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# THE NEED FOR BIAXIAL FATIGUE TESTING AT A.R.L.

J.M. FINNEY and P.W. BEAVER







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# THE NEED FOR BIAXIAL FATIGUE TESTING AT A.R.L.

by

J.M. FINNEY and P.W. BEAVER

SUMMARY

The need for biaxial fatigue testing at ARL is discussed. The acquisition of a facility is based on the grounds of improving fatigue and fracture prediction in aircraft, and enhancing ARL's capability of responding to Service problems.



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## 1. BASIS

A biaxial fatigue test facility is needed at ARL to:

(i) significantly improve the prediction of fatigue and fracture in aircraft structures; and

(ii) provide a research tool that will enhance ARL's ability to give expert information to the Services.

Fatigue and fracture prediction at ARL, although state-of-the-art, generally does not account for multiaxiality. Therefore, supportive arguments cannot cite cases where multiaxial fatigue data have improved prediction substantially. The Sections below follow an alternative strategy and attempt to show that:

- fatigue-prone areas in aircraft are subject to substantial levels of multiaxial stress;

- current methods of fatigue prediction, which generally ignore multiaxiality, are often quite inaccurate;

- multiaxial effects on fatigue are large, sometimes of the order of current prediction accuracy;

- multiaxiality cannot, at this stage, be accounted for properly by calculation.

## 2. REGIONS OF MULTIDIRECTIONAL STRESS IN AIRCRAFT

Structural fatigue in metal aircraft has a history of being associated with wing spars and skins (often at or near fuselage joints), fuselage frames, and fin components. These structural regions are frequently subject to multidirectional loading during flight.

The local area of fatigue failure in these structural regions is, most often, associated with a stress raiser such as a bolt hole or a change of section. Such stress raisers produce their own multiaxial stress field even under unidirectional loading. (For example, in the practical case of a remotely loaded thick plate containing a hole filled with the same material, the through-thickness stress in the fatigue-critical region is about 30% of that in the loading direction, and the in-plane orthogonal stress is about 15% (but opposite in sign) of that in the loading direction).

The Mirage aircraft, still under examination by ARL, provides typical examples of fatigue-prone areas subject to multiaxial stressing. For example:

- the main spar of the wing is subject to both bending and torsion,

- the wing pick-up attachment of frame 26 is subject to bending and torsion loads from the wing, fuselage bending loads, and engine loads through frame 27,

- the stressed skin in the lower wing drain hole region is subject to both wing bending and torsion and local buckling,

- frame 20 of the fuselage is subject to fuselage bending plus the direct loads from the carriage of stores,

- the fin main-spar pick-up attachment has a complicated geometry in relation to fin bending such that multi-directional stresses occur.

Other prominent aircraft components with substantial levels of multiaxial stress are undercarriages, helicopter rotor head components, and gas turbine engine discs.

## 3. CURRENT FATIGUE ASSESSMENT METHODS AND ACCURACIES

Fatigue analysis usually consists of determining the stress in a given direction, or the maximum principal stress under the combined loading, and utilizing this with unidirectionally-obtained fatigue data (life, crack growth rate, cyclic hardening exponent, etc.).

For aircraft structures the assessment of total life (or crack initiation life) is related to the 'safe life' method of operation and predictions are made using procedures falling between two extremes. One extreme uses Miner's cumulative damage rule combined with S/N data for the material of interest. With this procedure the life cannot be predicted with confidence to better than a factor of about 10 on actual life. One of the contributing factors is an inadequate accounting of multiaxiality. The other extreme is to carry out a full-scale test under an appropriate flight-by-flight sequence of loads. This procedure is usually believed to be quite accurate but simulating flight stress distributions in a test rig can sometimes pose problems. For example, the $1M ARL Mirage wing test made in the mid-1970's indicated much lower crack growth rates in the main spar bolt holes than was subsequently found in service. This may have arisen because of atypical reaction loads.

