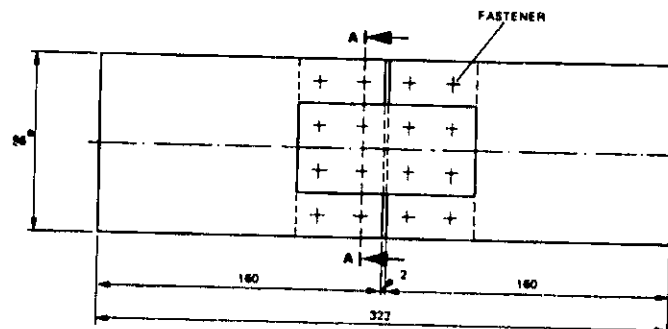
TYPE 2
FOR DIMENSIONS
SEE TYPE 1
ABOVE* FOR $d = 8 \text{ mm}$

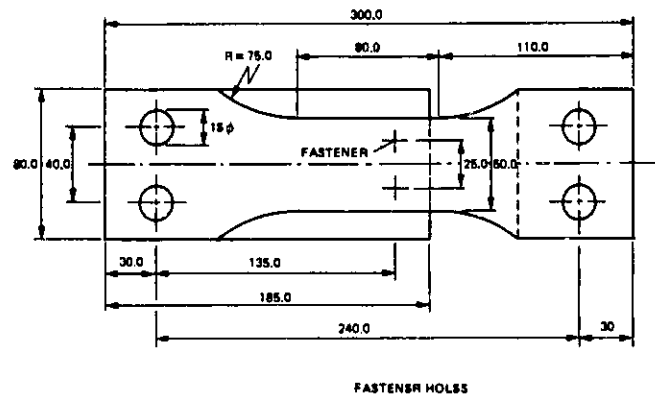
Fig. 9 High load transfer single shear X joints - Sweden



SECTION A - A

Fig. 10 High load transfer Q joint - United Kingdom

UK
DIMENSIONS IN mm

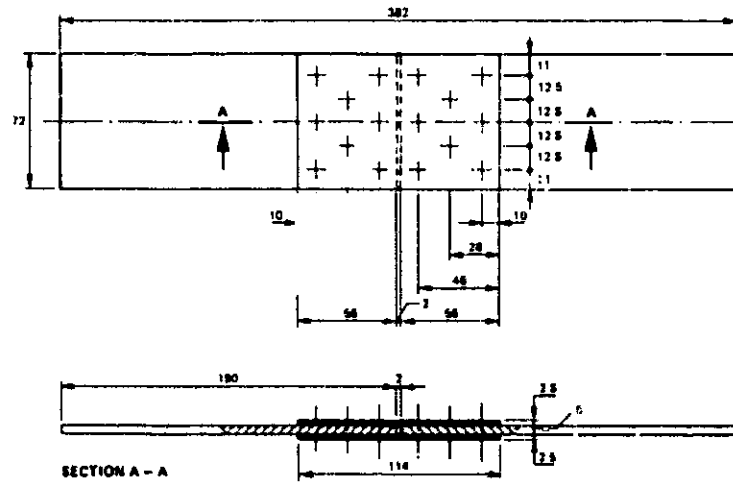


TYPE 1 1/2 D (USA) (NL)

TYPE 1 1/2 DS (NL)

DIMENSIONS IN mm

Fig. 11 The 1 1/2-dogbone specimen, type 1 1/2 D, and its double shear equivalent design, type 1 1/2 DS - USA (1 1/2 D type) and the Netherlands (both types)



(F)

DIMENSIONS IN mm

Fig. 12 High load transfer double shear joint, type C1 - France

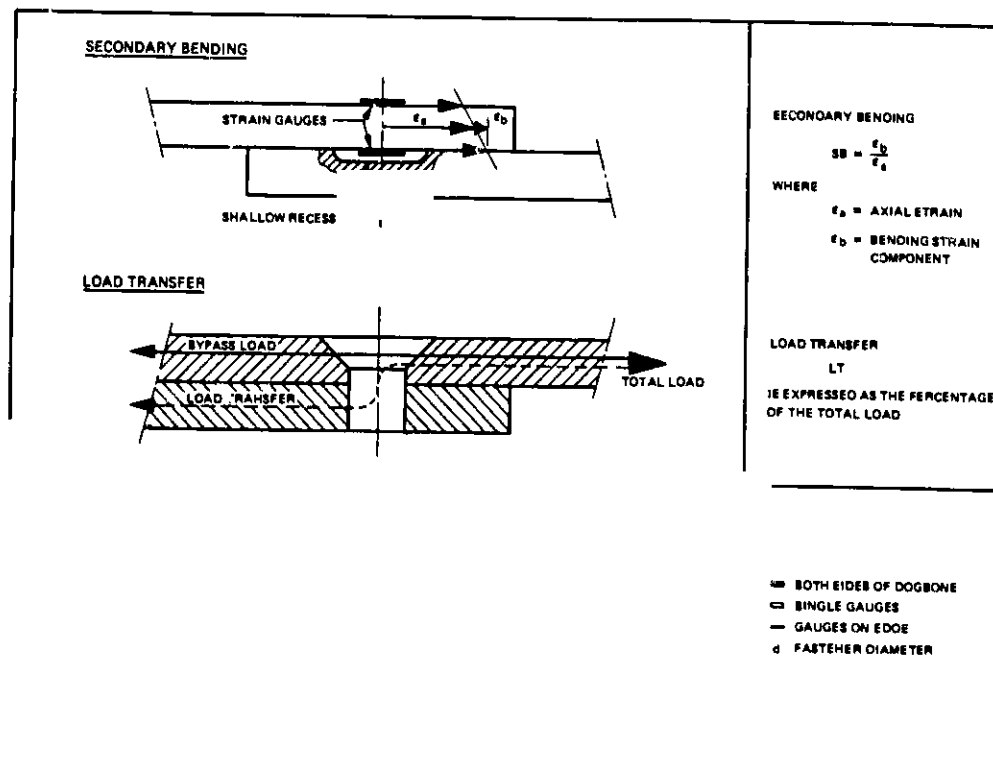


Fig. 13 Secondary bending and load transfer. Definitions and position of strain gauges

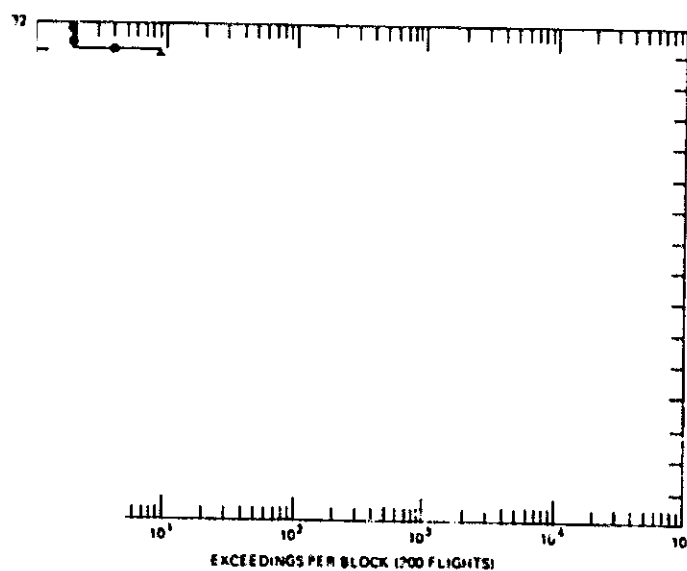


Fig. 14 FALSTAFF load spectrum

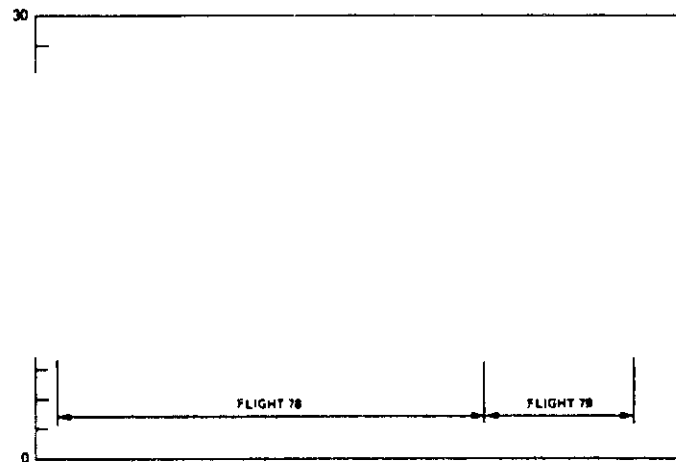


Fig. 15 Part of FALSTAFF sequence

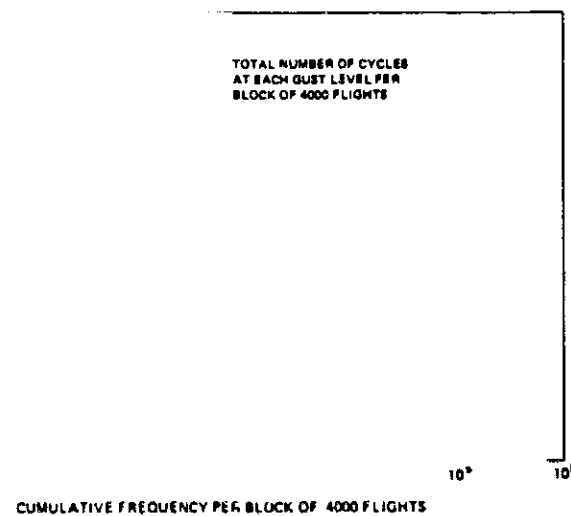


Fig. 16 The gust spectrum TWIST

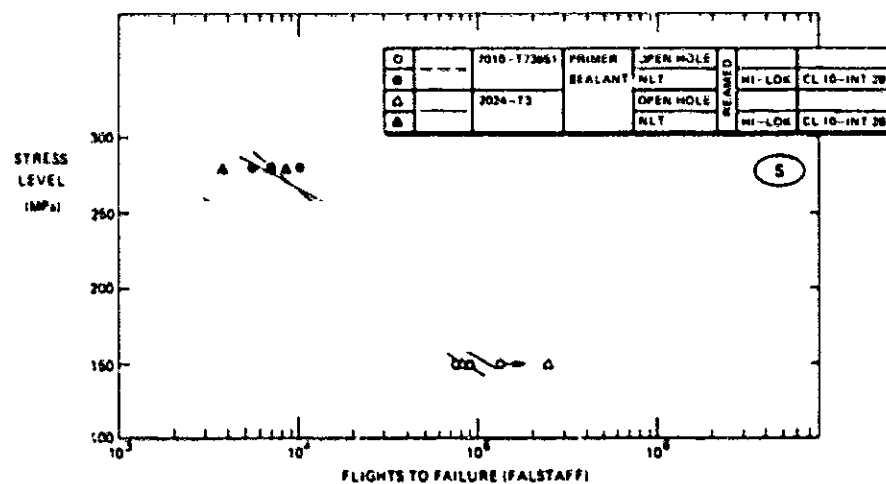


Fig. 17 Open hole specimen and no load transfer joints - Sweden

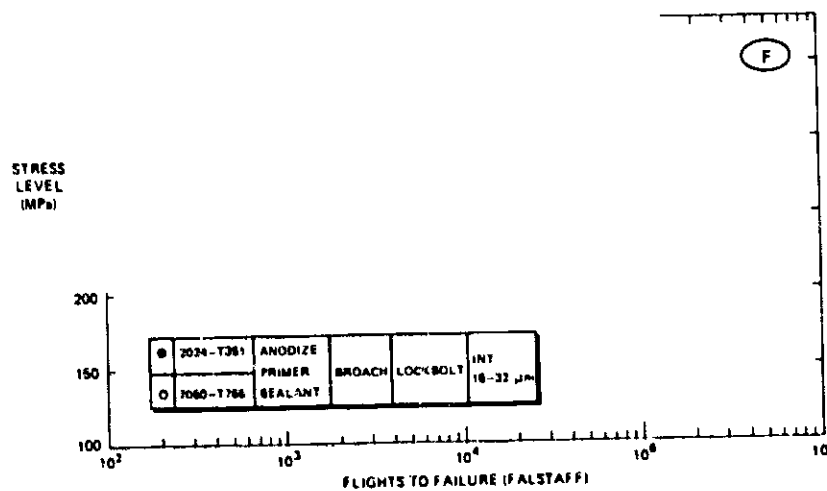
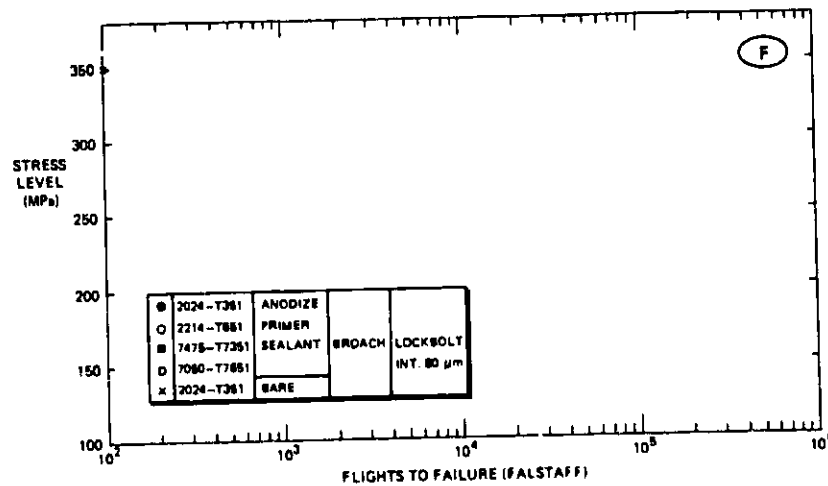
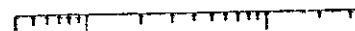


Fig. 19 Low load transfer joints - France



FLIGHTS TO FAILURE
(FALSTAFF)

Fig. 20 Low load transfer joints - France

10⁵ 10⁶
CYCLES TO FAILURE
(CONSTANT AMPLITUDE)

Fig. 21 Low load transfer joints - France

10² 10³ 10⁴
 FLIGHTS TO FAILURE (FALSTAFF)

Fig. 22 Low load transfer joints - Fed. Rep. of Germany

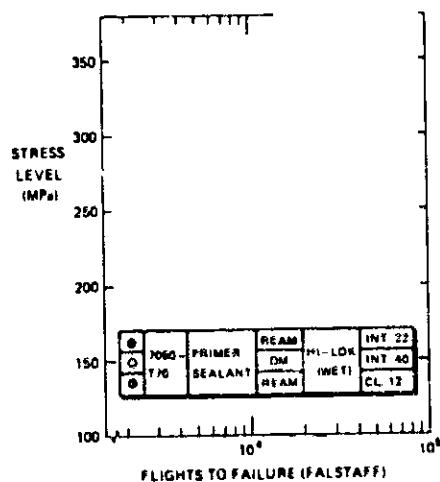


Fig. 23 Low load transfer joints - FRG

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 24 Low load transfer joints - FRG

