Fatigue Crack Growth under Flight Spectrum Loading with Superposed Fuselage Cabin Pressure

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ABSTRACT. *Pressurized transport aircraft fuselage panels see the combined action of gust loading and internal pressurization that causes a rather complex biaxial cyclic loading action. In an attempt to investigate fatigue crack growth under such conditions, cruciform test coupons cut from 2.7 mm thick 2024-T3 Al-Cu alloy were tested under a modified TWIST load spectrum superposed with biaxial quasi-static load simulating internal cabin pressure. The TWIST spectrum was modified into blocks of load cycles re-arranged so as to serve as microscopic markers of crack growth over 50 flights. Further, the magnitude of transverse load from pressurization was changed in a controlled sequence as a function of block count or crack size so as to induce changes in load biaxiality whose effect may be discernible at both the microscopic and macroscopic level.*

INTRODUCTION

Gassner [1] established a procedure to determine damage sums under variable amplitude loading that effectively serve as empirical fudge factors in fatigue life estimates. The actual reasons for non-linear damage accumulation began to unravel many decades later, when tensile overloads were unexpectedly found to retard fatigue crack growth [2]. More research in the seventies established that a number of load interaction mechanisms may be responsible for load sequence sensitivity of fatigue in metals [3]. These include crack-tip residual stress, crack closure, crack-front incompatibility, crack-tip blunting/re-sharpening, etc.

Over the years, a number of models have been developed to calculate variable amplitude fatigue crack growth. Each model is invariably built around a single load interaction mechanism, usually, crack closure [4] or residual stress [5, 6]. If a single mechanism model does correctly estimate residual life, one would invariably have to attribute it to fudging the dominance of one mechanism to approximate the actual result, which would not be much of an advancement over Gassner's approach. While research in uniaxial variable amplitude fatigue continues in an attempt to bridge this gap, problems of practical interest often relate to multi-axial loading conditions and call for the reexamination and extension of available understanding as stated above to the case of multi-axial loading.

Available experimental data on fatigue crack growth under biaxial loading with cruciform specimens are limited and somewhat contradictory by comparison to that under uniaxial fatigue. Liu and Dittmer observed that biaxiality does not affect crack growth rates under constant amplitude loading [7]. Yuuki et al [8] also did not find any effect of biaxiality at low stresses, but found the effect noticeable at high stresses. Hopper and Miller found a consistent retarding effect of tensile transverse stress on growth rate [9]. Anderson and Garrett also observed a close relationship between crack growth rate and biaxial stress field [10]. Their measurements were macroscopic and cannot be used to judge whether stress field variations cause an instantaneous, or a gradual change in growth rate.

Analytical studies also offer mixed conclusions. Ogura et al point out that K is insensitive to biaxiality[1] [11], and suggest that closure may be responsible for possible effects. However, McLung estimated that crack closure becomes sensitive to biaxiality only when stress exceeds 40% of yield stress [12], ruling out closure as a factor for most cases of practical interest. Adams found that tensile biaxiality affects plastic zone size [13]. This is supported by measurements by Liu and Dittmer [7], who as earlier noted did not however find any effect on constant amplitude crack growth rate.

Liu and Dittmer however found a significant *adverse* effect of tensile stress biaxiality on crack growth under periodic overloads and under what appears to be a simple combat aircraft load spectrum. They attribute this to the reduced overload plastic zone size in the presence of tensile transverse load. Interestingly, this is the opposite of what others have observed under constant amplitude loading [8-10].

One may conclude that available experimental data on biaxial fatigue crack growth under load sequences of practical interest are rather sketchy if not contradictory. They certainly underscore the need for much more experimental effort to cover cases of practical interest. Equally significantly, there has been a dearth of attention to the sensitivity of well-known load interaction mechanisms to biaxiality as well as the emergence of possible new mechanisms and factors associated with biaxial service loading that may not exist under uniaxial conditions.

The goal of this study was to investigate the growth of a circumferential crack in the upper panel of a pressurized fuselage cabin of a transport aircraft. The upper surface of the fuselage sees the same loads as the bottom surface of the wing. In case of pressurized cabins of transport aircraft, it will in addition, see the superposed action of internal pressure. Thus, the axial component of pressure-induced stress will add a tensile *offset* to the gust load spectrum. In addition, a hoop stress component that is *twice* the axial component will act in the transverse direction. This special case of biaxial loading involving tension-tension flight spectrum loading combined with a constant tensile transverse load was studied on a cruciform test coupon. The effect of biaxiality can be studied by varying the pressure induced component of loading and also, by merely changing only the transverse component in order to retain the asymmetry of axial loads.