Assessments of crack propagation life are related to the 'damage tolerance' method of operation and, again, predictions can be made with a wide variety of information. The least certain scheme is to use generalised handbook crack growth rate data (da/dN - ΔK) in conjunction with a crack growth model and (often) a load interaction model. Depending on the quality of the information crack growth life cannot be predicted with confidence to better than a factor of 5 to 10 on actual life. Another method is to measure crack growth (usually fractographically) on full-scale test specimens, and as one test only is usually made, variability in crack growth rate remains a significant problem.

## 4. LITERATURE REVIEW OF MULTIAXIAL FATIGUE AND FRACTURE

### 4.1 General

The main question arising from the discussion above is whether accounting for multiaxial stressing would improve fatigue prediction. Although a direct affirmative answer cannot be given the question has been considered indirectly by reviewing the literature on multiaxial fatigue, Ref. 1. The main conclusions of that review are now given and it is clear that multiaxial effects are sometimes very large (of the order of prediction accuracy), and that more research is needed to resolve conflicts and expand knowledge.

### 4.2 Conclusions

(1) The ultimate tensile strength of steel increases by up to 18% and the fatigue limit decreases by up to 48% as the stress state changes from uniaxial to biaxial to triaxial.

(2) The resistance of a metal to cyclic deformation is dependent on the biaxial stress ratio as well as the type of metal. Increasing the biaxial stress ratio from -1 (shear loading) to +1 (equibiaxial loading) increases the resistance to cyclic deformation.

(3) The fatigue life of metals is dependent on the biaxial strain ratio. Increasing this ratio from -1 to +1 can decrease fatigue lives in the high and low-strain regimes by factors of up to 10 and 20 respectively.

(4) Although there is some confusion in the literature concerning the effects of biaxial stresses on fatigue crack growth rates changeover tests have shown conclusively the following:

(a) A sudden change in the stress state from uniaxial to equibiaxial at the same nominal stress applied normal to the crack decreases the fatigue crack growth rate by a factor of 2. By comparison, the growth rate is increased by a factor of 4 when the stress state is suddenly changed from equibiaxial to uniaxial. A similar trend is observed on stiffened panels with the stiffeners either cracked or intact.

(b) A sudden change in stress state from uniaxial tension to pure shear, by applying a cyclic compressive stress parallel to the crack, increases the fatigue crack growth rate by a factor of 3.

(5) Experiments have shown that the crack opening displacement and the degree of crack closure decrease with increasing biaxial stress ratio when cycling about zero mean stress. Both properties are independent of biaxial ratio when the load range is from zero to a positive load.

(6) Fatigue properties are affected by out-of-phase biaxial stresses and the associated rotation of the principal stresses, as follows.

(a) Fatigue strength is decreased as the phase angle between the normal stresses is increased at any given biaxial ratio.

(b) Yielding is initiated at a lower stress for in-phase compared with out-of-phase loading.

(c) The cyclic stress/strain response of a material is affected by the phase angle - hysteresis loops change shape and rotation of the principal stresses produces additional cyclic hardening.

(d) LCF life is reduced by up to a factor of 4 with out-of-phase cycling - a phase angle of 90° giving the lowest life.

(e) Both the Tresca and octahedral shear strain criteria, commonly used for design purposes, are non-conservative under out-of-phase conditions.

(7) The critical fracture load (and critical stress intensity for fracture) is dependent on both the biaxial stress ratio and Poisson's ratio. Fracture loads increase with increasing biaxial ratio for Poisson's ratios less than 1/3 and the reverse occurs when Poisson's ratios are greater than 1/3.

(8) The critical stress intensity factors for stiffened panels, and cylindrical and spherical shells containing cracks, increase with increasing biaxial stress ratio.

(9) The stress intensity correction factors used to predict the fatigue lives of notched components are dependent on the biaxial stress ratio. A biaxial ratio of -1 increases the correction factors whereas a ratio of +1 decreases the correction factors compared with uniaxial tension.

(10) The effects of a notch on fatigue crack growth rates are greater for biaxial ratios of -1 and +1 compared with a ratio of zero.