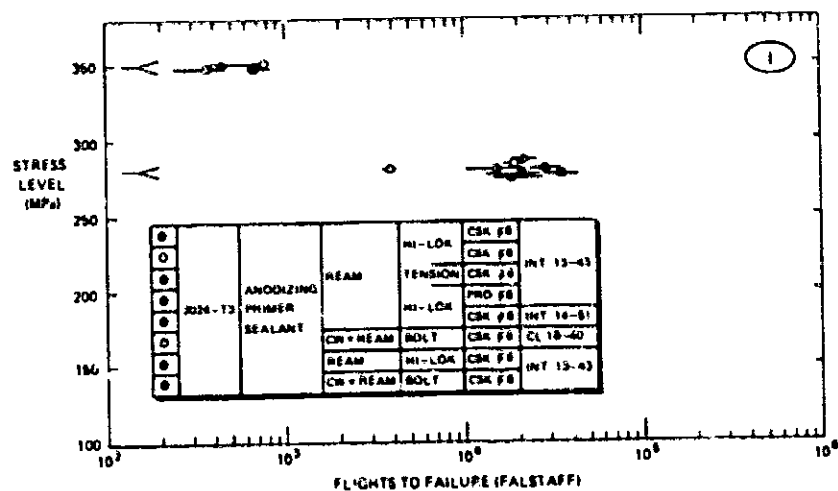


Fig. 25 Low load transfer joints - Italy

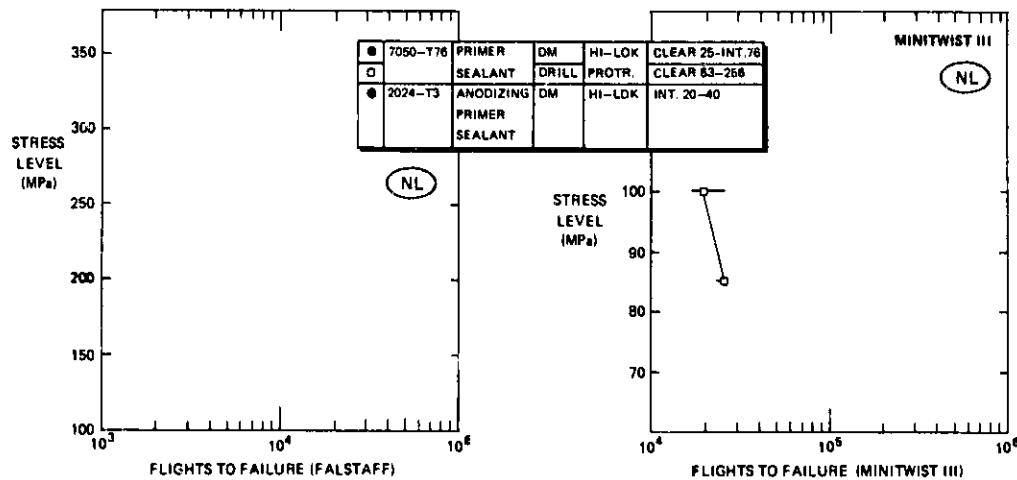


Fig. 26 Low load transfer joints - the Netherlands

Fig. 27 Low load transfer joints - the Netherlands

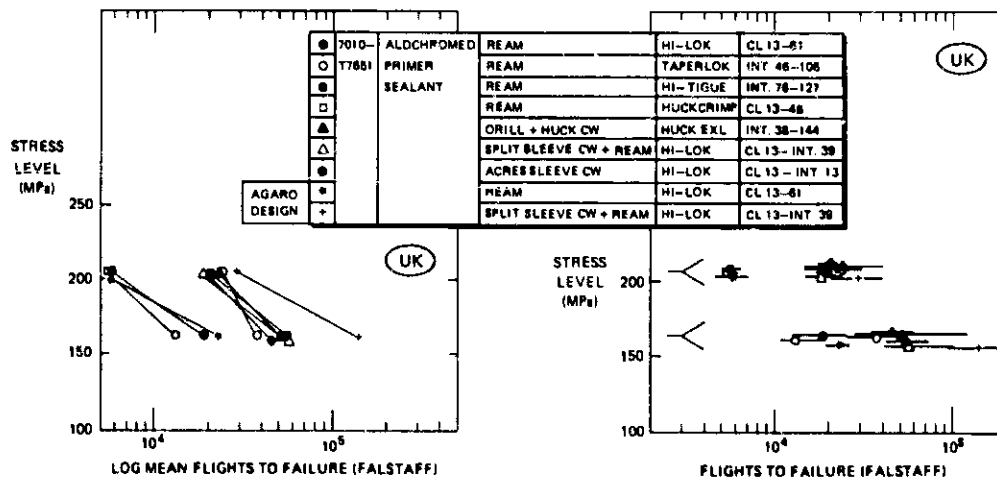


Fig. 28a Low load transfer joints - UK

Fig. 28b Low load transfer joints - UK

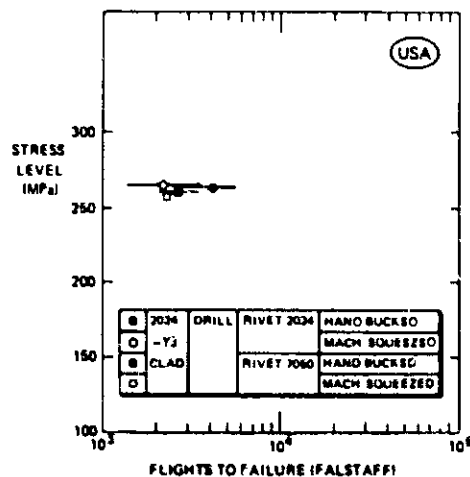


Fig. 29 Low load transfer joints - USA

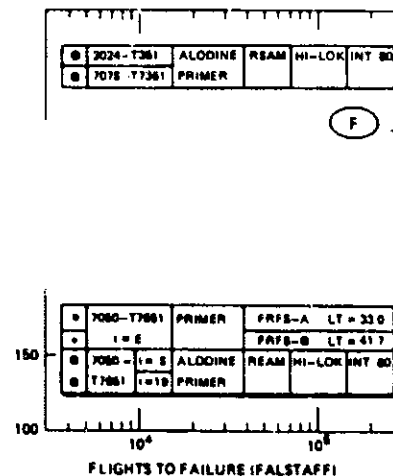


Fig. 30 Type D double shear joints - France

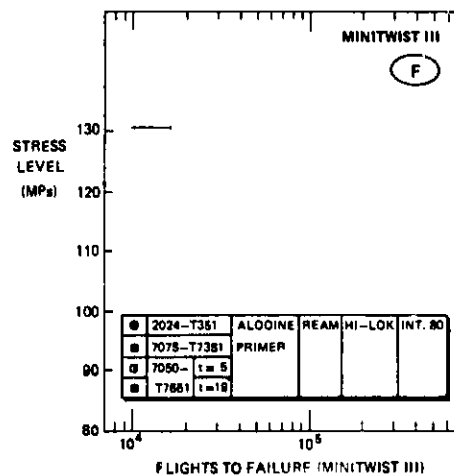


Fig. 31 Type D double shear joints - France

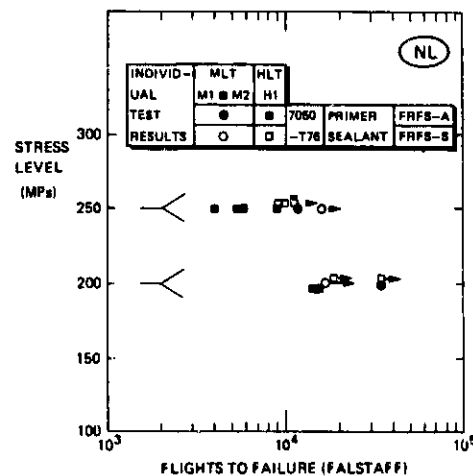


Fig. 32 Medium and high load transfer double shear joints - the Netherlands

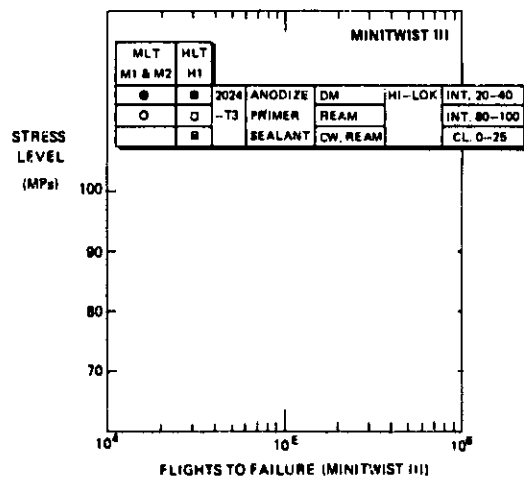


Fig. 33 Medium and high load transfer double shear joints - the Netherlands

Fig. 34 High load transfer double shear joints - United Kingdom

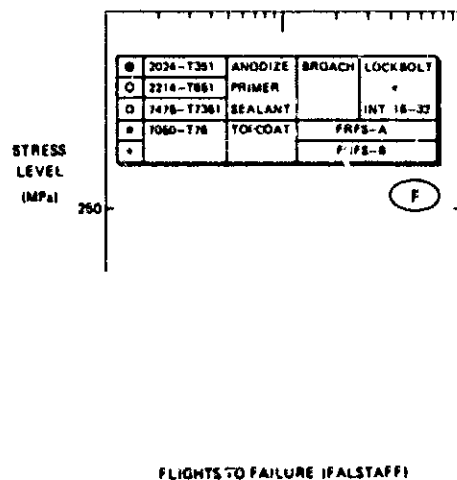


Fig. 35 Type C lap joint - France

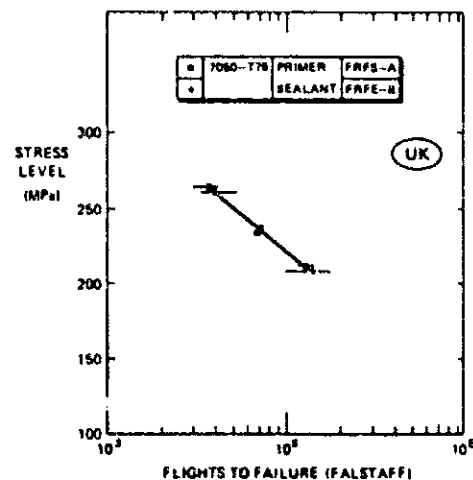


Fig. 36 Q-type joint - United Kingdom

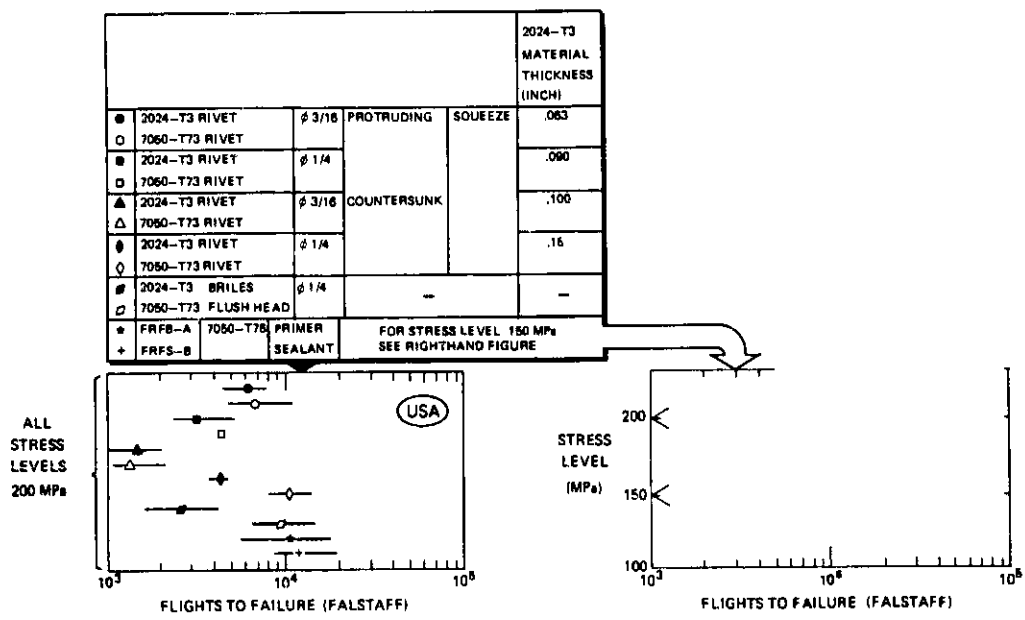


Fig. 37 Type C2 lap joints - USA

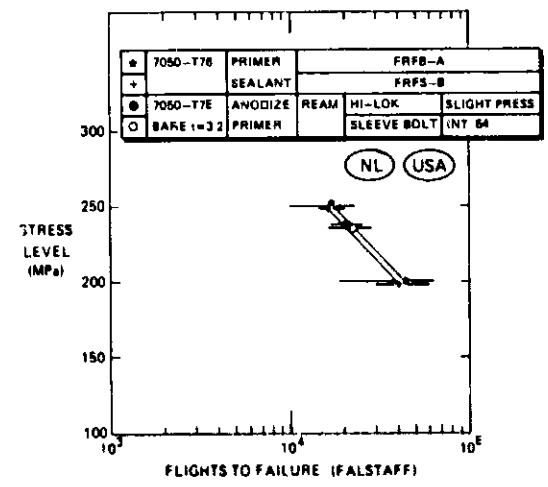


Fig. 38 1 1/2 dogbone joints - the Netherlands and USA

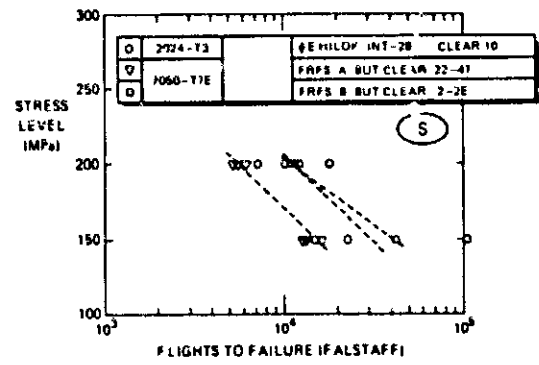


Fig. 39 Single shear X joints - Sweden

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 40 Type C1 double shear joint - France

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 41 1½ double shear joint - the Netherlands

Fig. 42 Clamping head used for reverse double dogbone specimen

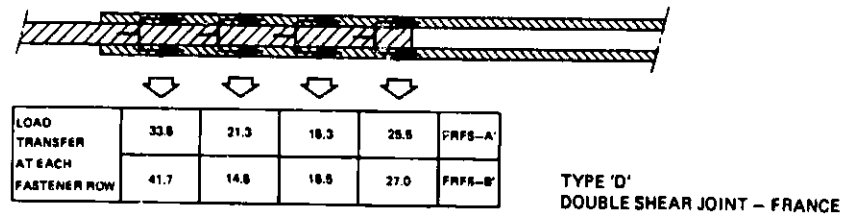
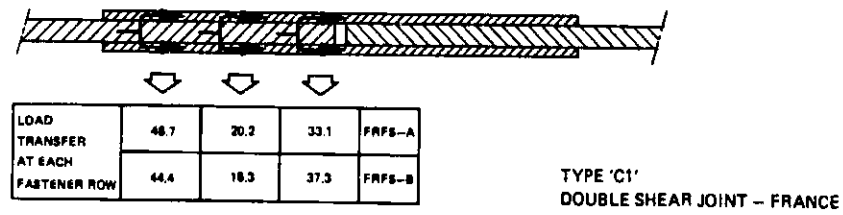


Fig. 43 Load transfer at each fastener row in multiple row double shear joints

PURCHASE COST
(US \$/PIECE)

4

Fig. 44 Purchase cost per fastener (US \$)