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[1] One may note that standard expressions for K only represent the first term of series. The others are neglected as secondary, but they can be sensitive to biaxiality.

The next section describes the design of the experiments, which is followed by a summary of test results and their discussion.

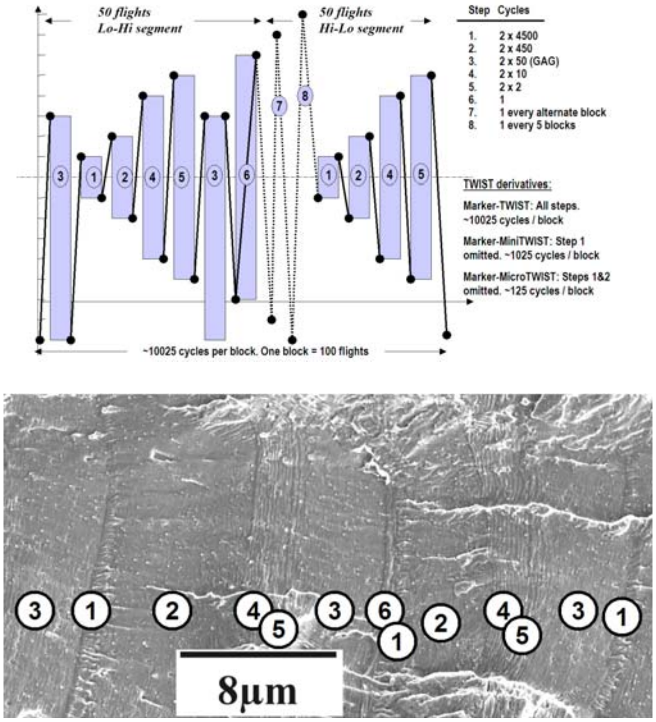

Figure 1. (Top) The Marker-TWIST load sequence and its derivatives Marker-MiniTWIST and Marker-Micro-TWIST used in the experiments. (Bottom) Typical fractograph obtained under Marker-TWIST to validate its application in quantitative analysis of contribution of individual load levels as indicated by encircled step number.

Experimental Procedure

Test System and Test Coupon

Ref. 14 provides a detailed description of the test process employed, including the cruciform test specimen and computed gauge area stress distribution and K-function, gripping and alignment measures, 4-actuator vertical load frame and the test process. For this study, a 2.7 mm thick 2024-T3 Al-alloy sheet specimen with 30 mm wide loading flaps and 75 mm diameter gauge area was used. This geometry provides practically unchanged extent of biaxiality up to half crack size of 20 mm. The extent of biaxiality can change by up to about 20% over the next 20 mm of half crack growth. Also, at this point, crack direction can deviate towards the shortest path of resistance across a loading flap. Testing was stopped at a half crack size of 40 mm, or, when difference between the two half crack sizes exceeded 5 mm. Perhaps because of specimen alignment features [14], and also because average growth rates were low enough to keep the crack front flat, crack direction never deviated noticeably from original plane, even beyond the gauge area.

Load Spectrum and Biaxial Loading

The TWIST load spectrum [15] is by far the most widely used transport aircraft wing load spectrum in fatigue studies. A unique feature of the TWIST load spectrum is the more or less even distribution of damage content from individual load levels [16]. Unlike most other load spectra, even the smallest amplitude load cycles in TWIST contribute as much as 20% of fatigue damage even if they may lie below the fatigue threshold. This feature makes TWIST an excellent candidate for variable amplitude fatigue studies because it permits assessment of susceptibility of individual load levels to load interaction under biaxial loading. This in turn is likely to impact the objectivity of research conclusions covering the entire bandwidth of possible crack growth rates.