(11) The stress state affects the deformation mechanisms and the deformed microstructure of metals during cyclic loading. The resistance to dislocation movement and the formation of a recovered dislocation sub-structure are increased, and the degree of stress relaxation is reduced, as the stress state changes from uniaxial to biaxial to triaxial.

(12) The orientation of the crack path and the failure mode are dependent on the degree of multiaxiality.

## 5. MULTIAXIAL FATIGUE AND FIBRE COMPOSITE MATERIALS

The conclusions above relate to metals but it is apparent from a review of the effects of multiaxial stressing on fibre composite materials that similar conclusions will apply. For example, Figures 1 and 2 show the effect of applying combined axial and torsion loads on the fatigue life of graphite/epoxy tubes, Ref. 2. The tubes had carbon fibre layup directions of ±45° and contained a small hole.

Fig. 1 indicates that when the torsion stress is equal to the axial tension stress the fatigue life is reduced by a factor of about 100 compared with tension alone, and when the torsion stress is double the tension, the life reduction is about $10^5$.

In order to compare the results on a more scientific basis the octahedral shear stresses were calculated for each of the conditions and Fig. 2 shows the transformed data. On this basis the multiaxial effects are reversed and again huge life differences are apparent.

## 6. CAN MULTIAXIALITY BE ACCOUNTED FOR WITHOUT RECOURSE TO TESTING?

More than twenty multiaxial fatigue criteria exit (Ref. 3) which aim to reduce the multiaxial stress state to an equivalent uniaxial stress state. The early theories were based upon either static yield of ductile metals or fracture of brittle materials, for example:

Tresca's maximum shear stress criterion,

$$\tau_{max} = \text{const} = (\sigma_1 - \sigma_3)/2, \text{ or}$$

the octahedral shear strain criterion,

$$\gamma_{oct} = \text{const} = \tfrac{2}{3}\left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_1 - \varepsilon_3)^2\right]^{\frac{1}{2}}.$$

These simple criteria are not universally satisfactory in fatigue and can sometimes lead to dangerous predictions, Ref. 4. More recent criteria appear to be empirically-based and require more test information; for example, Brown and Miller (Ref. 4) have proposed:

$$\frac{\gamma_{max}}{2}\left(= \frac{\varepsilon_1 - \varepsilon_3}{2}\right) = f\left[\varepsilon_n\left(= \frac{\varepsilon_1 + \varepsilon_3}{2}\right)\right].$$

There are several difficulties with all current criteria. Multiaxial tests have shown the existence of two main crack growth geometries, each with its own characteristic life under given multiaxial stresses, and at present it cannot be determined a priori which geometry will prevail. A further problem with many criteria is that they do not account for the effect on multiaxial fatigue life of the orientation of the three-dimensional strain field with respect to the surface.

Fracture mechanics should be useful in accounting for multiaxiality in fatigue and fracture. The linear elastic variety however, indicates that loads parallel to a crack should not influence crack behaviour, but it has been shown experimentally that fatigue crack growth under biaxial loading is dependent on the crack line load component and, moreover, on whether this component is static or cyclic, and if cyclic, whether in or out-of-phase with the crack-normal loads.

It is clear that for multiaxial fatigue life criteria, and for crack growth predictions under multiaxial stress, theory must be tested by experiment, and the usual course of delineating phenomena by experiment that must be accounted for by theory will be followed in multiaxial fatigue and fracture.

## 7. CURRENT TASKS FOR WHICH A BIAXIAL TEST FACILITY IS ESSENTIAL OR DESIRABLE

(i) DST 82/008 Fatigue of materials and components research

This basic research task is aimed at understanding the factors which influence the fatigue behaviour of materials and components in relation to the durability and damage tolerance of aircraft structures. Accurate predictions of damage tolerance in many aircraft locations will require a knowledge of crack growth behaviour under multiaxial stress and the foregoing indicates that, at present, this knowledge cannot be adequately determined from uniaxial behaviour.