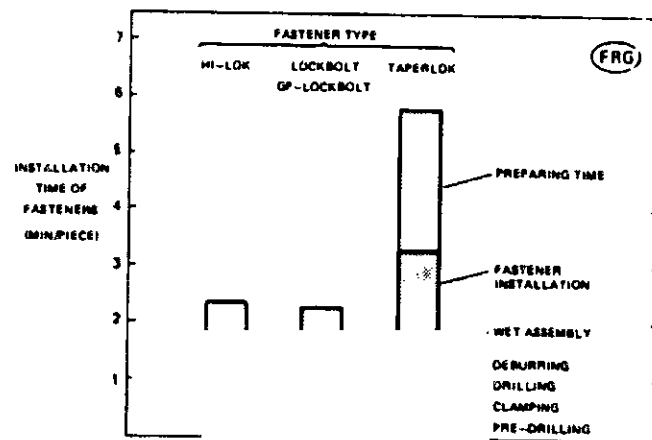


Fig. 45 Installation time of FRG fastener systems

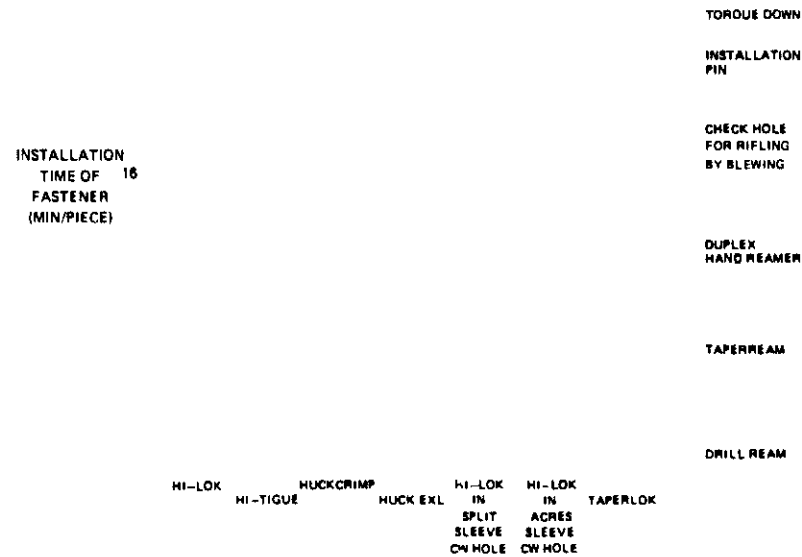


Fig. 46 Installation time of UK fastener systems

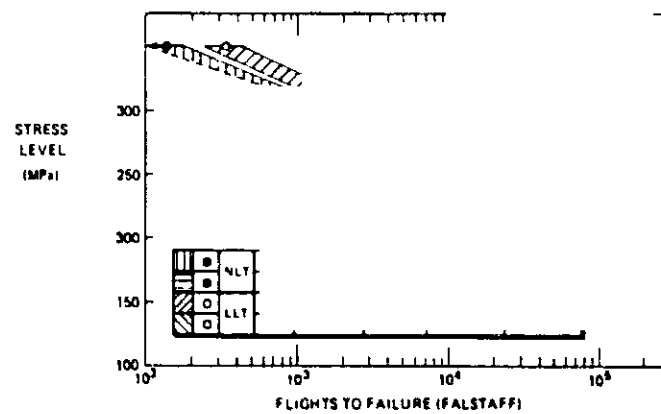


Fig. 47 No load transfer and low load transfer joints - France

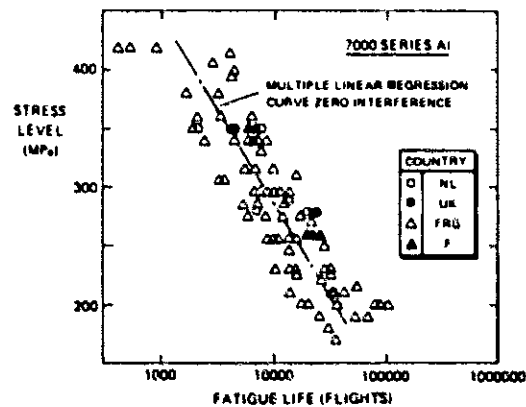


Fig. 48 Analysis of LLT-reverse double dogbone 7000 series specimens

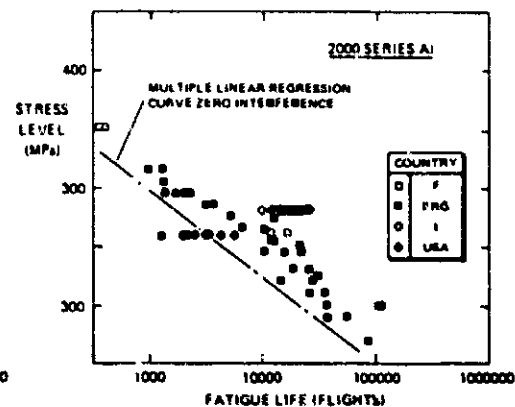


Fig. 49 Analysis of LLT-reverse double dogbone 7000 series specimens

4x10⁴ 10⁵ 10⁶
FLIGHTS TO FAILURE (FALSTAFF)

Fig. 50 Fit versus fatigue life, NLT and low load transfer joints, stress level 280 MPa

2x10⁴ 10⁵ 10⁶
FLIGHTS TO FAILURE (FALSTAFF)

Fig. 51 Fit versus fatigue life, NLT and LLT joints, stress level 280 MPa

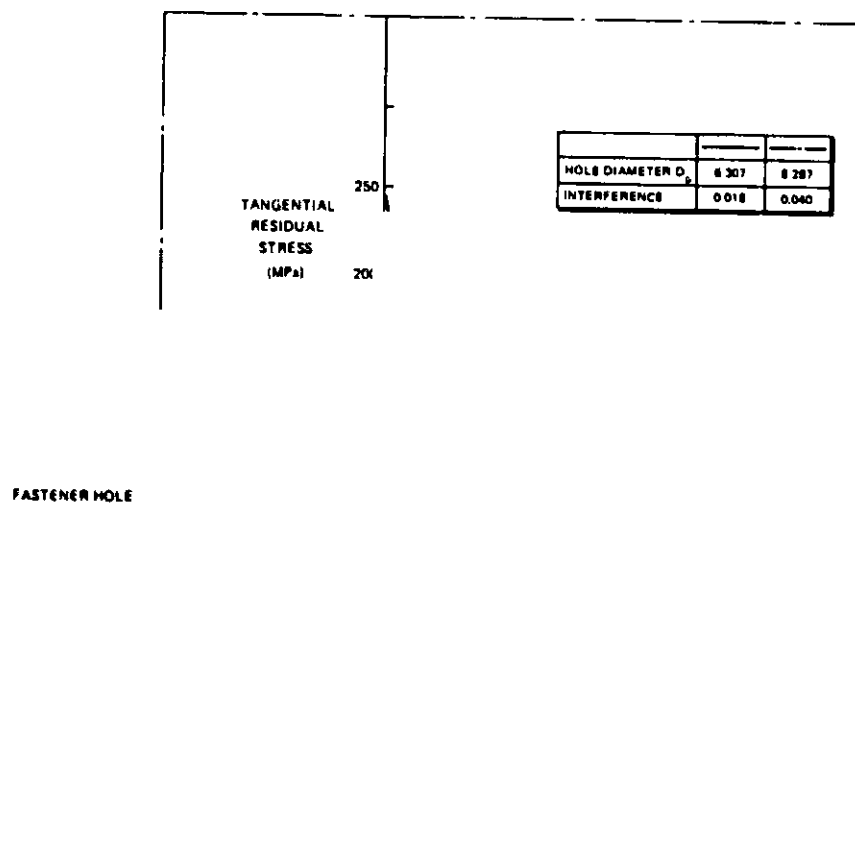


Fig. 52 Tangential stress at fastener hole as a function of the interference, (MAB-VFW)

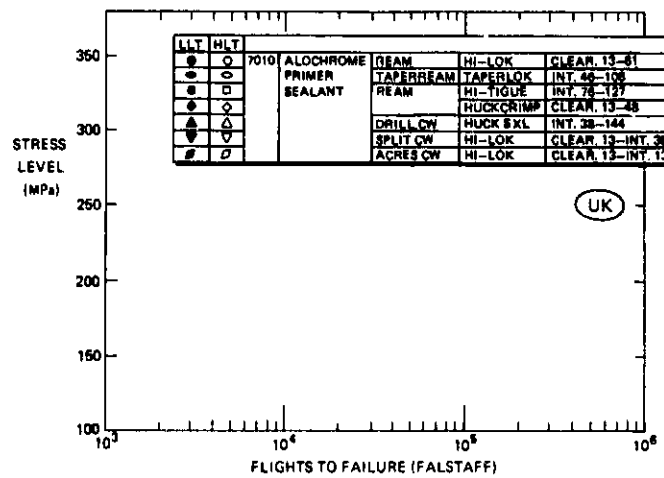


Fig. 53 Log mean fatigue lives of low load transfer and double shear specimens - UK

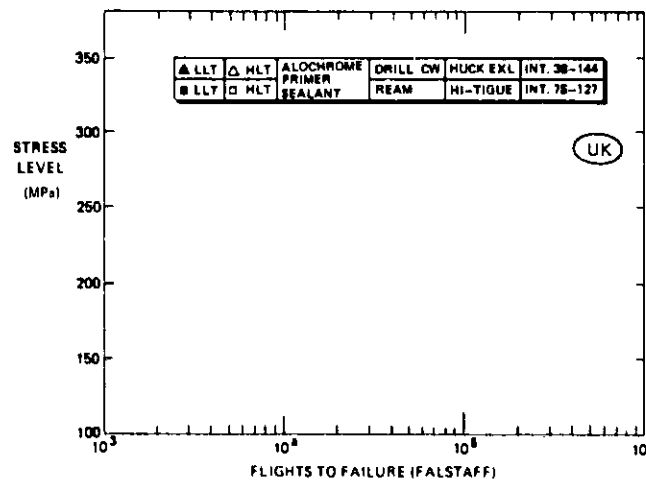


Fig. 54 Fatigue lives of low load transfer and double shear joints - UK

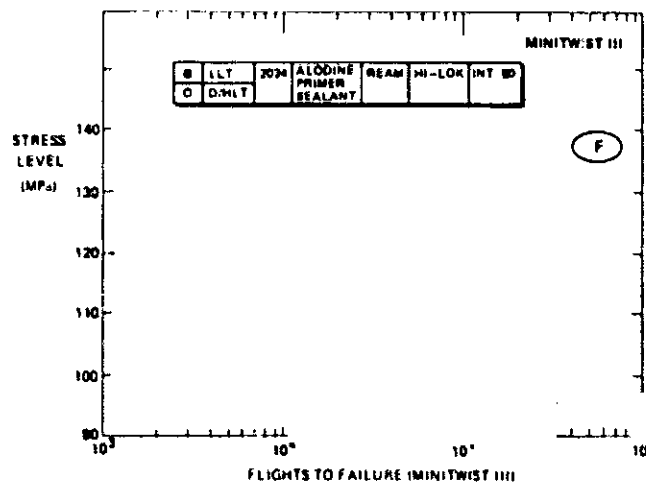


Fig. 55 Fatigue lives of low load transfer and double shear joints - France

FLIGHTS TO FAILURE (MINITWIST III)

FLIGHTS TO FAILURE (MINITWIST III)

Fig. 56 Fatigue lives of low load transfer and double shear (type D) specimen - France

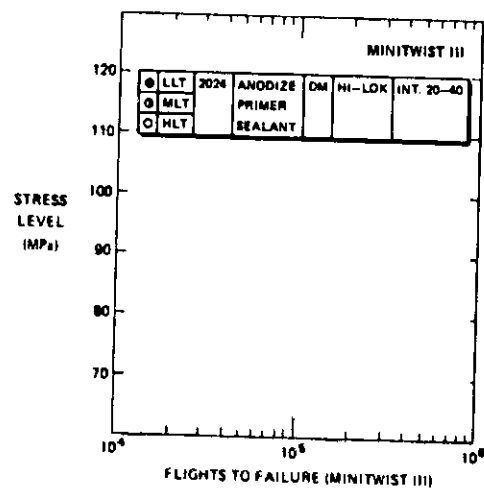


Fig. 57 Low load transfer, medium and high load transfer double shear joints - the Netherlands

FLIGHTS TO FAILURE (FALSTAFF)

Fig. 58 Single shear and double shear core programme specimens

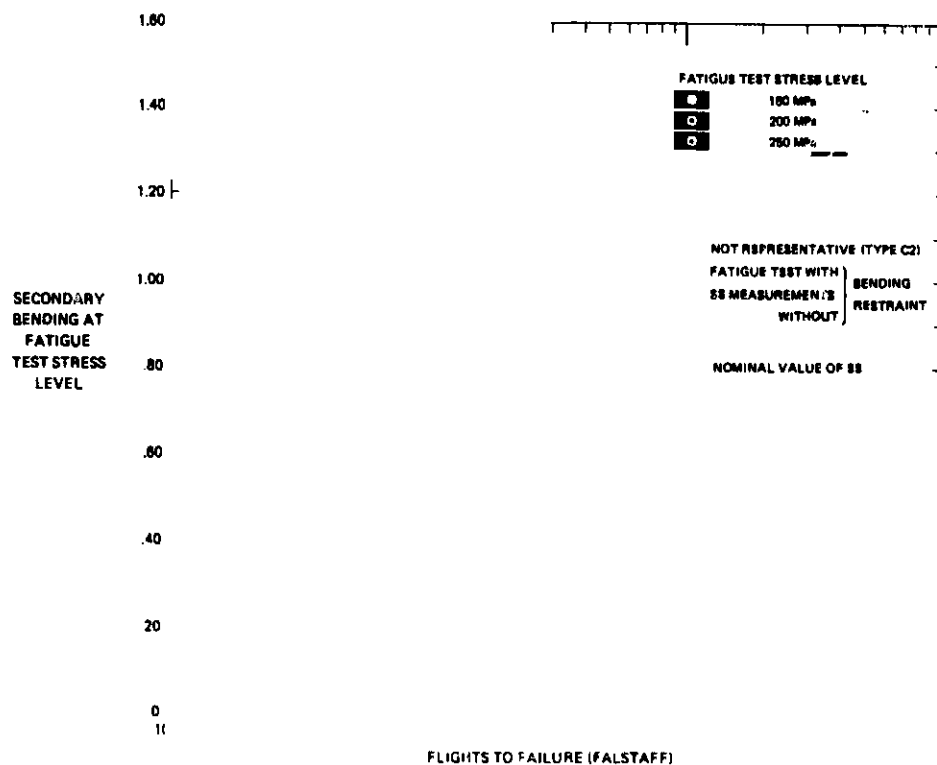


Fig. 59 Fatigue life versus secondary bending for single shear core programme specimens having FRFS-A or FRFS-B

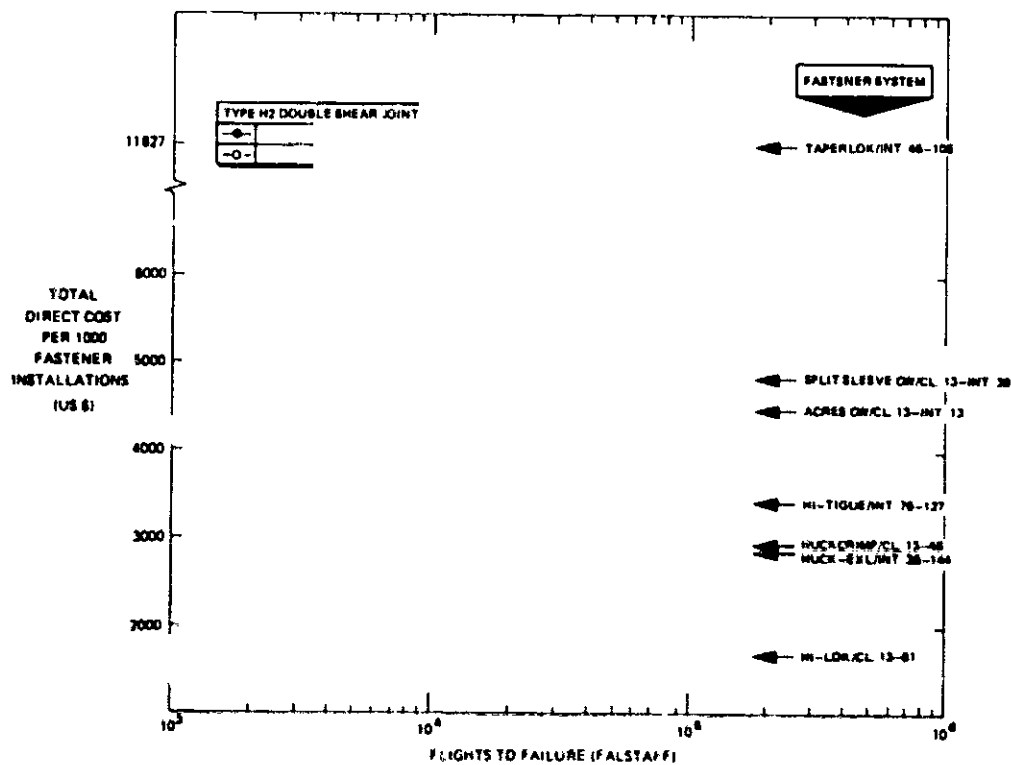


Fig. 60 Log mean fatigue life versus total direct cost per 1000 fastener installations

