Nationaal Lucht- en Ruimtevaartlaboratorium
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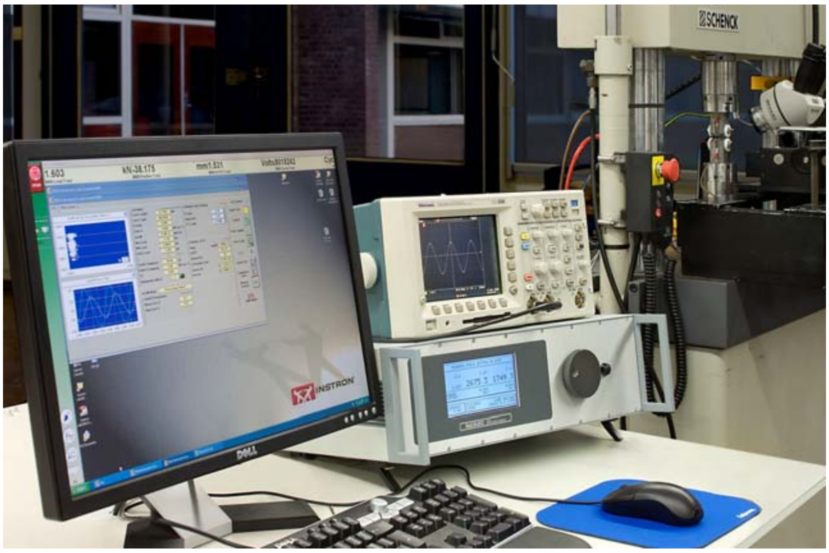
Executive summary

Thirty years on from the paper "Gust Spectrum Fatigue Crack Propagation in Candidate Skin Materials", Fatigue of Engineering Materials and Structures, Vol. 1, pp. 5-19



Problem area
Many unexpected fatigue problems can occur in aircraft, despite decades of R&D, including flight simulation fatigue testing and analysis. Several fatigue design philosophies have been developed, but it is increasingly recognised that a holistic total life approach is advisable or even necessary.

Description
The paper "Gust spectrum fatigue crack propagation in candidate skin materials" appeared in the first issue of *Fatigue of Engineering Materials and Structures*, now *FFEMS*. The present report briefly covers the intervening thirty years of materials and flight simulation fatigue development, and also looks to current problems and future work on fatigue life assessment, in particular the requirements for implementing the total life approach.

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Summary

The paper "Gust spectrum fatigue crack propagation in candidate skin materials" appeared in the first issue of *Fatigue of Engineering Materials and Structures*, now *FFEMS*. The present report briefly covers the intervening thirty years of materials and flight simulation fatigue development, and also looks to current problems and future work on fatigue life assessment, in particular the requirements for implementing a holistic total life approach.

Contents

Thirty years on from the paper "Gust Spectrum Fatigue Crack Propagation in Candidate Skin Materials", *Fatigue of Engineering Materials and Structures*, Vol. 1, pp. 5-19

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ABSTRACT

The paper "Gust spectrum fatigue crack propagation in candidate skin materials" appeared in the first issue of *Fatigue of Engineering Materials and Structures*, now *FFEMS*. The present article briefly covers the intervening thirty years and also looks to current problems and future work on fatigue life assessment.

Keywords fatigue, crack growth, spectrum loading

INTRODUCTION: IMPACT OF THE PAPER

The paper "Gust spectrum fatigue crack propagation in candidate skin materials" (Wanhill 1979) addressed a very specific topic, and by itself would not have had much impact in the intervening years. However, most of the paper's content was subsequently included in an extensive report on the Damage Tolerance (DT) properties of aluminium alloys (Wanhill 1994a). This report enabled guidelines for flight simulation fatigue crack growth testing to be formulated (Wanhill 1994b, 2002).

TOPIC DEVELOPMENT

Materials

During the 1970s there was much interest in developing DT structural concepts for transport aircraft using high strength AA7000 series aluminium alloys, and even titanium alloys, instead of the "traditional" AA2000 series DT alloys. However, this proved to be impractical for various reasons, including increased manufacturing difficulties and costs, and also lack of DT capability in the candidate newer materials, specifically with respect to fatigue crack growth.

From the mid-1970s through to the late 1980s the so-called second generation of aluminium-lithium (Al-Li) alloys was developed. These alloys offered substantial weight savings, owing to decreased density and higher elastic modulus, compared with the AA2000 series DT alloys. Unfortunately, this second generation of Al-Li alloys had several shortcomings, including a tendency to have strongly anisotropic mechanical properties (low short-transverse ductility and fracture toughness), thermal instability (Lynch *et al*. 2003), problematical stress corrosion resistance (Schra and Wanhill 1999) and inferior flight simulation fatigue crack growth properties (Wanhill 1994a).