(ii) DST 82/009 Structural mechanics research

The development of elastic-plastic fracture mechanics to predict the fracture and fatigue behaviour of cracked structures under multiaxial stress is a leading research topic which requires a concurrent theoretical and experimental approach. (This requirement is a restatement of (i) above, and under which task the work would proceed is not relevant to the argument).

(iii) DST 82/141 LCF life prediction methods for aircraft engines

This task is to advance prediction methods for determining the LCF life of components in aircraft propulsion systems and is related to the TF30 and F404 engines. (The task is managed by Aero Propulsion Division and Materials and Structures Divisions also collaborate). Highly stressed rotor discs are, and are likely to remain, the main problem components and the areas of fatigue initiation are subject to high degrees of biaxiality or triaxiality, e.g. bolt holes, blade attachment roots. Present methodology attempts to 'calibrate out' the influence of multiaxiality by matching uniaxial data with service and test-bed experience. The pursuit of higher cost-effectiveness is, however, creating the need to include explicitly all major variables in the fatigue process, including multiaxiality. It is to be noted that the impetus for ARL acquiring a biaxial fatigue machine came initially from Aero Propulsion Division 3-4 years ago.

(iv) AIR 80/126 Fibre composite materials research

Part of this task is concerned with the fatigue of a box-beam containing a carbon-fibre composite skin, and associated coupon fatigue tests. Because of the deliberately designed directional properties of the fibre composite materials it is important to determine whether multiaxiality significantly affects both fatigue and fracture behaviour. This task will lead naturally into research related to the fibre composites in the F/A-18.

(v) DST 83/005 Fatigue life enhancement

The essence of this task is to understand the science of various fatigue life enhancement procedures in order to advise the RAAF on refurbishment within a useful timescale. The task at present is concentrating on interference-fit fasteners and cold expansion of holes. The general approach is to determine residual stress fields around life-enhanced holes, examine how these stresses change with fatigue loading, and use fatigue data obtained under simpler conditions to predict crack growth. Apart from the residual stress field the hole itself introduces multiaxial stresses under unidirectional loading and it would appear essential to use fatigue data (e.g. cyclic stress/strain data, crack growth data) obtained on larger, fully-defined samples under multiaxial stressing.

(vi) A biaxial machine would also enable a number of Materials Division's tasks to be extended, including DST 83/008 Advanced Materials for Aircraft, and DST 82/020 Physical Modelling of the Performance of Aircraft Materials.

## 8. THE CASE FOR BIAXIAL FATIGUE TESTING

The foregoing has attempted to indicate that the critical fatigue locations in aircraft structures are often regions of significant multiaxial stress, and that current fatigue estimation procedures do not adequately take this into account. There is sufficient information showing sizeable effects of multiaxiality in fatigue and it follows, reasonably, that the accuracy of these estimation procedures will be improved by a better representation of the applied stresses.

It is also evident that, at present, multiaxiality cannot adequately be accounted for by calculation and that testing is necessary.

Some experiments on multiaxial fatigue were made earlier this century but most were related to total fatigue life and to determining equivalent uniaxial stress states. There has been a resurgence of interest in the last 10 years, particularly in the UK and USA, and topics such as crack propagation, cyclic stress/strain behaviour, creep/fatigue interactions, and environmental effects are now under scrutiny in multiaxial stressing. Such studies are highlighting previously unknown phenomena, such as varieties of cracking modes, and it is apparent that if ARL is to be an adequate source of expertise for the Services in relation to fatigue then multiaxial testing must proceed alongside a theoretical understanding.

## 9. PROPOSED BIAXIAL FATIGUE MACHINE

### 9.1 Specimen Configuration

A wide variety of techniques and specimen configurations has been used to test laboratory specimens under biaxial fatigue. The commonest methods are to use cruciform plates with in-plane orthogonal loads, and to subject thin-walled tubes to axial and torsion loads or to axial loads combined with internal and external pressure. The advantages and disadvantages of these respective configurations are as follows.