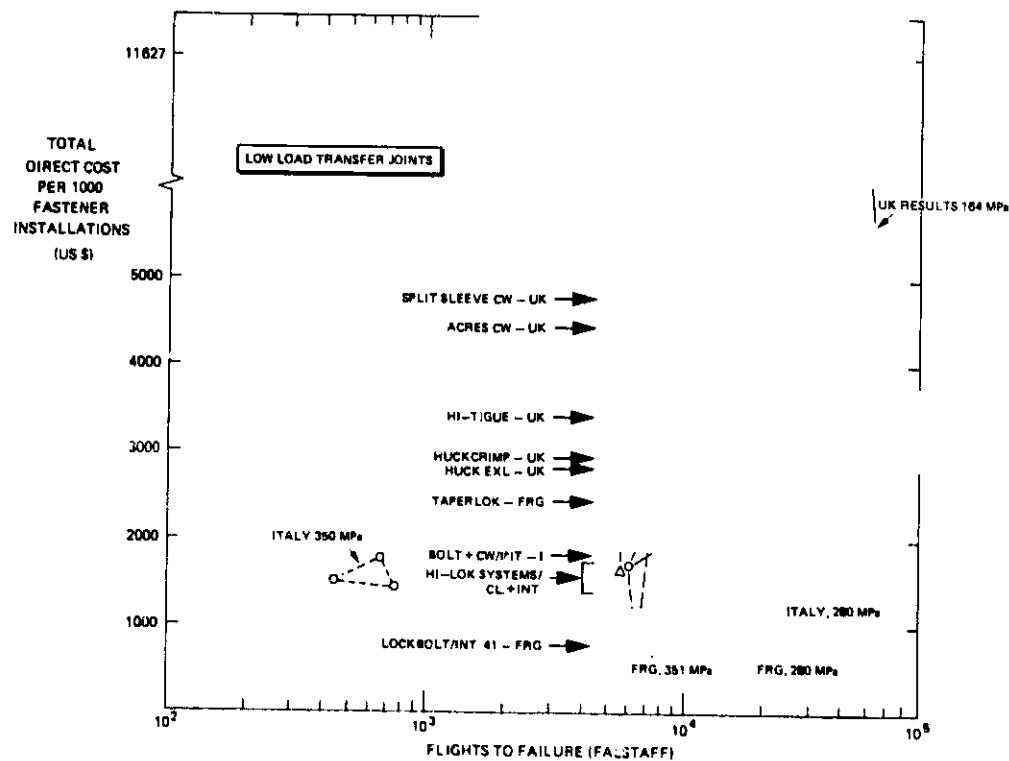


Fig. 61 Log mean fatigue life versus total direct cost per 1000 fastener installations

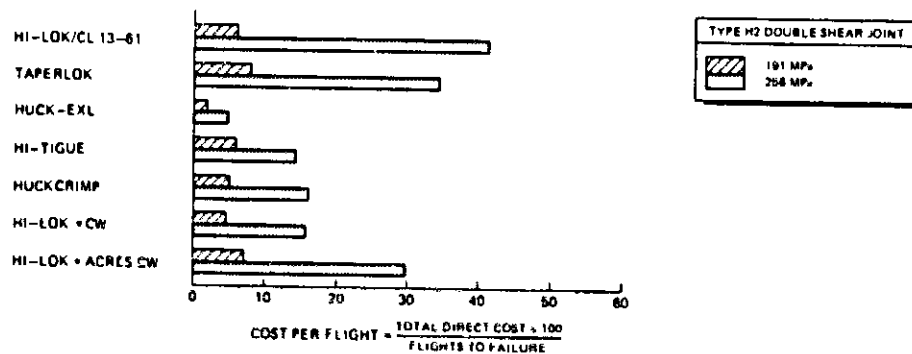


Fig. 62 Comparison of cost per 1000 fastener installations relative the number of flights to failure

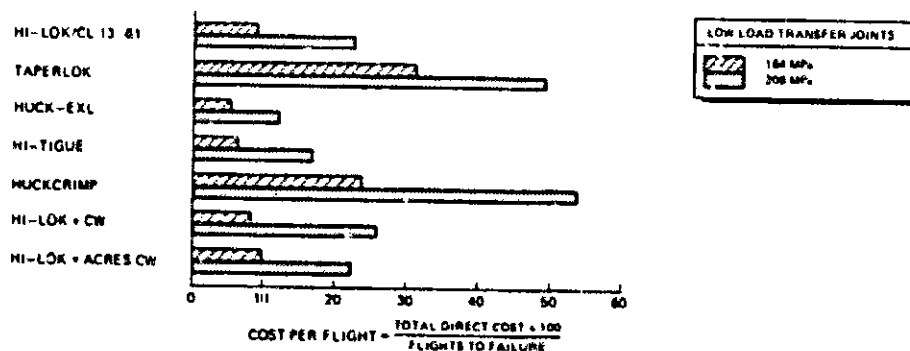


Fig. 63 Comparison of cost per 1000 fastener installations related to the number of number of flights to failure

OBJECTIVES

- DETERMINATION OF FATIGUE LIVES FOR A RANGE OF FATIGUE RATED FASTENER SYSTEMS AND MATERIAL IN COMBINATION WITH HOLE PREPARATION TECHNIQUES
- ESTABLISHMENT OF COST FIGURES IN RELATION TO FATIGUE PERFORMANCE
- IDENTIFICATION OF THE PRIME PARAMETERS INVOLVED IN FASTENER SYSTEM SELECTION
- DEVELOPMENT OF A REFERENCE DATUM FOR THE COMPARISON OF TEST RESULTS PRODUCED IN DIFFERENT COUNTRIES USING DIFFERENT SPECIMEN GEOMETRIES
- DEVELOPMENT OF EXPERIMENTAL METHODS FOR FASTENER SYSTEM FATIGUE RATING

Fig. 1-1 AGARD SMP working group on fatigue rated fastener systems

- EACH PARTICIPANT IDENTIFIED HIS OWN PROGRAMME (ACTIVE OR DESIRED)
- A COMPOSITE TEST MATRIX HAS BEEN CONSTRUCTED FOR DIFFERENT TYPES OF JOINTS.
 - NO LOAD TRANSFER SPECIMENS
 - LOW LOAD TRANSFER SPECIMENS (REVERSE DOUBLE DOGBONE)
 - DOUBLE SHEAR SPECIMENS
 - SINGLE SHEAR SPECIMENS (SECONDARY BENDING)
- MAIN VARIABLES
 - ALUMINIUM ALLOYS
 - PAINT SURFACE TREATMENT
 - MATERIAL THICKNESS
 - FASTENER SYSTEMS IN COMBINATION WITH FIT
 - HOLE PREPARATION TECHNIQUES
 - FALSTAFF / MINITWIST
 - LOAD LEVELS
- FATIGUE RATED FASTENER SYSTEMS PROGRAMME
 - ADJUSTMENT OF PROGRAMMES TO ELIMINATE UNNECESSARY DUPLICATION AND TO OBTAIN BEST OVERALL PROBLEM COVERAGE
 - DEFINITION OF CORE PROGRAMMES TO CORRELATE TEST RESULTS
 - A LACK OF A SINGLE SHEAR STANDARD SPECIMEN. A RANGE OF JOINT DESIGN WILL BE EVALUATED AND COMPARED
 - FATIGUE LIVES WILL BE EVALUATED IN TERMS OF
 - INSTALLATION COSTS OF THE FASTENER SYSTEM
 - FASTENER SYSTEM AND HOLE PREPARATION TECHNIQUE USED
 - LOCATION OF THE FATIGUE CRACK INITIATION SITES

Fig. 1-2 Methods and means of accomplishment

● NO LOAD TRANSFER JOINTS

● TEST PROGRAMMES: PER THE PARTICIPANTS STANDARDS

● CORE PROGRAMME, WHICH WILL SERVE AS A REFERENCE DATUM FOR THE COMPARISON OF TEST RESULTS PRODUCED IN FRANCE AND SWEDEN

- PARTICIPANTS	FRANCE AND SWEDEN
- MATERIAL	2024-T3, BARE (t = 4 mm)
- INTERFAY SURFACE TREATMENT	-
- FASTENER SYSTEM	TI BOLTS, HEX. AND CSK, ϕ 8 mm DRY INSTALLED
- FIT	PER THE PARTICIPANTS STANDARD
- HOLE QUALITY	PER THE PARTICIPANTS STANDARD
- LOAD LEVEL	200 MPa AND 351.8 MPa GROSS AREA STRESS (FALSTAFF)

● MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)

● LOW LOAD TRANSFER JOINTS

● TEST PROGRAMMES

- ALL PARTICIPANTS, EXCEPT FOR THE UK, USE THE STANDARD REVERSE DOUBLE DOGBOONE SPECIMEN (AS USED IN THE CRITICALLY LOADED HOLE TECHNOLOGY PROGRAMME)
- FIVE LOAD LEVELS: 200 MPa AND 351.8 MPa GROSS AREA STRESS (FALSTAFF)

● CORE PROGRAMME TO CORRELATE UK TEST RESULTS WITH RESULTS OF THE OTHER PARTICIPANTS

- PARTICIPANT	UK
- MATERIAL	7010-T7681 (t = 5 mm)
- INTERFAY SURFACE TREATMENT	PR 1422
- FASTENER SYSTEM	HI-LOK, ϕ 8.35, CSK
- FIT	CLEARANCE, PER UK STANDARD
- HOLE QUALITY	REAMED, PER UK STANDARD
- LOAD LEVELS	COLD WORKED, REAMED, PER UK STANDARD 280 MPa AND 350 MPa NET SECTION STRESS (FALSTAFF)

● MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)

● FRACTOGRAPHIC INVESTIGATION TO ESTABLISH STATISTICAL INFORMATION OF THE CRACK INITIATION SITES

● DOUBLE SHEAR JOINTS

● TEST PROGRAMMES

THREE DESIGNS (100%, 50% AND 25% LOAD TRANSFER) WILL BE INVESTIGATED BY THREE PARTICIPANTS
FIVE LOAD LEVELS: 200 MPa AND 250 MPa (SEE TABLE 1) GROSS AREA STRESS (FALSTAFF)

● CORE PROGRAMME TO CORRELATE TEST RESULTS OF DIFFERENT COUNTRIES

- PARTICIPANTS	SWEDEN, UK, THE NETHERLANDS
- MATERIAL	7050-T76 (t = 5 mm)
- INTERFAY SURFACE TREATMENT	EPOXY PRIMER AND INTERFAY SEALANT PR-1431-G
- FASTENER SYSTEMS	HI-LOK CLEARANCE, REAMED HOLE HI-LOK INTERFERENCE, COLD WORKED HOLE, REAMED HOLE OPTIONAL HI-LOK INTERFERENCE, REAMED HOLE
- LOAD LEVELS	200 MPa AND 250 MPa (SEE TABLE 1) GROSS AREA STRESS (FALSTAFF)

● MEASUREMENT OF LOAD TRANSFER OF TEST PROGRAMME - AND CORE PROGRAMME SPECIMENS USING STANDARD PROCEDURES. MEASUREMENTS ON EACH COMBINATION OF SPECIMEN DESIGN AND FASTENER SYSTEM

● MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)

● FRACTOGRAPHIC INVESTIGATION TO ESTABLISH STATISTICAL INFORMATION OF THE CRACK INITIATION SITES

Fig. 1-1 Fatigue rated fastener programme, Summary

to be continued

● SINGLE SHEAR JOINTS

● TEST PROGRAMMES: A RANGE OF HIGH LOAD TRANSFER SINGLE SHEAR JOINTS WILL BE TESTED

— FRFS LOAD LEVELS

150, 200 AND 250 MPa (SEE TABLE 1.2) GROSS AREA STRESS (FALSTAFF)

● CORE PROGRAMME TO EVALUATE AND COMPARE DIFFERENT HIGH LOAD TRANSFER SINGLE SHEAR JOINTS. TESTS ON SINGLE SHEAR JOINTS AND THEIR DOUBLE SHEAR EQUIVALENT DESIGNS. THE DOUBLE SHEAR EQUIVALENT DESIGN IS A SIMPLE DERIVATIVE OF THE SINGLE SHEAR SPECIMEN:

THE ASYMMETRICAL SIDEPLATE IS REPLACED BY TWO SYMMETRICAL SIDE PLATES OF THE HALF THICKNESS. THE DOUBLE SHEAR SPECIMEN HAS NO SECONDARY BENDING.

— PARTICIPANTS

UEA, FRANCE, SWEDEN, THE NETHERLANDS, UK

— MATERIAL

7050-T7B II = 5 mm (IF NECESSARY MATERIAL SHOULD BE MILLLED DOWN TO 2.5 mm)

— INTERFAY SURFACE TREATMENT

EPOXY PRIMER AND INTERFAY SEALANT PR-1431-G

— FASTENER SYSTEM

a. HI-LDK, CLEARANCE, REAMED HOLE

b. HI-LDK, INTERFERENCE, COLD WORKED HOLE, REAMED

c. OPTIONAL: HI-LDK, INTERFERENCE, REAMED HOLE

— LOAD LEVELS

150, 200 AND 250 MPa (SEE TABLE A.2) GROSS AREA STRESS (FALSTAFF)

● MEASUREMENT OF LOAD TRANSFER AND SECONDARY BENDING OF TEST PROGRAMME— AND CORE PROGRAMME SPECIMENS USING STANDARD PROCEDURES. MEASUREMENTS ON EACH COMBINATION OF SPECIMEN DESIGN AND FASTENER SYSTEM

● MEASUREMENT OF FIT AND SURFACE ROUGHNESS (EACH HOLE)

● FRACTOGRAPHIC INVESTIGATION TO ESTABLISH STATISTICAL INFORMATION OF THE CRACK INITIATION SITES

Fig. 1-3 Concluded

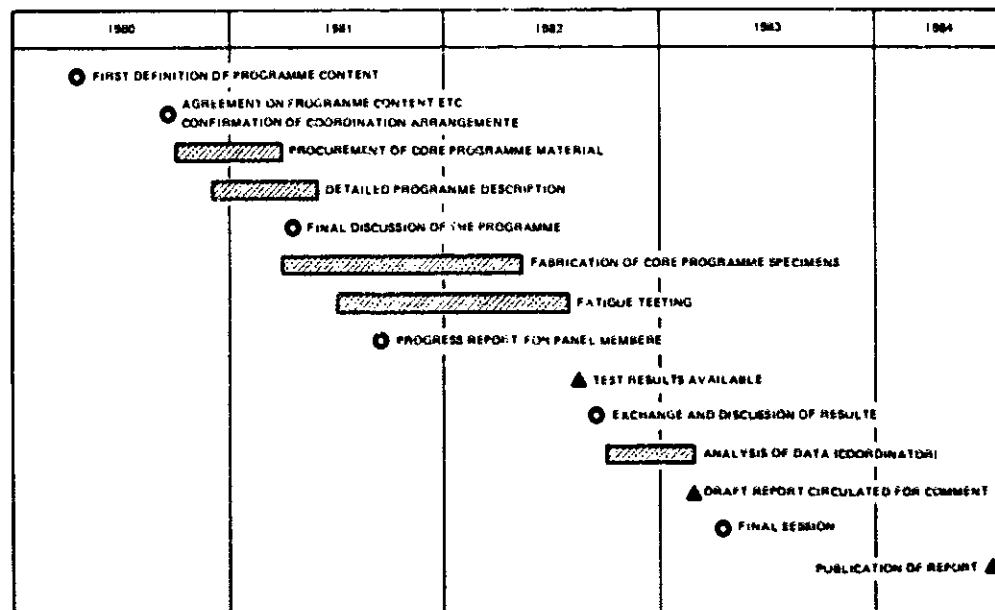


Fig. 1-4 Schedule and milestones for the FRFS programme

TABLE 1-1
Number of specimens for different load levels of the
double shear joints core programme