Marker-TWIST [17], a modified version of the TWIST spectrum was employed in our experiments. The Marker-TWIST spectrum is statistically similar to TWIST and causes similar crack growth rates, but is rearranged as shown in Figure 1. The primary idea behind the Marker-TWIST spectrum is to provide a reproducible loading standard for quantitative fractography. As illustrated in Fig. 1, fractographs obtained under this sequence can provide irrefutable reference data on contribution of individual load levels to crack extension. An ideal analytical model would reproduce this picture. Fractures obtained in the ongoing study will be studied as part of future effort.

Table 1. Load details for each test

Test No	**Spectrum**	**Axial load offset**	**Static transverse load**	**Remarks**
1	Marker-MiniTWIST	1.5 kN	3 kN	
2	Marker-MiniTWIST	1.0 kN	2 kN	
3	Marker-MiniTWIST	0.5 kN	1 kN	
4	1. Marker-MicroTWIST 2. Marker-MiniTWIST 3. Marker-TWIST	1.5 kN	Toggled between 0. and 3 kN after each 1 mm crack increment	Spectrum #1 to 33 mm, #2 to 37 mm and #3 to 40 mm

In the present study, the spectrum was truncated three levels down. As a consequence, just 10 blocks (1000 flights) are adequate to completely reproduce the spectrum. Further, two more derivatives of Marker-TWIST were used. These are Marker-MiniTWIST that reduces cycle duration by about 90% and Marker-MicroTWIST that just over one cycle on an average for every flight (or 125 per block). These two derivatives were employed when lower crack growth rates were encountered. In terms of crack extension per flight or per block, Marker-MicroTWIST causes about 50%

retardation, but reduces test duration by almost two orders of magnitude when compared to the full spectrum.

All tests were performed with a spectrum mean load of 1.5 kN and individual load amplitudes suitably scaled as per the TWIST loading standard. The superposed axial and transverse loading details and other related information appears in Table 1. The tests were performed uninterrupted on a 24/7 basis at constant load rate of about 60 kN/s. This results in test frequency of about 25 Hz for the smallest amplitude and of the order of 5 Hz for the highest load levels. Iterative adaptive control ensured reproduction of required load history with peak error under +5% and average error under 2%, irrespective of transverse load magnitude.

The transverse load, as well as the axial load offset are maintained static even though in reality, the cabin pressure component will diminish to zero at the conclusion of each flight. It is assumed that this aspect will have a negligible effect on test results given the fact that most peak loads occur at full cabin pressure.

Test Results and Discussion

Fig. 2a shows crack growth rates versus average (half) crack size from tests 1-3 with different spectrum load offsets and transverse load. The tests simulate the effect of retaining a constant spectrum mean load of 1.5 kN, but varying the superposed load to simulate different fuselage cabin pressures. Thus, at 3 kN transverse load, a tensile axial load offset of 1.5 kN is added to the flight spectrum applied. At reduced transverse load, the axial offset is also proportionately reduced.

The results in Fig. 2a reflect the combined action of two variables. One is the offset or asymmetry in applied axial spectrum loading. The other is the magnitude of the static transverse load due to hoop stress in a pressurized fuselage. Spectrum load crack growth rate can only *increase* with increasing upward shift of mean stress. However, the limited data in Fig. 2a appear to suggest that increasing cabin pressure will actually *decrease* crack growth rate caused by the wing load spectrum. Further increase in cabin pressure may altogether eliminate the probability of circumferential cracking in favour of axial fatigue crack growth under cyclic hoop stress. This needs to be also viewed in the context of the rolling direction of load carrying sheet material lay up and the design of forgings, stampings and their jointing to form the fuselage assembly.

Effect of transverse load

In an attempt to isolate the effect of transverse load, Test 4 was performed with constant axial spectrum load offset of 1.5 kN, but with transverse load toggled every 2 mm of crack size increment between zero and 3 kN. Also, in an attempt to obtain results over a wider range of growth rate, the crack was initially grown under Marker-MicroTWIST, then switched to Marker-MiniTWIST and on to Marker-TWIST over the final stage. The results appear in Fig. 2b, with spectrum change crack size also indicated. In this test, the left and right crack size remained very similar throughout. Growth rate data were sorted into intervals with and without transverse load.

From the data in Fig. 2b, one may conclude that transverse tensile load indeed retards spectrum load crack growth rate by a factor of 3 to 4. The present results are similar to results from previous work under constant amplitude loading [9, 10], but contradict other results obtained under periodic overloads [7].