(1) Cruciform specimen

(a) Advantages:

(i) a full range of biaxial stress and strain ratios can be obtained using a single specimen geometry.

(ii) the test section is readily observed and is suitable for NDI.

(iii) the mean load level and amplitude on each axis can be controlled independently.

(iv) it is the most suitable system for crack growth studies and is suitable for elevated temperature studies.

(v) low-cycle fatigue and crack initiation studies are possible.

(b) Disadvantages:

(i) stresses and strains must be determined independently; finite element analyses and strain gauge measurements are commonly used. Once general yielding has occurred in the test section, however, the stress distribution cannot be determined by the use of strain gauges.

(ii) the test section area must be a compromise between obtaining a uniform strain distribution and preventing buckling.

(2) Thin-walled tubular specimen

(a) Advantages:

(i) the stresses in the test section can be determined readily as the applied loads are fully supported by this region. Strains can be determined by using a biaxial extensometer.

(ii) stress/strain hysteresis loops can be readily determined.

(iii) low-cycle fatigue and crack initiation studies are possible.

(iv) specimens can be readily tested at elevated temperature.

(b) Disadvantages:

(i) the range of biaxial stress and strain ratios is limited.

(ii) a compromise must be reached in wall thickness between reducing strain gradients and preventing buckling.

(iii) pressurization instead of torsion permits the full range of biaxial ratios but gives its own problems, namely:

- through-thickness cracks may prevent pressurization

- the oil used for pressurization may influence the initiation and growth of cracks

- a 'hydrowedge' effect on crack opening may be encountered

- elevated temperature studies may be limited by the oil. Rubber sleeving may eliminate some of the difficulties above but suitable sleeving for elevated temperature testing remains a problem.

On balance, the cruciform specimen shape appears the most suited to ARL's tasks. Although not as suitable as tubular specimens for determining cyclic stress/strain behaviour, the cruciform shape is much better for crack propagation studies. ARL is well placed to determine stresses and strains in such specimens by either finite element analysis or strain gauge measurements. The necessary load frame for cruciform specimens also allows realistic biaxial testing of components.

### 9.2 Test Arrangements

The specimen shape and loading actions dictate the general test arrangement. The following is a guide recommended for specifying a biaxial test facility for ARL:

(1) A load frame with four actuators mounted as orthogonal pairs, each actuator to be fitted with a load cell and to be capable of tension and compression loading to at least 200 kN and preferably up to 500 kN. The dimensions of the load frame and actuator strokes are to be such that a specimen of overall dimensions up to 0.5 m x 0.5 m, at least, can be accommodated.

(2) Servo control consoles, which allow control of load, position, and strain independently in the two principal directions.

(3) Signal conditioners for specimen strain gauges.

(4) Computer for control and data acquisition.

(5) Hydraulic power supply for powering the actuators.

(6) Crack length measurement system.

(It is noted that the control and hydraulic systems are fairly universal, that is, specially-made rigs or adjustable load frames could utilize most of the equipment above for special tests. The control units are identical with those operating tension/torsion or tension/pressure biaxial systems).

### 9.3 Suppliers

W.H. Mayes and Son Ltd. (They manufacture a Cambridge Unversity design).

Instron Pty. Ltd.

MTS Corporation.