LOAD LEVEL (MPa)	FASTENER SYSTEM		
	HI-LOK, CLEARANCE, REAMED HOLE	HI-LOK, INTERFERENCE, REAMED HOLE	HI-LOK, INTERFERENCE, COLD WORKED AND REAMED HOLE
	NUMBER OF SPECIMENS		
200	3	(3)	3
250	3	(3)	3
280	(3)	(3)	(3)

() OPTIONAL

TABLE 1-2
Number of specimens for different load levels of the single
shear joints / double shear equivalent core programme

SPECIMEN DESIGN	LOAD LEVEL (MPa)	FASTENER SYSTEM		
		HI-LOK, CLEARANCE, REAMED HOLE	HI-LOK, INTERFERENCE, REAMED HOLE	HI-LOK, INTERFERENCE, COLD WORKED AND REAMED HOLE
		NUMBER OF SPECIMENS		
SINGLE SHEAR JOINTS	150	3	(3)	3
	200	3	(3)	3
	250	(3)	(3)	(3)
DOUBLE SHEAR EQUIVALENT	150	3	(3)	3
	200	3	(3)	3
	250	(3)	(3)	(3)
1 1/2 DOGBONE TYPE JOINTS	150	(3)	(3)	(3)
	200	3	(3)	3
	250	3	(3)	3
DOUBLE SHEAR EQUIVALENT	150	(3)	(3)	(3)
	200	3	(3)	3
	250	3	(3)	3

() OPTIONAL

ANNEX 2

ORIGINALLY PUBLISHED AS: APPENDIX A/FRFS/NOV. 1981

FASTENER SYSTEMS

Three fastener systems are selected for application in two core programmes of the Fatigue Rated Fastener Systems programme (see reference 1).
Basically the fastener systems are as follows:

fastener system	hole quality	fastener	fit + clearance - interference (mm)
FRFS-A	reamed cold-worked (3 %) and reamed	HI-Lok, CSK, Ø 6.35 mm	+ .020 ± .010
FRFS-B			- .025 ± .010
FRFS-C -OPTIONAL-			- .090 ± .010

The fastener type selected, hole production procedures, interlay surface treatment and installation procedures are described.

Fasteners

All fasteners to be used are cadmium plate steel HI-Lok HL-19-8-7 together with HL-70-8 collars.

The coding HL-19-8-7 refers to:

HL-19: pin part number

- 8: 8/32 inch or 6.35 mm nominal diameter pin
- 7: 7/16 inch or 11.11 mm maximum grip length.

The collars are made of 2024-T6 aluminium alloy;

the coding - 8 refers to nominal thread size of 8/32 inch or 6.35 mm. The nominal diameter of the pin is 6.35 mm; the specified minimum and maximum diameter are 6.312 mm and 6.337 mm respectively. However, practice shows that the pin diameter is between 6.325 and 6.337 mm.

Fastener holes

Table 2-1 gives the hole preparation for each fastener system. Nominal tool diameters should be selected very carefully by each participant to arrive at the required fit.

The cylindrical parts of all fastener holes must be reamed as a last working procedure.

Countersinking is done after reaming of the cylindrical parts of the fastener holes.

Dimensions of the countersink are given in the following figure:

100° ± 30°

1.524 ± 0.025 mm

Dimensions of the countersink

After countersinking all hole edges at interfacing and break out surfaces, except the countersink, are lightly deburred.

As indicated earlier the fastener system B is an interference fit HI-Lok in a cold-worked, reamed hole (see table 2-1).

The holes must be cold-worked using the Split Sleeve Cold Expansion Process (CX) of Fatigue Technology Inc., USA; detailed information about the hole production is given in the following (see also reference 2). The starting holes shall be reamed to dimensions as given in table 2-1; these dimensions correspond with those of reference 2. If a cutting fluid leaves an excessive lubricant residue in the hole, the residue must be removed before split sleeve cold expansion.

The major and minor diameter of the mandrel are given in figure 2-1. The mandrel major diameter is allowed to shrink or wear a maximum of .015 mm (.0006 inches) from the nominal diameter before replacement.

Use of a reamer with a non-cutting pilot is required as a quality control measure to ensure that all holes are cold expanded prior to post sizing. The pilot diameter will not fit into a starting hole, but will fit into a cold expanded hole.

The cold expanded hole has an axial ridge which corresponds with the position of the split in the sleeve.

Post sizing is required to clean up the hole in order to provide the desired fastener fit.

The maximum metal removal is limited to 10 % of the nominal hole diameter or 1.575 mm (0.062 inches), whichever is less.

The FTI process specification allows that the finished hole contains a region near the entry, exit or interface which does not totally clean up during the post sizing operation. The hole will be acceptable providing the region does not extend axially by more than .508 mm (.020 inches) or 10 % of the detail thickness, whichever is less.

Machining of countersinks shall be performed after post size reaming. All hole edges at interfacing and break out surfaces, except the countersink, are lightly deburred.

- cleaning (degreasing) with suitable solvent;
- application of epoxy primer, except in counteraunk holes, to a dry film thickness of .05 - .13 mm;
- cure primer;
- upon assembly the facing surfaces of the joint specimens will be coated with Producta Research and Chemical Corporation (PRC) PR-1431G or equivalent. The sealant is applied using a standard short nap paint roller (see PRC Interim Technical Data Sheet for the PR-1431-G corrosion inhibitive sealant);
- no topcoat is to be applied to the specimens.

References

1. Van der Linden, H.H., AGARD SMP Working Group on FRFS, Revision C, July 1981.
2. CX Process Specification: Cold Expansion of Fastener and other Holes using the Split Sleeve System, FTI 8101, Fatigue Technology Inc. Draft, May 1981.
3. Measurement of fit and surface roughness, Appendix B / FRFS, August 1981. Also as Annex 3 of this report.

TABLE 2-1
Fastener systems

FASTENER SYSTEM CODE	FRFS-A	FRFS-B	FRFS-C optional
FASTENER	Hi-LOK HL-19-8-7. nom. dia 6.35 min. dia. 6.312, max. dia. 6.337 practice: <u>dia. 6.325 - 6.337</u>		
PREDRILL	X	X	X
DRILL	X	X	X
REAM	X	TO: 5.71 - 5.79 mm	X
COLD WORK		3 X split sleeve process (CK) of FTI	
REAM		X	
COUNTERSINKING. DEBURRING OF ALL HOLE EDGES, except the counteraink MEASUREMENT OF FIT INTERFAY SURFACE TREATMENT - cleening - epoxy primer - sealant PR-1431-G WET INSTALLATION OF FASTENERS (PR-1431-G)			
FIT + clearance -interference	+ .010 + .020	+ .010 - .025	+ .010 - .090

(dimensions in mm)

MAJOR DIAMETER MINOR DIAMETER NOSECAP

MANDREL
ATTACHMENT

FASTENER SYSTEM 2

FTI STANDARD TOOL NUMBER 6-3-N

MANDREL MAJOR DIAMETER 5.064 ^{+0.05}/_{-0.18} mm

MINOR DIAMETER 5.283 ^{+0.13}/_{-0.11} mm

SLEEVE DIMENSION

THICKNESS 152 ⁻⁰/_{-0.13} mm

Fig. 2-1 Split sleeve cold expansion mandrel

ANNEX 3

ORIGINALLY PUBLISHED AS: APPENDIX E / FRFS - AUGUST 1981

MEASUREMENT OF FIT AND SURFACE ROUGHNESS

In order to establish the fit of each fastener/hole combination the hole and fastener dimensions should be characterized. Measurements should be noted on a special form (table 3-1), developed by VFW-Bremen.

The procedure is as follows (see table 3-1)

* Each Specimen:

- specimen identification;
- identification of the fastener holes.

* Each fastener hole

- a measurement of two diameters (perpendicular) on the top side of the specimen, calculation of the average value;
- b measurement of two diameters (perpendicular) on the bottom side of the specimen, calculation of the average value;
- c average figures found under a and b;
- d measure the fastener diameter (twice);
- e calculate the average fastener diameter;
- f establish the fit.

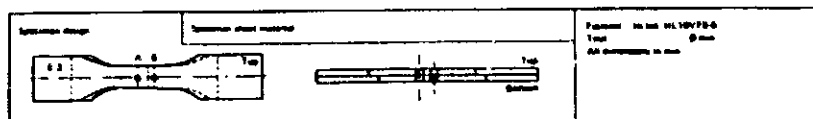
An example is given in table 3-2.

The hole surface roughness should be characterized using in house equipment.

TABLE 3-1
Measurement of fit and surface roughness

[illegible]

TABLE J-2
Measurement of fit and surface roughness. An example

[illegible]

ANNEX 4

DETERMINATION OF SECONDARY BENDING AND LOAD TRANSFER

SUMMARY

For use in the AGARD SMP Fatigue Retard Fastener Systems Programme a procedure for the determination of secondary bending and load transfer is described.

1. INTRODUCTION

At the fall 1980 FRFS Working Group meeting agreement was reached on the programme content (references 1, 2). In the "Single Shear Joints Core Programme" the amount of secondary bending and load transfer is to be measured. The Working Group adopted a procedure for the measurement of secondary bending; this procedure was proposed by Dr. D. Schütz (LBF) and is described fully in this annex. This memorandum also describes a procedure for the determination of load transfer; this procedure will also be used in the "Double Shear Joints Core Programme". It is strongly recommended by the FRFS Working Group members to use the procedures described herein.

2. DETERMINATION OF SECONDARY BENDING

By definition secondary bending is caused by an eccentricity. The procedure described is based on the measurement of strains during loading and unloading. The position of the strain gauges, the definition of secondary bending, the load application and a typical example are described in the following.

2.1 Position of the strain gauges

The secondary bending is of interest at the critical cross-section, i.e. the cross-section where the fatigue crack occurs. Usually a crack will start at a hole or at the facing surface close to a hole. The location of crack initiation is not accessible in most cases; so a neighbouring position must be used for the measurement.

The following convention has been adopted (reference 3) for choosing the position of the strain gauges.

- In the case of joints with several fasteners in a row the position of the strain gauges is given in figure 4-1.
- In the case of joints with one fastener in a row the position of the strain gauges is given in figure 4-2.

At each position, as defined under a) and b), two strain gauges should be bonded, i.e. one at each side of the plate (figures 4-1 and 4-2). In order to accommodate the interference gauge(s) and wires shallow recesses should be manufactured in the opposite plate (references 3, 4, 5).

Further it is recommended to use strain gauges with a grid length and width of 3 mm and 1.5 mm respectively.

2.2 Definition of secondary bending

The definition of secondary bending is given in figure 4-3. The bending and axial component of the strain are derived using the strains measured at the opposite sides of the plate. The secondary bending ratio (references 4, 6) is given by the ratio of the bending strain and the axial strain at this position under consideration.

2.3 Load application

The measurement of secondary bending is carried out under static loading. The load steps are given in table 4-1. Load is given relative to the maximum load in the PALSTAFF sequence. 1)

Table 1 also may be used for reporting of the measurements made.

During the first load cycle a hysteresis loop, load vs strain, may be obtained indicating that residual deformation is involved arising from the fastener deformation and yielding of highly stressed regions. Therefore the measurement should be repeated after a number of load cycles, in order to obtain a stabilized load-strain curve (see also 2, 4).

- Note: The loads applied in the measurement should cover the loads that will be applied in the fatigue tests.

2.4 A typical example

A typical joint, namely the single shear lap joint (figure 4-4) was investigated in reference 1. The loads applied were established in such a way that all fatigue tests carried out remained within the load range as used in the measurement of secondary bending. The load sequence applied was: zero-maximum load-zero-minimum load-zero.

Results of the first load cycle are given in figure 4-5. Also stabilized load-elongation curves were obtained: an approximate linear relationship was found (figure 4-5).

3. DETERMINATION OF LOAD TRANSFER

In joints load is transmitted from one plate to another at each fastener row. The determination of load transfer is based on strain measurements during loading and unloading. The position of the strain gauges, the definition of load transfer and load application are described in the following.

3.1 Position of the strain gauges

The position of the strain gauges is given in figure 4-6. At site 'a' the total (axial) load, carried through the joint, is measured. At site 'c' the bypass load (figure 4-7) is measured. The variation in load transfer over cross-section "A" is established using a number of strain gauges; the position of the strain gauges is given in figure 4-6. In order to exclude the effect of secondary bending loads the strain gauges should be bonded on opposite sides of the plate. Shallow recesses should be manufactured in the opposite plate to accommodate the interference gauge(s) and wires; the dimensions of the shallow recess are given in figure 4-1. The dimensions of the strain gauges are given in section 2.1.

3.2 Definition of load transfer

Load transfer is defined as the load which is transferred from one plate to another. That part of the load which is not transferred is called the bypassing load. Load transfer and bypassing load are given schematically in figure 4-7. Load transfer - in most cases - is expressed as the percentage of the total load each fastener row transmits (reference 4); therefore the percentage of load transfer is given by:

$$\frac{\text{axial load site 'a' - axial load site 'c'}}{\text{axial load site 'a'}} \times 100 \%$$

3.3 Load application

The procedure is identical to the one used in the determination of secondary bending; therefore see section 2.3 of this memorandum.

4. CONCLUSIONS

Procedures for the determination of secondary bending and load transfer, based upon the usage of strain gauges have been described. The strain gauge measurements are carried out at a number of steps under static loading. From the measurement the secondary bending ratio and the percentage of load transfer can be derived.

5. REFERENCES

1. Heath, W.G., Fatigue Rated Fasteners. AGARD SMP. Sub-Committee Report, Fall 1980.
2. Van der Linden, H.M., Working Group on Fatigue Rated Fastener Systems, Revision C, July 1981.
3. Schütz, D. and Lowack, H., The Effect of Secondary Bending on the Fatigue Strength of Joints. Laboratorium für Betriebsfestigkeit, Report FB - 113 (1974). REA Library Translation 1858.
4. Perrett, B., Some Measurements of Load Transfer and Secondary Bending in Fastener - Joint Specimens for the Proposed Evaluation of 'Fatigue Resistant' Fasteners. REA Tech. Memo Structures 950.
5. Jarfall, J., Review of Some Swedish Works on Aeronautical Fatigue During the Period May 1973 to April 1975. FFA Technical Note No. NE-1684. Also in: Minutes of the Fourteenth Conference on the International Conference on Aeronautical Fatigue (ICAF), Lueneburg, 1975, ICAF-Documents No. 800.
6. Schütz, D., Frenz, J. and Gerhartz, J.J., Der Einfluss der Lastübertragung auf der Schwingfestigkeit von Fügungen mit Schubbeanspruchten Befestigungselementen. Fraunhofer Institut für Betriebsfestigkeit (IBF), Institutveröffentlichungen, Heft 9, 1980, pp. 141-154.