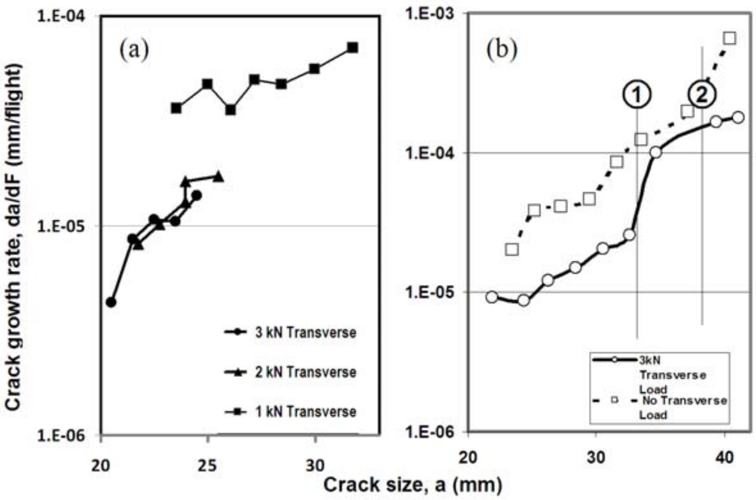

Figure 2. (a) Crack growth rates under Marker-MiniTWIST at P_{mean} = 1.5 kN with superposition of forces from three different levels of cabin pressure. Transverse loads of 1, 2 and 3 kN were associated with axial load offset, P_{offs} = 0.5, 1, 1.5 kN respectively. Note that two of the tests were prematurely terminated at average crack size of under 27 mm because of difference between left and right crack size exceeding 5 mm. (b) Spectrum load crack growth rate versus crack size at P_{mean} = 1.5 kN and P_{offs} = 1.5 kN. Transverse load was toggled between 0 and 3 kN every 1 mm of crack extension. Growth rates were estimated for intervals of constant transverse load and sorted accordingly into two curves.

Considering crack extension occurs during the upper half of the rising portion of the load cycle, one may assume that static transverse load and cyclic in-phase transverse load with the same maximum will cause similar crack growth behaviour. In this context both compliance and closure under constant transverse load become relevant parameters for examination because of their potential sensitivity to biaxiality.

Compliance measurements

A constant amplitude test was performed without transverse load at P_{max} = 3.5 kN and P_{min} = 0.5 kN. Every two mm of crack extension, the test was interrupted for unloading compliance measurements with and without transverse load over a data window 50% to 100% of P_{max}. The results appear in Fig. 3. They suggest that unloading compliance measured at the centerline may be used to measure crack size in automated testing. However, they also show that transverse load has a discernible effect on unloading compliance. This is highlighted by the plot of compliance ratio versus crack size. Unloading compliance appears to be attenuated by tensile transverse load. Liu attributes it to possible finite width effect [7] because the effect was not observed at smaller crack size. For reasons that are unclear, the ratio increases towards axial-only loading with increasing crack size, then diminishes again. This may be due to variation in biaxiality caused by non-uniform stress distribution across the gage section. Irrespective of the actual underlying reasons for compliance ratio variation, ignoring it can cause errors in crack size estimate of 3-5 mm. As compliance is a mechanics, rather than mechanism driven parameter, the observed effects may be studied through analytical simulation and perhaps as a variable to be accounted for in biaxial variable amplitude fatigue. As pointed by Adams [12] unloading compliance will determine crack opening displacement and may therefore be one way in which transverse load affects fatigue crack growth. However, one may note that at the point where compliance readouts are almost the same with and without transverse load (at about 30 mm crack size), spectrum load growth rates still remain quite sensitive to transverse load.