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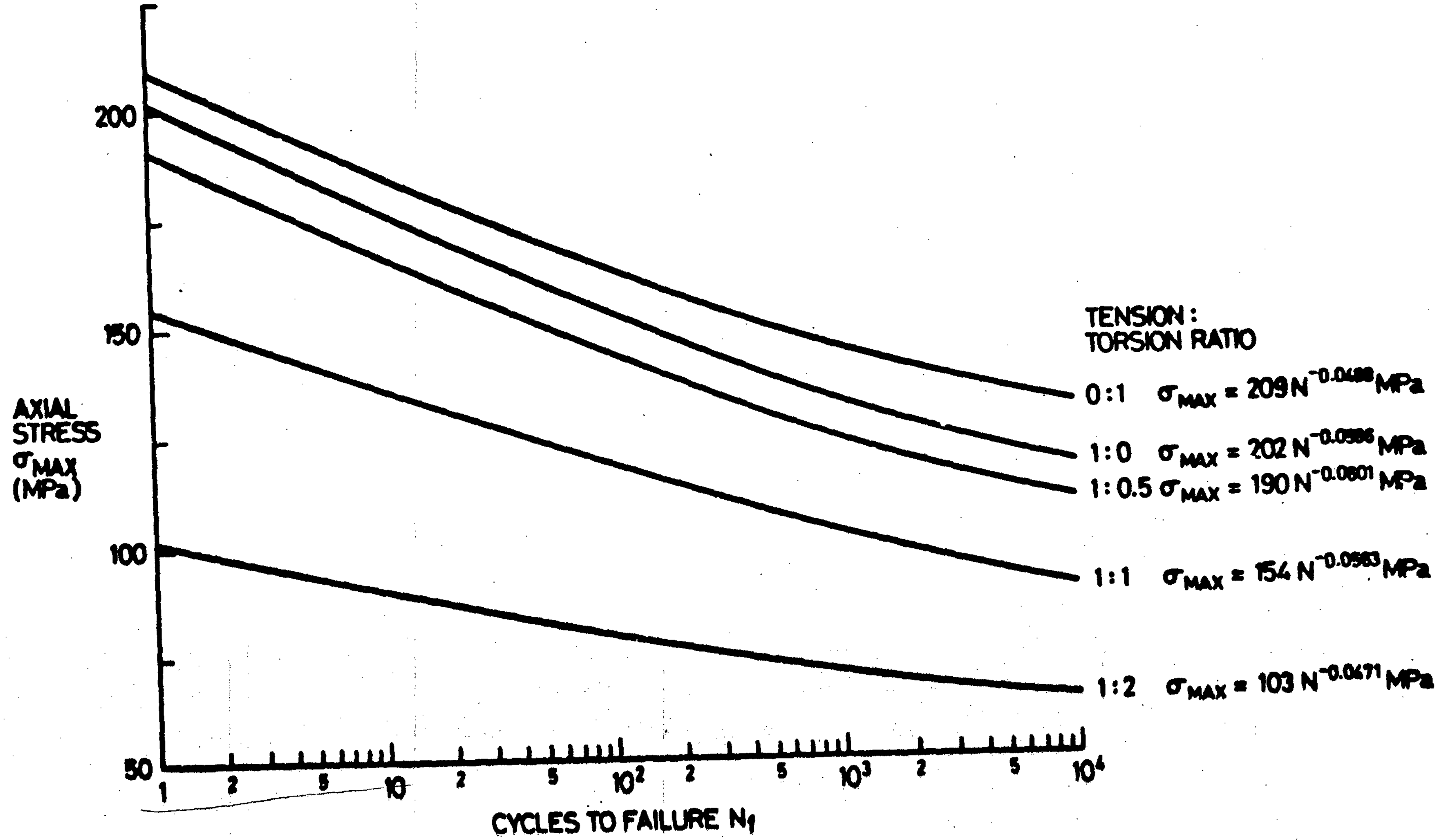


FIG.1 S-N CURVE FOR BIAXIAL FATIGUE LOADING OF $[\pm 45]_S$ GRAPHITE EPOXY TUBES WITH A 4.8mm DIA. HOLE [2] (S = MAXIMUM AXIAL STRESS)