TABLE 4-1
Values of load transfer and secondary bending ratio

Specimen type		
Specimen number		
Max. load (MPa)		
Min. load (MPa)		
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0		
16.7		
33.3		
50		
66.7		
83.3		
100		
83.3		
66.7		
50		
33.3		
16.7		
0		
minimum load		
0		

TANGENT TO THE SHAFT
OF THE FASTENERS

SECTION A - A

SHALLOW RECESS
(WIDTH 5.5 mm)

Fig. 4-1 Position of strain gauges in secondary bending measurements in joints with several fasteners in a row

A diagram of a beam under bending. A vertical line represents the neutral axis. Two strain gauges are attached to the top and bottom surfaces, labeled ϵ_1 and ϵ_2 respectively. A horizontal arrow labeled ϵ_{axial} points to the right, and a diagonal arrow labeled $\epsilon_{bending}$ points upwards and to the right. A dashed line indicates the beam's deflection. A box on the right contains the formula:
$$S0 = \frac{\epsilon_{bending}}{\epsilon_{axial}}$$

FASTENER
MILK RAIL STEEL
3.76

Fig. 4-4 Single shear lap joint used for measurement of secondary bending (Ref. 4.3)
- Not the FMPS procedure

ZERO POINT FOR
STABILIZED
MEASUREMENT

Fig. 4-5 Relationship between measured elongation and external load; single shear lap joint (fig. 4.4)
(Ref. 4.3)

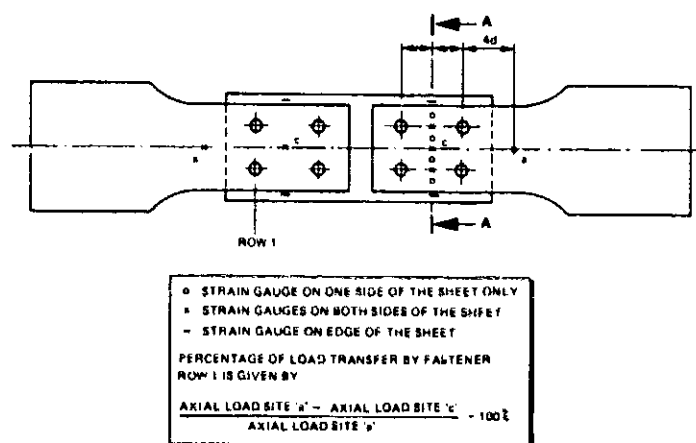


Fig. 4-6 Determination of the percentage of load transfer

ANNEX 5

RESULTS OF THE MEASUREMENTS OF SECONDARY BANDING AND LOAD TRANSFER

This section presents the full details of the measurements of secondary banding and load transfer. Table 5-1 to 5-18 presents the values of secondary banding and load transfer as reported by the participants. Figures 5-1 to 5-3 present graphically the secondary banding and load transfer as function of the applied load. Table 13 of the main section of this report summarizes the values of secondary banding and load transfer.

TABLE 5-1
Values of load transfer and secondary
banding ratio - France

Specimen type	REVERSE DOUBLE DOGBONE		
Specimen number	7-1 2024 "Gamma D" - HI-LOK		
	REAM; INTERFERENCE 80 μ m		
	Alodine 1200, primer + PR1422		
Max. load (MPa)	250		
Min. load (MPa)	-54		
% of the maximum load in FALSTAFF	Secondary banding ratio		% load transferred
	SB1	SB2	
0	.409	.249	-
16.7	.359	.231	8.7
33.3	.333	.211	7
50	.314	.193	6.4
66.7	.295	.177	5.8
83.3	.273	.159	5.3
100	.256	.150	4.9
83.3	.277	.161	4.3
66.7	.298	.174	4
50	.322	.192	4
33.3	.342	.215	4.1
16.7	.366	.240	5.9
0	.397	.254	-
minimum load	.370	.234	-10.4
0	.371	.243	-

$$LT = \frac{M_2 - M}{M} \times 100$$

$$M = \frac{M_1 + M_2}{2}$$

M = axial strain (mean)
in top sheet

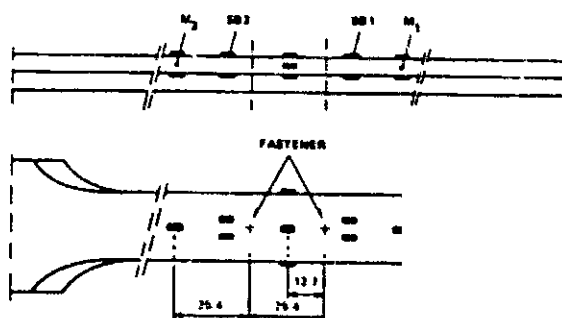


TABLE 5-2
Values of load transfer and secondary
bending ratio - France

TABLE 5-3
Values of load transfer and secondary
bending ratio - France

Specimen type
Specimen number
Max. load (MPa)
Min. load (MPa)

TABLE 5-4
Values of load transfer and secondary
bending ratio - France

Specimen type	TYPE C - FRANCE, HI-LOK, CLEARANCE 10-30 μ m, FRFS-A	
Max. load (MPa)	200	
Min. load (MPa)	-53.3	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	-	-
16.7	1.37	48.2
33.3	1.45	55.4
50	1.42	55.4
66.7	1.35	54.8
83.3	1.29	54.3
100	1.23	53.9
83.3	1.23	56.9
66.7	1.26	59.5
50	1.30	62.9
33.3	1.32	68.3
16.7	1.28	84.5
0	-	-
minimum load	-6.39	38.1
0	-	-

TABLE 5-5
Values of load transfer and secondary
bending ratio - France

Specimen type	C, HI-LOK, COLD WORK, INTERFERENCE 15-35 μ m, FRFS-B	
Max. load (MPa)	200	
Min. load (MPa)	-53.3	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	-	-
16.7	1.62	43.2
33.3	1.68	42.4
50	1.64	41.2
66.7	1.57	41.5
83.3	1.49	41.8
100	1.42	43.1
83.3	1.45	45.5
66.7	1.49	41.7
50	1.53	41.3
33.3	1.57	39.7
16.7	1.58	38
0	-	-
minimum load	-2.95	24.8
0	-	-

NOTE: without sealant

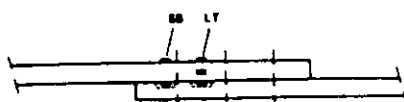


FIGURE SEE TABLES-4

TABLE 5-6
Values of load transfer and secondary
bending ratio - UK

Specimen type	Q-TYPE, NON COLD-WORKED, H1-LOK	
Specimen number	10	
Max. load (MPa)	350 NET	
Min. load (MPa)	-107 NET	
test run, cycle nr.	AFTER 20.000 CYCLES BETWEEN 0 AND 30 kN	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	0	0
16.7	.245	34.0
33.3	.295	38.5
50	.360	42.5
66.7	.395	45.5
83.3	.430	47.5
100	.440	49.0
83.3	.400	50.0
66.7	.350	48.0
50	.300	52.5
33.3	.260	54.0
16.7	.370	55.0
0	0	0
minimum load	.360	40.0
0	0	0

TABLE 5-7
Values of load transfer and secondary
bending ratio - UK

Specimen type	Q-TYPE, COLD-WORKED, H1-LOK	
Specimen number	3	
Max. load (MPa)	380 NET	
Min. load (MPa)	-85.6 NET	
test run, cycle nr.	AFTER 20.000 CYCLES BETWEEN 0 AND 30 kN	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0	0	0
16.7	.344	33.5
33.3	.442	33.2
50	.522	39.6
66.7	.547	40.9
83.3	.537	42.1
100	.528	43.3
83.3	.512	43.4
66.7	.493	43.3
50	.475	43.8
33.3	.471	44.3
16.7	.487	44.5
0	0	0
minimum load	.277	37.0
0	0	0

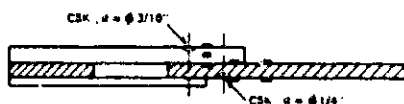


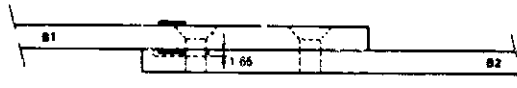
FIGURE SEE TABLE 5-4

TABLE 5-8
Values of load transfer and secondary
bending ratio - USA

Specimen type	C2 SINGLE SHEAR	
Specimen number	B1/B2	
Max. load (MPa)	196.85	
Min. load (MPa)	0	
test run/cycle nr.	4	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0		not established
16.7	1.32	
33.3	1.30	
50	1.18	
66.7	1.09	
83.3	1.07	
100	1.05	
83.3	1.04	
66.7	1.02	
50	1.11	
33.3	1.24	
16.7	1.43	
0		
minimum load	-	
0	-see note-	

secondary bending ratio for strain gauges:		
1&2	3&4	5&6
1.37	1.34	1.24
1.37	1.31	1.23
1.23	1.20	1.12
1.12	1.10	1.04
1.08	1.09	1.04
1.05	1.06	1.03
1.09	1.03	1.00
1.03	1.04	1.00
1.12	1.12	1.08
1.27	1.25	1.21
1.45	1.44	1.40
see figure below		

1) average of 6 gauges



NOTE:
STRAIN GAUGE
INSTRUMENTATION
NOT ACCORDING TO
FRFS PROCEGURES

USA

DIMENSIONS IN mm

TABLE 5-9
Values of load transfer and secondary
bending ratio - The Netherlands

Specimen type	1½ DOGBONE - FRFS-A				
Specimen number	3A1				
Max. load (MPa)	60.5 kN				
Min. load (MPa)	-16.2 kN				
cycle nr.	5 and 100				
% of the maximum load in FALSTAFF	Secondary bending ratio		% load transferred		
	cycle 5	cycle 100	cycle 5	cycle 100	cycle 1000
0	0	0		0	
16.7	.018	.041		25.2	25.9
33.3	.068	.018		23.7	24.7
50	.009	.027		23.8	23.8
66.7	-.048	-.005		24.6	24.6
83.3	-.094	-.055		25.5	25.1
100	-.126	-.095		25.8	25.7
83.3	-.082	-.058		25.5	25.5
66.7	-.041	-.028		24.7	24.3
50	+.019	+.001		24.1	23.1
33.3	.067	+.026		23.5	22.4
16.7	.065	+.026		22.6	20.9
0					
minimum load	-.075	+.054		13.6	12.7
0					

TABLE 5-10
Values of load transfer and secondary
bending ratio - The Netherlands

Specimen type	1½ DOGBONE - FRFS-B		
Specimen number	3B1		
Max. load (MPa)	60.4 kN		
Min. load (MPa)	-16.2 kN		
cycle nr.	5		
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred	
	cycle 5	cycle 5	cycle 1000
0	0	0	0
16.7	-.086	20.1	22.6
33.3	.031	21.5	22.1
50	.152	22.1	22.1
66.7	.187	26.2	22.2
83.3	.110	25.5	23.2
100	.121	25.1	23.8
83.3	.111	24.5	23.3
66.7	.180	23.5	22.9
50	.140	21.2	23.1
33.3	.060	19.7	23.6
16.7	-.023	15.4	24.9
0	-	-	-
minimum load	-.055	32.6	19.5
0	-	-	-

No data at
cycle 1000
available

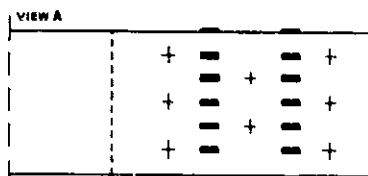
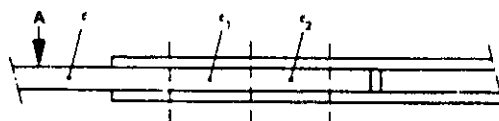
TABLE 5-11
Values of load transfer and secondary
bending ratio - France

Specimen type	C1, HI-LOK, CLEAR. 10-30 μ m
Max. load (MPa)	FRFS-A 250
Min. load (MPa)	-66.7

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred	
		LT1	LT2
0		-	-
16.7		43.9	68.2
33.3		44.6	68.4
50		45.5	67.5
66.7		46.1	67.1
83.3		46.5	67
100		46.7	66.9
83.3		47.1	68.8
66.7		47.1	69.6
50		46.6	70.7
33.3		45.6	72.4
16.7		42.4	76.6
0		-	-
minimum load		46.2	62.8
0		-	-

NOTE: without sealant $LT1 = \frac{\epsilon - \epsilon_1}{\epsilon} \times 100$

$LT2 = \frac{\epsilon - \epsilon_2}{\epsilon} \times 100$



(F)

TABLE 5-12
Values of load transfer and secondary
bending ratio - France

Specimen type	C1, COLD WORK, INT. 15-35 μ m		
Max. load (MPa)	FRFS-B		
Min. load (MPa)	250		
	-66.7		
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred	
		LT1	LT2
0		-	-
16.7		43	52.1
33.3		41.9	57.5
50		41.7	59.5
66.7		42.8	61.3
83.3		43.7	62
100		44.4	62.7
83.3		44.4	63.5
66.7		44.4	63.7
50		44.2	63
33.3		43.6	62.9
16.7		38.2	58.7
0		-	-
minimum load		44.6	58.2
0		-	-

NOTE: without sealant

FIGURE SEE TABLES-11

TABLE 5-13
Values of load transfer and secondary
bending ratio - France

Specimen type	D			
Max. load (MPa)	FRFS-A'			
Min. load (MPa)	250			
	-66.7			
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred		
		LT1	LT2	LT3
0		-	-	-
16.7		23.8	47.3	54.9
33.3		28.5	51.7	69.7
50		31.5	53.8	73.2
66.7		32.4	54.5	74.2
83.3		33.5	54.8	74.4
100		33.9	55.2	74.5
83.3		32.9	55.1	75.7
66.7		32.3	54.8	76.2
50		31.6	54.7	76.1
33.3		29.4	54.0	76.7
16.7		22.9	53.4	79.3
0		-	-	-
minimum load		54.0	62.6	88.7
0		-	-	-

$$LT_1 = \frac{e - e_1}{e} \times 100$$

NOTE: without sealant

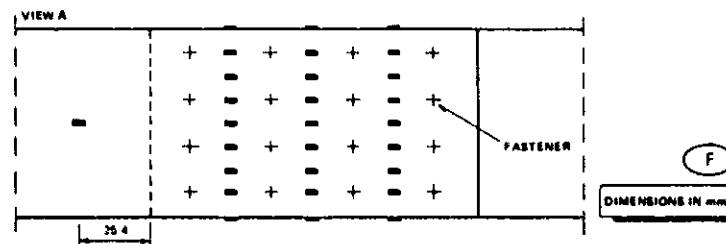
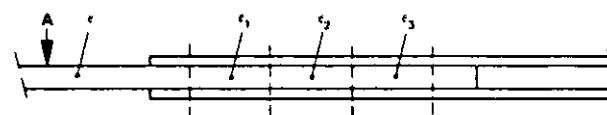


TABLE 5-14
Values of load transfer and secondary
bending ratio - France

Specimen type	D, FRFS-B', COLD WORK			
Specimen number	HI-LOK, Int. 15-35 μ m			
Max. load (MPa)	250			
Min. load (MPa)	-67			

% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred		
		LT1	LT2	LT3
0		-	-	-
16.7		46.3	57.6	67.2
33.3		44.1	57.1	69.8
50		42.9	57.1	71.0
66.7		41.8	56.6	71.3
83.3		41.7	56.4	72.2
100		41.7	56.5	73.0
83.3		41.1	56.1	73.2
66.7		40.8	55.7	72.7
50		40.4	55.2	72.6
33.3		40.8	55.5	72.6
16.7		39.2	54.4	72.4
0		-	-	-
minimum load		-	-	-
0		-	-	-

NOTE: without sealant

FIGURE SEE TABLE 5-13

TABLE 5-15
Values of load transfer and secondary
bending ratio - The Netherlands

Specimen type	1½ DOGBONE DOUBLE SHEAR	
Specimen number	4A11 FRFS-A	
Max. load (MPa)	250 MPa, 60.5 kN	
Min. load (MPa)	-16.2 kN	
cycle nr.	1000	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0		-
16.7		41.9
33.3		35.7
50		35.7
66.7		35.2
83.3		34.7
100		35
83.3		32.8
66.7		31.3
50		29.3
33.3		25.6
16.7		15.2
0		-
minimum load		-
0		-

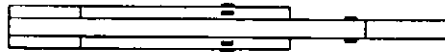


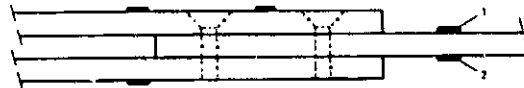
TABLE 5-16
Values of load transfer and secondary
bending ratio - The Netherlands