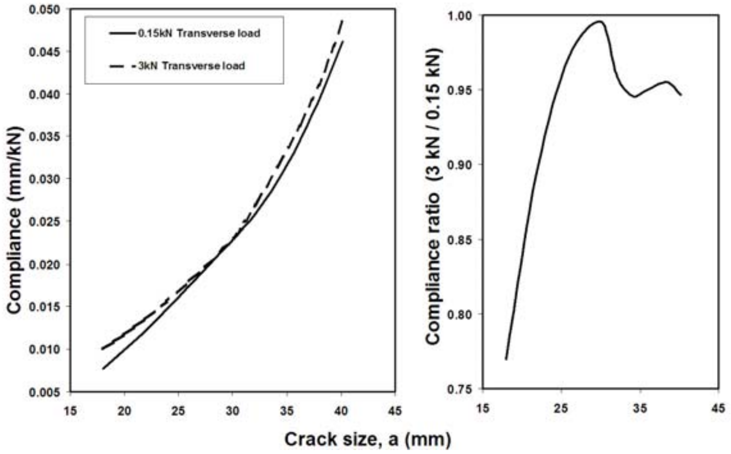

Fig. 3 (Left) Unloading compliance versus crack size, estimated with and without transverse load. (Right) Ratio of the two compliance values plotted against crack size.

Crack closure

McClung analytically determined that closure is insensitive to biaxiality until applied stress levels exceed 40% of yield stress. To experimentally investigate whether closure may be sensitive to transverse load, Load-COD data were logged under slow unloading with three different transverse loads at a crack size of 30 mm. Compliance compensated COD data for the three cases appear in Fig. 4. The leftward shift between curves was caused by reduction in COD readout at maximum load under the influence of transverse load. From these three curves, one may get the impression that tensile transverse load in fact increases closure level. One may note however, that the measurement being remote from the crack tip area, may actually not reflect actual crack tip response, but rather, a far field wake response that has no bearing on crack growth behaviour. This aspect demands further study using near-tip measurement techniques such as fractography or laser indentation interferometry [18].

Let us consider how other load interaction mechanisms may be affected in biaxial fatigue and examine the means to study them.

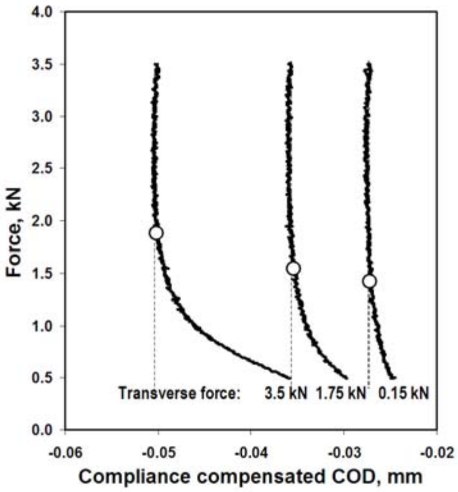

Figure 4. Load versus crack opening displacement response recorded at a = 30 mm during interrupted constant-amplitude cycling.

Crack front orientation evolves under the influence of the dominant crack extension mechanism as shown by experiments on the same material under the influence of environment [19] and represents potential for load interaction due to crack front incompatibility [20]. The sensitivity of crack extension mechanisms to biaxiality remains to be established experimentally. In the present study, growth rates were too low to induce change in crack front orientation.

Mean stress and residual stress effects on metal fatigue have been known ever since Wohler's pioneering research. However only recently, the underlying scientific rationale for the residual stress effect was discovered [21]. Specially designed experiments demonstrate that crack-tip stress levels control the kinetics of crack-tip surface chemistry, which in turn determine fatigue resistance of the crack tip and thus, crack growth itself. These stress levels are influenced by the response of material inside the crack-tip *cyclic* plastic zone. This region sees the effects of cyclic stress-strain hysteretic response and local stress triaxiality, which will moderate the action of active species at the crack tip. These two are interrelated, rendering applied stress biaxiality an important variable. As crack-tip surface chemistry is involved, the significance of this phenomenon is restricted to lower growth rates and naturally diminishes into the Paris regime. A better understanding is expected from fractographic studies under Marker-TWIST that may reveal how stress biaxiality affects growth rate due to individual load levels in a load spectrum and may provide a clue as to why literature data sometimes appear contradictory.

CONCLUSIONS

1. Fatigue crack growth was studied in 2.7 mm thick 2024-T3 alloy sheet cruciform specimens under a modified TWIST spectrum superposed with axial and transverse loads to simulate fuselage cabin pressure.
2. In conditions simulating increasing fuselage cabin pressure, the retarding effect of hoop stress induced transverse tensile load is more dominant than the adverse effect of the tensile offset in axial load, leading to lower crack growth rate, an effect confirmed by tests where only transverse load was varied.
3. Available data appear insufficient to draw conclusions on how individual load interaction mechanisms may be sensitive to load biaxiality.

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