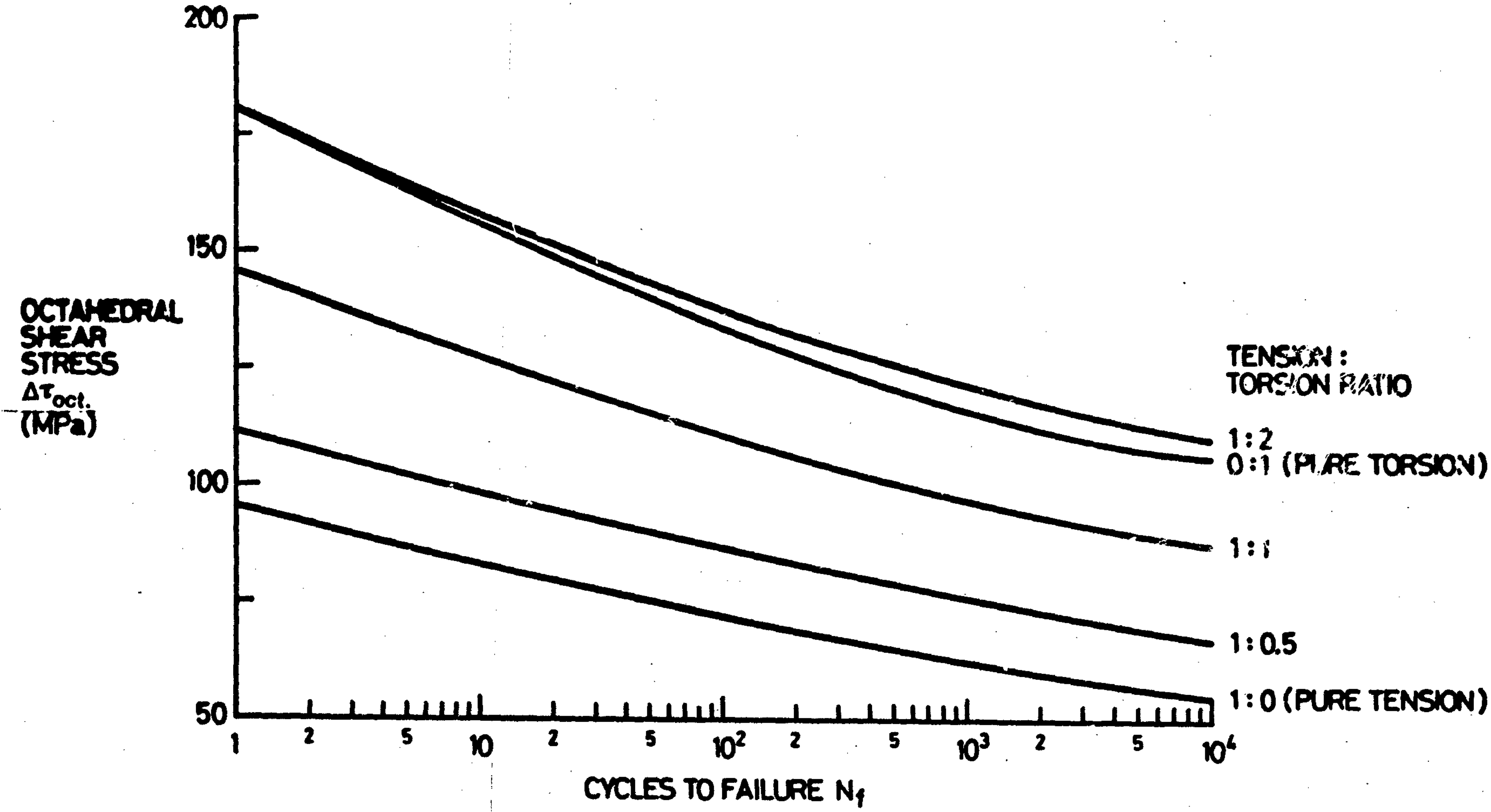


FIG. 2 S-N CURVE FOR BIAXIAL FATIGUE LOADING OF $[\pm 45]_S$ GRAPHITE EPOXY TUBES WITH A 4.8 mm DIA. HOLE [2] (S = OCTAHEDRAL SHEAR STRESS)

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16. Abstract

The need for biaxial fatigue testing at ARL is discussed. The acquisition of a facility is based on the grounds of improving fatigue and fracture prediction in aircraft, and enhancing ARL's capability of responding to Service problems.

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