Specimen type	1½ DOGBONE DOUBLE SHEAR	
Specimen number	4B11 FRFS-B	
Max. load (MPa)	250 MPa, 60.5 kN	
Min. load (MPa)	-16.2 kN	
cycle nr.	1000	
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred
0		-
16.7		47.5
33.3		47.3
50		45.9
66.7		43.6
83.3		42.0
100		40.3
83.3		40.3
66.7		39.8
50		40.4
33.3		41.2
16.7		42.2
0		-
minimum load		48.1
0		-

FIGURE SEE TABLE 5-15

TABLE 5-17
Values of load transfer and secondary
bending ratio - USA

Specimen type	DOUBLE SHEAR EQUIVALENT						
Specimen number	01-1						
Max. load (MPa)	196.85						
Min. load (MPa)	0						
Test run, cycle nr.	1						
% of the maximum load in FALSTAFF	Secondary bending ratio	% load transferred $1 - \frac{7+8}{3+5} \times 100 \%$	strain at gauge nr.				
			3	5	7	8	
0		-	-	-	-	-	-
16.7		1-77 = 23	191	192	146	148	
33.3		1-67 = 33	405	404	267	279	
50		1-59 = 41	628	628	365	381	
66.7		1-55 = 45	853	855	468	471	
83.3		1-52 = 48	1077	1083	564	562	
100		1-50 = 50	1302	1312	648	652	
83.3		1-51 = 49	1070	1085	550	552	
66.7		1-53 = 47	853	860	457	453	
50		1-57 = 43	630	632	357	363	
33.3		1-62 = 38	407	408	248	255	
16.7		1-68 = 32	196	196	133	132	
0		-	-	-	-	-	-
minimum load		-see note-					
0		-					



NOTE:
STRAIN GAUGE
INSTRUMENTATION
NOT ACCORDING TO
FRFS PROCEDURES



USA

200 300
APPLIED STRESS (MPa)

Fig. 5-1 Secondary bending and load transfer of reverse double dogbone specimen - France

0 100 200 100 200 300
APPLIED STRESS (MPa) APPLIED STRESS (MPa)

Fig. 5-2a Secondary bending and load transfer of type C lap joint - France

●	Q JOINT	FRFS-A
+		FRFS-B



Fig. 5-2b Secondary bending and load transfer of the Q joint - UK

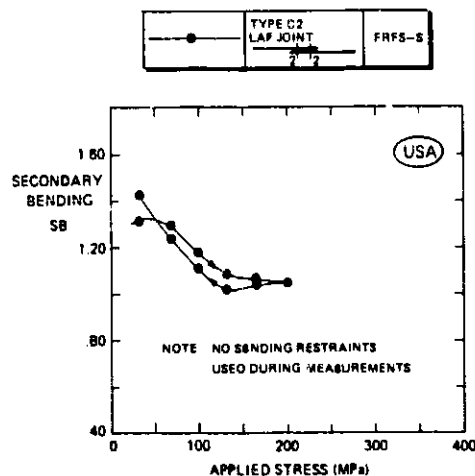


Fig. 5-2c Secondary bending of the type C2 lap joint - USA

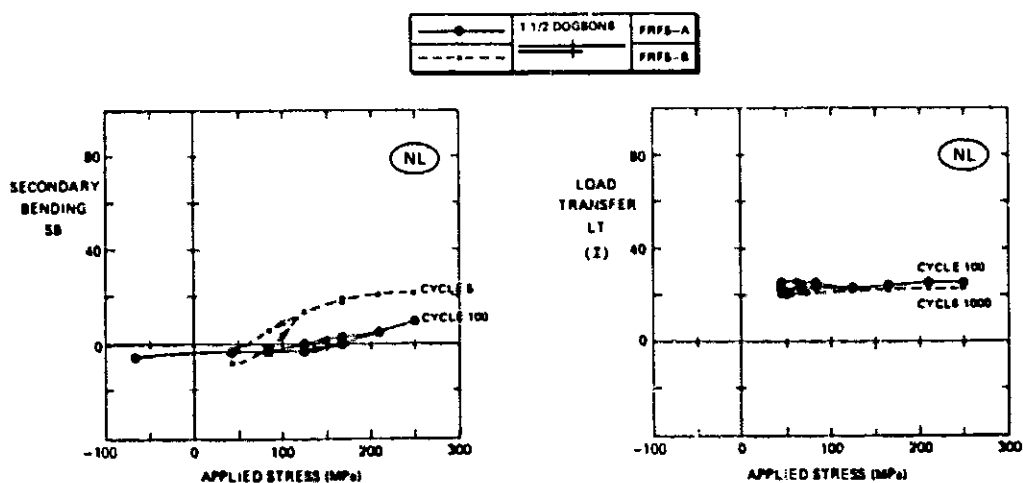


Fig. 5-2d Secondary bending and load transfer of 1 1/2 dogbone joint - the Netherlands

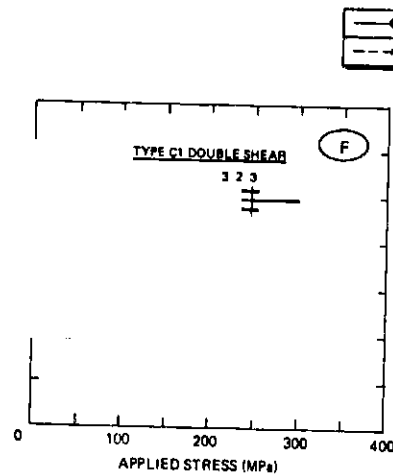


Fig. 5-3a Load transfer of type C1 double shear joint - France

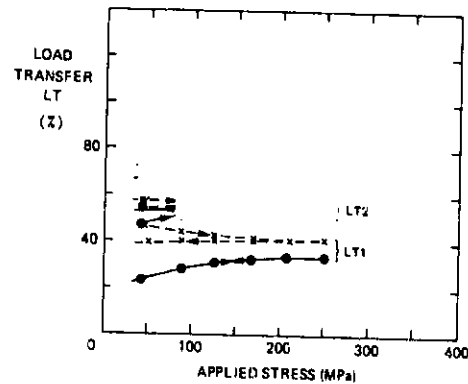


Fig. 5-3b Load transfer of type D double shear joint - France

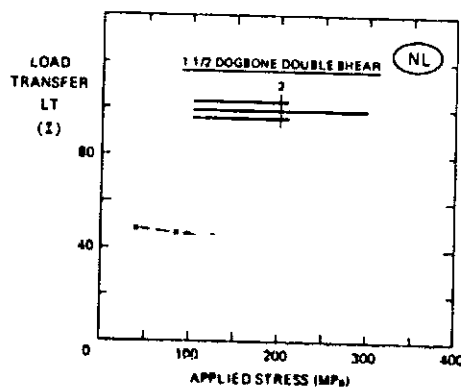


Fig. 5-3c Load transfer of 1 1/2 dogbone double shear joint - the Netherlands

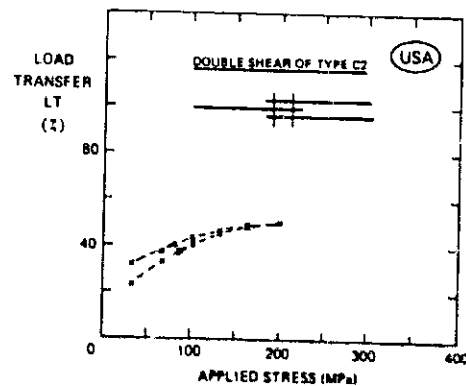


Fig. 5-3d Load transfer of type C2 double shear joint - USA

ANNEX 6

TABULAR PRESENTATION OF THE FATIGUE LIFE DATA

The complete set of fatigue life data for the FRFS programme is given in table 6-1 to 6-21; the framed numbers are the log mean life figures.

TABLE 6-1
Open hole specimen results - Sweden

OPEN HOLE SPECIMEN		SWEDEN		
MATERIAL	HOLE	LOAD LEVEL (MPa), Flights to failure and log mean		
		FALSTAFF		
		150	180	234
2024-T3 t = 5 mm	Ø 6 REAM	83281		6372
		92355		5631
		25000		6631
		251000		6191
		124539		
7010-T73651 t = 120 mm 1)	Ø 6 REAM	92150	11452	5359
		78845		3572
		134558		5172
		99249		4626

1) Specimen width in the short transverse direction; specimen thickness = 5 mm

TABLE 6-2
No load transfer joints - France

NO LOAD TRANSFER JOINTS					FRANCE						
MATERIAL					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN						
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT (μm)	FALSTAFF						
					200	222	260	290	300	351.6	392.5
2024-T351	ANODIZE PRIMER SEALANT	BROACH	LOCKBOLT	INTERFERENCE 16-32	82973 78139 30960 58550		24925 29150 27173 27900		2052 2000 2016	173 173 81 134	
2214-T651	FAST. DRY INST.				60032 133860 69632 82400		23232 24173 24081 23800			8225 7373 7373 7650	
7475-T7361					43344 35160 68234 47000		13432 14726 12760 13600			373 432 573 452	
7050-T7651					81560 168287 81755 103900					10173 8930 8426 9150	
2024-T351	BARE					61684 83428 66832 70060		3831 6232 4973 3232 4430			25 12 17

log
mean
life

TABLE 6-3
No load transfer joints - Sweden

NO LOAD TRANSFER JOINTS					SWEDEN	
MATERIAL					FALSTAFF (MPa)	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μm	200 MPa	280 MPa
2024-T3	EPOXY PRIMER SEALANT	REAM	MLM-11-06-11 Ø 5.990	INT. AVE. -7	> 120000 75851 112572	3772 7031 8572
7010-T73651 1)	PR1431G			INT. -28 TO CLEAR +10	44972 27929 74170	7031 5572 10172

1) Specimen width in the short transverse direction.
t = 120 mm - t = 5 mm

TABLE 6-4
No load transfer joints - France

LOW LOAD TRANSFER JOINTS					FRANCH								
REVERSE DOUBLE DOGBOONE													
MATERIAL	FASTENER SYSTEM				LOAD LEVEL (MPa) FLIGHTS TO FAILURE AND $\frac{1}{2}$ - MEAN								
ALLOY	PAYING SURFACE	HOLE QUALITY	FASTENER	FIT (um)	FALSTAFF			MINI-TWIST III			CAL. 8 - 0.1		
					200	260	331.6	96	109	130		180	225
2024-T351	ANODIZING PRIMER SEALANT	BROAD	LOCKBOLT	INTERFERENCE 16-32	> 108716	17232	232	log mean life					
					> 120478	17225	373						
					11913	432							
					> 114430	13260	335						
7050-T1451					85432	28150	6425						
					> 110000	23518	6422						
					11130	20905	1432						
							8312						
					94980	23560	8650						
2024-T351	ALUMINE PRIMER SEALANT	XRAN	NI-LOE	INTERFERENCE 80				86311	96190		296880	155360	
							319538	108612		246650	159580		
							233656	18924		271920			
							159008		9318				
								9119					
2015-T1351								188650	51189	9241	202385	157650	
								18836					
								94106	31665		222730	88680	
								91550	83861	18836	122130	49820	
								241857	74385		170510		
								81656	31865				
								85560	50066	24430	1168000	38250	
7030-T1651													
								113578	38836	44612	186360	85660	
								101377	89318	38196	137670	18230	
								98856	10190		139120		
								104330	54300	41200	159800	80960	

TABLE 6-5
Low load transfer joints - Germany

LOW LOAD TRANSFER JOINTS				FED. REP. GERMANY								
REVERSE DOUBLE ENDMENT												
MATERIAL		INNER SYSTEM		FALSTAFF		FALSTAFF		FALSTAFF		FALSTAFF		
ALLOY	WATER SURFACE	WIRE QUALITY	PARTNER	FIT	LOAD LEVEL (MPa)	FLIGHTS TO FAILURE	LOAD LEVEL	FLIGHTS TO FAILURE	LOAD LEVEL	FLIGHTS TO FAILURE	LOAD LEVEL	FLIGHTS TO FAILURE
2024-T3	ARMOZ-ING PRIMER SEALANT	SEAM	HI-LOW	INTERFERENCE 17	170 180 210 220	63031 58431 27400 15172	230 240 240 250	17772 15072 10759 12354	260 270 240 290	11011 5372 5372 5372	290 300 310 1021	2122 1372 1372 1021
		DRILL		INTERFERENCE 36	190 210 210 220	57480 38120 15772 70312	220 230 240 250	13014 20720 22372 71012	250 260 270 280	12011 6431 11172 1759	290 300 310 1021	2122 1372 1372 1021
		SEAM		INTERFERENCE 22	210 230	61772 10772	270 270	11372 12000	290 290	0145 7731		
	2024-T3	DRILL		INTERFERENCE 40	250 290	10972 16259	280 290	12141 11772	300 240	7411 0129		
		SEAM		CLEARANCE 11	230 230	30424 10559	270 280	0207 1729	290 300	7732 7431		
		DRILL	LOW-LOAD ONLY	INTERFERENCE 11	170 180 190 200	37031 32132 25770 10877	210 230 230 270	14572 10772 9172 00729	280 310 240 350	7423 0024 4982 7051	300 300 300 350	2122 1129 631 631
2024-T3	DRILL		INTERFERENCE 31	190 200 210 220	31159 20772 34372 27631	270 280 240 270	21231 16759 14831 14831	280 280 240 300	11172 12011 7237 0031	150 200 300 420	4372 3372 3372 330	
	DRILL	LOW-LOAD ONLY	INTERFERENCE 42	190 200 210	77031 30011 35750	230 230 270	35431 16772 13772	290 310 340	10811 10929 2970	300 400 620	5122 4031 012	
	PRIMER SEALANT	TAPERED BEAMS	TAPERED	INTERFERENCE 21	210 220 230	10772 30377 29077	270 280 310	23572 14772 10700	330 340 360	8031 9172 7051	350 440 410	4372 2072 4372

TABLE 6-6
Low load transfer joints - Italy

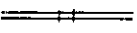
LOW LOAD TRANSFER JOINTS					ITALY	
 REVERSE DOUBLE DOGBONE					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm		
					280	351.6
2024-T3	ANODIZING PRIMER SEALANT	REAM	HI-LOK T1 CSK Ø 5	INTERFER- ENCE 13-43	29125 31373 26232 34929 23628 28791	log mean life
			HI-LOK T1 CSK Ø 6 TYPE LN29797		22061 17032 19820 20032 16632 19008	773 832 832 632 768 764
			HI-LOK TENSION T1 CSK Ø 6		10026 18232 12625 13080 27276 15245	773 373 432 373 373 444
			HI-LOK T1 PROT- RUDING Ø 6		19302 21432 18424 22432 25360 21253	
			HI-LOK T1 CSK Ø 8	INTERFER- ENCE 14-51	26673 21432 25773 13232 20573 20924	
		COLD WORK REAM	BOLT T1 CSK Ø 6	CLEARANCE 10-40	3929 4142 3574 3726 3817	232 432 373 373 432 360
		REAM	HI-LOK T1 CSK Ø 6 TYPE MSTM11	INTERFER- ENCE 13-43	27202 16425 16667 14715 17863 18180	
		COLD WORK REAM	BOLT T1 CSK Ø 6		39308 30013 28491 34832 44872 35395	832 632 626 632 632 666

TABLE 6-7
Low load transfer joints - The Netherlands

LOW LOAD TRANSFER JOINTS					THE NETHERLANDS				
REVERSE DOUBLE DOGBONE									
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN				
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μm	FALSTAFF		MINITWIST III		
					280	351.6	70	85	100
7050-T76	PRIMER SEALANT	DM DRILL	HI-LOK PROTRUDING	CLEARANCE	14111	8325		66323	32106
				25-	23772	9159		> 148000	48412
				INT. 76	24560			> 175000	77378
								261655	> 98632
	FAST. WET INST. WITH SEALANT				20440	8732	log mean 11fa	> 145604	> 58687
		STANDARD DRILL		CLEARANCE	6372	2129		22790	25656
				63-255	7124	2231		26581	16095
					8929			26858	17378
					7401	2179		25369	19268
2024-T3	ANO-DIZING PRIMER SEALANT	DM DRILL	HI-LOK CSK	INTERFERENCE 20-40			253646	120501	56106
							359896	124708	75260
							> 400000	147856	
	FAST. WET INSTAL. WITH SEALANT						331758	130194	54981