Further developments from the late 1980s onwards have resulted in a third generation of Al-Li alloys. These alloys have reduced lithium contents, much tighter controls on impurity levels, and improved thermomechanical processing. They have potential for widespread DT applications in transport aircraft, including the newer Airbus models, but they have to compete with carbon fibre composite structures (Boeing 787, Airbus A350 XWB).

One other material should be mentioned: GLARE (GLAss REinforced aluminium laminates). This material has been developed since the late 1980s (Vogelesang 2004) and is currently used in the Airbus 380 fuselage. GLARE consists of alternating layers of aluminium and glass fibre reinforced adhesive, and has excellent DT properties owing to "fibre crack bridging", whereby intact glass fibres in the adhesive layers impose a significant restraint on crack growth in the aluminium layers.

Flight simulation fatigue crack propagation

Use was made of the gust spectrum load sequence TWIST (De Jonge *et al.* 1973) for the tests reported in Wanhill (1979). TWIST consists of repeated blocks of 4000 simulated flights that had been fully defined to enable the comparison of results from different laboratories. This meant that there were only one or two issues to consider for the tests. These were the choice of clipping level for high gust loads and the possibly unrealistic influence of severe simulated flights if the crack propagation lives would be shorter than about 2 flight blocks.

These issues are still relevant, and it is perhaps worth mentioning the many aspects that must be considered when developing flight simulation load sequences for fatigue investigations. The following list is from Iyyer (2008):

(1) Significant factors
- Mission mix in flight block;
- Load levels for each mission event;
- Clipping of infrequent high tensile and compressive loads;
- Truncation (omission) of frequent low loads near 1g and other small cyclic perturbations;
- Valley-peak coupling to provide realistic event sequencing;
- Loads averaging interval ~ 0.1g.

(2) Other factors
- Flight block size;
- Mission sequencing;
- Truncation of low load compression-compression cycles;
- Perturbations in 1g flight and Δg loads.

CURRENT PROBLEMS

The use of DT principles for determining the fatigue lives of aircraft structures calls for eliminating the time it takes a fatigue crack to initiate, since it is to be assumed that cracks are already present at the start of the service life. This assumption supposedly simplifies analysis of each critical area, but real structures are usually complex and not easily fully analysed. As a result, in-service fatigue problems that were not predicted from the original DT analyses can occur. This is particularly the case in tactical aircraft, for which unexpected fatigue cracking has resulted in costly structural repairs and unscheduled frequent inspections (Jones *et al.* 2006; Moore 2007). In retrospect these discrepancies should have been expected, since in-service load histories can differ markedly from the design assumptions and full-scale test conditions. The service usage may be more severe, the aircraft's role may change, the overall weight may increase, and the environment may be different.

The situation appears to be less severe for transport aircraft, but similar problems with service load histories, changed mission types and increasing weights do occur. In addition, though this is not confined to transport aircraft, there may be incentives to fly the aircraft well beyond the original design goals, the so-called "geriatric" aircraft problem (Ramsden 1977).

Owing to the many (unexpected) fatigue problems that can occur during the life of an aircraft, there has recently been a shift in the focus of fatigue research from the original DT concept, as set out in MIL-STD-1530A (1975), to a holistic total life approach that includes fatigue crack initiation mechanisms and short crack growth analyses (Glaessgen *et al*. 2008; Liao *et al*. 2008). This approach somewhat belatedly recognises that in many cases most of the fatigue life is spent while fatigue cracks are initiating and small, a fact known for many decades (Schijve 1967).

Fatigue cracking – in both critical and apparently non-critical locations − may start from small discontinuities in the material (constituent particles and voids), manufacturing defects such as scratches, burrs, nicks and excessive pitting from surface treatments, design inadequacies (unexpected stress concentrations), or degradation processes such as corrosion and fretting. Use of an holistic approach makes it necessary to determine (1) the nature of the fatigue crack origins, (2) the times it takes for cracks to initiate and (3) the growth rates both when the cracks are small[1] as well as large enough to be detectable by Non-Destructive Inspection (NDI). All three aspects require post-test study of the fatigue fracture surfaces by Quantitative Fractography (QF).

QF of fatigue crack growth requires an ability to match features found on the fracture surfaces with the loading/environmental history of the specimen or component. This is sometimes possible as a natural consequence of the test load histories, when it turns out that well-defined fracture surface markers occur at regular intervals along the crack path. However, QF's main usefulness lies in reconstructing the fatigue initiation and crack growth processes during tests with load histories modified to produce fracture surface markers.

A recent report (Barter and Wanhill 2008) discusses many QF examples for a variety of fatigue load histories and crack sizes, in order to provide guidelines for obtaining recognisable markers with minimal disturbance of the crack growth process. These guidelines are applicable to aerospace alloys tested as coupons, components and full-scale test articles, and should be very useful in choosing marker load strategies for the holistic approach to fatigue life assessment.

[1] Fatigue cracks less than about 0.5 mm in size often grow faster or more erratically than would be predicted from long crack data (Suresh and Ritchie 1984; Wanhill 1986; Wanhill 1994a) This is the so-called "small crack anomaly".

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