TABLE 6-8
Low load transfer joints - United Kingdom

LOW LOAD TRANSFER JOINTS					UNITED KINGDOM	
REVERSE DOUBLE DOGBONE UK-DESIGN						
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μm	FALSTAFF	
					164 (= 280 NET)	206 (= 350 NET)
7050-T7651	ALCOCHROMED PRIMER SEALANT	REAM	HI-LOK	CLEARANCE 13-61	25231 12372 21359 19292 18938	6631 5711 4929 5715
		TAPER REAM	TAPERLOK	INT. 46-106	54231 37772 50631 24831 27863 37254	22972 30796 14224 27172 26811 23606
		REAM	HI-TIGUE	INT. 76-127	55351 54772 53172 42172 74772 55109	17080 17729 22959 21572 23372 20368
		REAM	HUCKCRIMP	CLEARANCE 13-48	12929 10724 13172 11011 18959 13069	5280 5698 6128 5024 5024 5414
		DRILL HUCK MANDRELL COLD WORK	HUCK EXL	INT. 38-144	27531 80280 120272 39759 36431 52132	14224 20631 26490 39111 24205 23625
		SPLIT SLEEVE COLD WORK REAM	HI-LOK	TRANSITION: 13 CLEAR. TO 39 INT.	72372 82172 40529 43372 60572 57585	14725 20711 18031 23359 16559 18431
		ACRES SLEEVE COLD WORK	HI-LOK	TRANSITION: 13 CLEAR. TO 13 INT.	54625 34372 40511 38231 44231 45364	19372 17031 21231 22989 19972 20020
		REVERSE DOUBLE DOGBONE ACARD DESIGN				
		REAM	HI-LOK	CLEARANCE 13-61	26337 19972 21724 24129 23172 22986	6221 7031 6011 4480 4729 5613
		SPLIT SLEEVE COLD WORK REAM	HI-LOK	TRANSITION: 13 CLEAR. TO 39 INT.	136464 173572 50759 178745 240231 138559	19172 33880 32031 22329 39824 28408

TABLE 6-9
Low load transfer joints - USA

LOW LOAD TRANSFER JOINTS				USA
REVERSE DOUBLE DOGBONE				
MATERIAL		HOLE QUALITY	FASTENER	
ALLOY	FAYING SURFACE			261.9
2024-T3 CLAD c = 3.2		STANDARD DRILL, DEBURR	RIVET 2024 HAND BUCKED (ICE BOX)	4372 5772 2572 log mean 4019 Life
			RIVET 2024 MACHINE SQUEEZED (ICE BOX)	1372 3572 2214
			RIVET 7050 HAND BUCKED	2024 3480 2654
			RIVET 7050 MACHINE SQUEEZED	2231 2430 2328

TABLE 6-10
Type D double shear joint - France

DOUBLE SHEAR JOINTS					FRANCE					
TYPE D JOINT					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN					
MATERIAL		FASTENER SYSTEM			FALSTAFF			CAL R=.1	MINI-TWIST	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μ m	200	250	300	180	109	130
2024-T351	ALODINE PRIMER	REAM	HI-LOK	INTERFERENCE 80	>139726 233130 >174000 >272195 >198187	64797 73973 40573	13373 23760 39173	126750 285020 187560 765210	117653 98856 73656 87513	25656 9656 21656 18856
					57940	23200	205891	93000	17850	
7075-T7351	ALODINE PRIMER	REAM	HI-LOK		138373 94832	29740 47295 59573	41226 30422 21632	184070 225630 395080 185550 189710	136412 98786 65099 108095	50682 41656 45656 62682
					114550	43760	30050	225000	98700	49600
7050-T7651	EPOXY PAINT	BROACH		CLEARANCE 10-30	9179 9373 10973 9810	3730 4912 3373				
		(PKFS-A)		3954						
		COLD WORK BROACH		INTERFERENCE 15-35	69760 85032 50025 58725	16632 15773 28730 24432 20717				
		(PKFS-B)		20717						
	ALODINE PRIMER	REAM	HI-LOK	INTERFERENCE 80		45973 18832 51573 35500			87391 134936 52965 88412 86200	
					144773 113373	55032 36797 50973	27225 40832 20632	195400 139340 120720 161418 163510	82682 66857 83841 71671	24501 41851 25356 33099
					128116	46900	26400	154000	75900	30550

TABLE 6-11
Medium load transfer double shear joint - The Netherlands

DOUBLE SHEAR JOINTS					THE NETHERLANDS				
TYPE M1 & M2-MEDIUM LOAD TRANSFER									
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN				
ALLOY	PAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	MINI-TWIST			FALSTAFF	
					70	85	100	200	250
2024-T3	ANODIZE PRIMER SEALANT	DOUBLE MARGIN DRILL	HI-LOK	INTERFERENCE 20-40	log mean life →	99898 183526 →315666 →179540	> 57120 > 87716 112446 → 82592		
		REAM		INTERFERENCE 80-100		>400000 164412 >250320 >259395 →400000	> 57377 78073 → 66929		
7050-T76	PRIMER SEALANT	REAM (FRFS-A)	HI-LOK	CLEARANCE 10-30				34432 →	11832 →
		GOLD WORK (FRFS-B)	COMPLETED	INTERFERENCE 15-35				>16773 →	>16044 →

TABLE 6-12
High load transfer double shear joint - The Netherlands

DOUBLE SHEAR JOINTS					THE NETHERLANDS				
TYPE M1 HIGH LOAD TRANSFER									
MATERIAL		FASTENER SYSTEM			LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN				
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μm	MINI-TWIST III			FALSTAFF	
					70	85	100	200	250
2024-T3	ANODIZE PRIMER SEALANT	DOUBLE MARGIN DRILL	HI-LOK	INTERFERENCE 20-40 log mean life	307691	56921 98496 121656	12412 24411		
				307691	88025	17407			
		REAM		INTERFERENCE 80-100	156684 157655	50991 61031	31691		
					157169	55726	31691		
		COLD WORK REAM		CLEARANCE 0-25	>400000	93197 108856 121578	13653 48417		
					>400000	108582	25701		
7050-T76	PRIMER SEALANT	REAM	HI-LOK	CLEARANCE 10-30				14432 15468	4041 5848 9573 5329
								5892	
		COLD WORK REAM		INTERFERENCE 15-35				>18636 >34529	8432 9625 13832 >14200
									>11236

TABLE 6-13
High load transfer double shear joint - United Kingdom

DOUBLE SHEAR JOINTS					UNITED KINGDOM	
TYPE H2 - HIGH LOAD TRANSFER					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT µm	191 280 NET	256 375 NET
7010-T7651	ALOCROME PRIMER SEALANT	REAM	HI-LOK	CLEARANCE 13-61	37898 23172 30839 34929 14821 log 26875 mean life	7572 4031 3559 3431 2959 4060
		TAPER REAM	TAPERLOK	INTERFERENCE 46-106	172929 91211 191085 134759 141963	21421 42929 29206 47772 33655
		REAM	HI-TIGUE	INTERFERENCE 76-127	66624 32796 52172 123227 41024 56510	34224 27749 27031 12972 20924 23368
		REAM	HUCKCRIMP	CLEARANCE 13-48	50911 14825 45274 143431 114529 56214	18943 14329 17031 20572 19524 17937
		DRILL HUCK MANDEL COLD WORK	HUCK EXL.	INTERFERENCE 38-144	211711 155031 155172 96996 146572 148580	87511 58880 55172 59429 52972 61814
		SPLIT SLEEVE COLD WORK REAM	HI-LOK	TRANSITION: 13 CLEAR. TO 39 INT.	51172 76759 > 224420 106196 93021 106386	31759 34525 27772 27359 30212
		ACRES SLEEVE COLD WORK	HI-LOK	TRANSITION 13 CLEAR. TO 13 INT.	124759 41929 45637 62034	13624 9031 16972 12329 30621 15113

TABLE 6-14
Type C lap joint - France

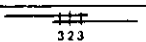
SINGLE SHEAR JOINTS					FRANCE		
TYPE C LAP JOINT 					LOAD LEVEL, FLIGHTS TO FAILURE AND LOG MEAN		
MATERIAL	FASTENER SYSTEM				FALSTAFF		
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μ m	112.5	150	200
2024-T3	ANODIZING PRIMER SEALANT	BROACH	LOCKBOLT	INTERFERENCE 16-22	53634 63426 71596 log mean <u>62450</u> life	10606 15432 14832 <u>13440</u>	1431 1432 1130 <u>1320</u>
2214-T651					41825 64944 56522 <u>53550</u>	16232 19822 20973 <u>18900</u>	3432 2925 4832 <u>3550</u>
7475-T7351					36206 26712 41625 <u>34270</u>	8330 12330 13185 <u>11060</u>	1681 1573 1112 <u>1430</u>
7050-T765	EPOXY PAINT	REAM (FRFS-A)	HI-LOK			9032 9632 8960 12144 <u>9860</u>	2981 3973 2573 2832 <u>3050</u>
		COLD WORK REAM (FRFS-B)				8832 13730 12173 7944 <u>10410</u>	3373 4973 3373 <u>3840</u>

TABLE 6-15
Q-type joint - United Kingdom

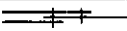
SINGLE SHEAR JOINTS					UNITED KINGDOM	
 Q-JOINT					LOAD LEVEL (MPa), FLIGHTS TO FAILURE LOG MEAN	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μm	191 280 NET	263 350 NET
7050-T76	PRIMER SEALANT	REAM (FRFS-A)	HI-LOK	CLEARANCE 10-30	12128 14431 12160 13831 log 14031 mean 13280 life	3925 2929 3444 4336 3639
		COLD WORK REAM (FRFS-B)		INTERFERENCE 15-35	9631 12424 12329 16224 17631 13337	3801 3172 3624 5323 3905

TABLE 6-16
1 1/2 Dogbone joint - USA

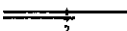
SINGLE SHEAR JOINTS					USA	
 1 1/2 DOGBONE					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT μm	238	
7075-T76 NAKRE t=3.2	ANODIZE PRIMER TOPCOAT ¹⁾ ¹⁾ not on faying surface	REAM	HI-LOK	SLIGHT PRESS	16772 22572 25529 19972 log mean 20961 life	
		REAM	SLEEVBOLT	INTERFERENCE 64	23231 28729 16117 22077	

TABLE 6-17
Type C2 lap joint - USA

SINGLE SHEAR JOINT					USA	
TYPE C2 LAP JOINT					LOAD LEVEL, FLIGHTS TO FAILURE AND LOG MEAN	
MATERIAL		PAYING SURFACE	HOLE QUALITY	FASTENER SYSTEM		FALSTAFF
ALLOY	THICKNESS (inch)			FASTENER		
2024-T3 CLAD	.63		STANDARD DRILL DEBURR	RIVET 2024-T3 (DD)-Ø3/16-SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD		200
				RIVET 7050-T73 (E)-Ø3/16-SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD	4880 5831 11159	
	.090			RIVET 2024-T3 (DD)-Ø1/4-SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD	2775 5031 2359	
				RIVET 7050-T73 (E)-Ø1/4-SQUEEZE-MS20470 UNIVERSAL (PROTRUDING) HEAD	4824 4031	
	.100			RIVET 2024-T3 (DD)-Ø3/16-SQUEEZE-MS20426 COUNTERSUNK HEAD	1772 2031 999 1372	
				RIVET 7050-T73 (E)-Ø3/16-SQUEEZE-MS20426 COUNTERSUNK HEAD	1172 1221 2129 1080	
	.160			RIVET 2024-T3 (DD)-Ø1/4-SQUEEZE-MS20426 COUNTERSUNK HEAD	4811 4396 4743 log mean 3711 life	
				RIVET 7050-T73 (E)-Ø1/4-SQUEEZE-MS20426 COUNTERSUNK HEAD	10830 14000 7996 10329	
				RIVET 2024-T3 (DD)-Ø1/4-SQUEEZE-BRFR8DD9 BRILES FLUSH HEAD	3372 1631 4221 2124	
				RIVET 7050-T73 (E)-Ø1/4-SQUEEZE-BRFR8E9 BRILES FLUSH HEAD	6311 1) 8580 1) 9526 1) 15000 2)	
					1) BRFA System "A" fastener 2) BRFA System "K" fastener	
					LOAD LEVEL, FLIGHTS TO FAILURE AND LOG MEAN	
					FALSTAFF	
7050-T76	5	PRIMER SEALANT	BEAM	HI-LOW CLEARANCE		150 200
			FRPS-A			24059 15370
						14812 13463
						22201 18000
						36925 5960
						33832 5626
						25464 11053
			COLD WORK BEAM	INTERFERENCE		51432 12639
			FRPS-B			21773 19281
						41300 9173
						18642 8425
						56118
						125430 112715

TABLE 6-18
1½ Dogbone joint - The Netherlands

SINGLE SHEAR JOINTS					THE NETHERLANDS	
1½ DOGBONE					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	PAVING SURFACE	HOLE QUALITY	FASTENER	FIT μm	200	250
7050-T76	PRIMER SEALANT	REAM	HI-LOK	CLEARANCE 10-30	18411 60372 56972 63831 log mean 44839	9559 15419 23373 22231 16635
		FRFS-A				
		COLD WORK REAM		INTERFERENCE 15-35	29572 40431 58231 35759 39722	13524 14231 17962 19172 16045
		FRFS-B				

TABLE 6-19
Single shear X joint - Sweden

SINGLE SHEAR X JOINT				SWEDEN	
~~7050-T76~~					
MATERIAL		FASTENER SYSTEM		FALSTAFF	
ALLOY	HOLE QUALITY	FASTENER	FIT	150 MPa	200 MPa
2024-T3	REAM	HLM-11-06-05	INT. AV. -7; -28 ~ +10	112081	10211 18359 8711 11776
7050-T76	REAM FRFS-A*	HL-19-8-7	CLEAR. 29; +22 ~ +47	13860 16972 13180 log mean 14582	5329 5590 6280 5721
7050-T76	COLD WORK REAM FRFS-B*	HL-19-8-7	CLEAR +9; +2 ~ +26	42772 30224	10929 11472 11372 11416

NOTE: FRFS-A*: falling +10 μm outside the specification of FRFS-A
FRFS-B*: ~10 μm clearance instead of 25 μm interference

TABLE 6-20
Type C1 double shear joint - France

DOUBLE SHEAR EQUIVALENT JOINT					FRANCE		
TYPE C1					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN		
MATERIAL		FASTENER SYSTEM			FALSTAFF		
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT	150	200	250
7050-T7651	EPOXY PAINT FASTENERS WET INSTALLED	FRFS-A	HI-LOK	CLEARANCE 10-30	106490	38373 23912 22637 21797 log mean + life 106490	8825 9173 10973
		FRFS-B		INTERFERENCE 15-35		86360 79575 89832 41899 46432 65450	28628 29160 27530 28430

TABLE 6-21
1/2 Double shear joint - The Netherlands

DOUBLE SHEAR JOINTS					THE NETHERLANDS	
1/2 DOUBLE SHEAR DOGBONE					LOAD LEVEL (MPa), FLIGHTS TO FAILURE AND LOG MEAN	
MATERIAL		FASTENER SYSTEM			FALSTAFF	
ALLOY	FAYING SURFACE	HOLE QUALITY	FASTENER	FIT	200	250
7050-T76	PRIMER SEALANT FASTENER WET INSTALLED	REAM FRFS-A	HI-LOK	CLEARANCE 10-30	28329 49772 28638 32631 log mean + life 33880	14772 16924 12372 18372
		COLD WORK REAM FRFS-B		INTERFERENCE 15-35	> 54756 > 99980 121194 87266	58172 90831 99211 93572 83688

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