PREDICTION OF FATIGUE CRACK GROWTH UNDER FLIGHT-SIMULATION LOADING WITH THE MODIFIED CORPUS MODEL

N95- 19471

U.H. Padmadinata
Laboratory for Strength of Materials, Components and Structures
PUSPIPTEK Serpong, Tangerang 15310, Indonesia

113055

J.Schijve
Faculty of Aerospace Engineering, Delft University of Technology
Kluyverweg 1, 2629 HS Delft, The Netherlands

ABSTRACT

The CORPUS crack growth prediction model for variable-amplitude loading, as introduced by De Koning, was based on crack closure. It includes a multiple-overload effect and a transition from plane strain to plane stress. In the modified CORPUS model an underload affected zone (ULZ) is introduced, which is significant for flight-simulation loading in view of the once per flight compressive ground load. The ULZ is associated with reversed plastic deformation induced by the underloads after crack closure has already occurred. Predictions of the crack growth fatigue life are presented for a large variety of flight-simulation test series on 2024-T3 sheet specimens in order to reveal the effects of a number of variables: the design stress level, the gust spectrum severity, the truncation level (clipping), omission of small cycles, and the ground stress level. Tests with different load sequences are also included. The trends of the effects induced by the variables are correctly predicted. The quantitative agreement between the predictions and the test results is also satisfactory.

INTRODUCTION

Fatigue crack growth predictions are needed in the aircraft industry for design and certification purposes. Predictions can indicate the trend of the effects of design variables, but it is meaningful only if the predictions are quantitatively reasonably accurate.

Fatigue loads in service, especially for wing structures, are generally a random variable-amplitude loading, rather than constant-amplitude loading. Different types of load sequences are known to induce load interaction effects, which can result in significant accelerations and retardations of fatigue crack propagation. Interaction effects imply that the crack extension in a load cycle depends on what occurred in the preceding cycles, i.e. on the previous load history. There are so-called history effects.

The modified CORPUS model [1] is a modification of the CORPUS model (Computation Of Retarded Propagation Under Spectrum loading), which was proposed by De Koning [2] in 1981. However, the CORPUS model gives a rather conservative prediction for cases, where the most severe negative gust is more compressive than the ground load of the flight simulation load history. The conservative prediction is caused by the rarely occurring most severe compressive gust, which governs the crack opening level in the plastic zone region created by the rarely occurring maximum overload. This underload effect of the severe negative gust is lasting very long, because it is coupled to a relatively large plastic zone region. In most cases it implies that it will last almost during the full flight-simulation history. The modified CORPUS model is "uncoupling" underload effects from plastic zone regions created by the maximum overload. In addition to the overload affected zone, which is used in the CORPUS model, an underload affected zone (ULZ) is introduced in the model.The ULZ is associated with compressive loads and reversed plastic deformation induced by those underloads, also by the frequently occurring ground load (once per flight).

The CORPUS model basically is associated with plastic deformation left in the wake of the crack (Elber's mechanism). Elber [3] observed that permanent plastic deformation ahead of the crack tip, generated by high load excursions, is still present on the crack surface after subsequent crack growth has occurred. These deformations can cause the crack surfaces to remain in partial contact even under tensile loading. Elber introduced the notion of the crack closure and crack opening load, defined as the load required for the entire crack surface to be free of contact. Loads exceeding this level will lead to crack extension.

The modified CORPUS model is, to a large extent, similar to the CORPUS model. The model includes consideration of plane stress and plane strain condition for the plastic zone size and a correction for the effect of high loads on the crack opening stress. The multiple overload interaction is maintained as an important feature, which leads to an increasing S_{op} .

The model is briefly described and prediction results for a large variety of flight-simulation test series are compared to test results. The comparison between predictions and test results is restricted to sheet material of the 2024-T3 alloy. Results on 7075-T6 sheet material are also covered in [1]. However, 2024-T3 is a more interesting material to check the validity of predictions of a crack growth model. First, 2024-T3 is usually adopted for fatigue critical components. Secondly, 2024-T3, in view of its larger ductility, gives larger plastic zones than 7075-T6. As a consequence, larger interaction effects occur, which implies that it is a more difficult material to arrive at accurate predictions.

FATIGUE CRACK GROWTH MODELLING

The model will not be described in full detail. The main features will be indicated. For a complete description the reader is referred to [1] and [2]. The process of crack growth modelling is illustrated in the flow diagram in Fig.1. As a consequence of crack closure, crack extension in every cycle is determined by the effective stress range. In cycle (i) Δa_i is:

$$\Delta a_i = f(\Delta K_{eff,i})$$

where: $$\Delta K_{eff,i} = C\ \Delta S_{eff,i}\ \sqrt{\pi a}$$

The cycle (i) is defined by a maximum $S_{max,i}$ followed by a minimum $S_{min,i}$. The effective stress range is determined as,

$$\Delta S_{eff,i} = S_{max,i} - S_{min,i} \text{ if } \sigma_{op} \leq S_{min,i}$$

$$\Delta S_{eff,i} = S_{max,i} - \sigma_{op} \quad \text{if } S_{min,i} < \sigma_{op} < S_{max,i}$$

where σ_{op} is the maximum crack opening stress level left from the load history.

Underload Affected Zone

The underload affected zone should be associated with compressive loads and reversed plastic deformation induced by underloads after the crack has been closed. The K range to be considered is $K_{op} - K_{min}$. It may be expected that severe downward loads will be able to induce reversed plasticity. It is assumed that this reversed plasticity in the underload affected zone occurs under plane strain conditions. The size of the reversed plastic zone is then approximated by the Irwin type equation:

$$D_u = \frac{1}{9\pi}\left[\frac{K_{op} - K_{min}}{2\sigma_y}\right]^2$$

As long as the crack tip is between a and ARP = a + D_u the underload will be effective. Here a is the crack length at the moment that the underload was applied.

An underload affected zone can overlap with another underload affected zone. The zones should be stored in the memory of the computer. However, the most severe underload is considered to be the dominant one. It is used to determine the S_{op} level.

Overload affected zone

The effect of an overload is effective as long as the crack tip is in its plastic zone. The plastic zone size depends on the state of stress at the crack tip, plane strain, plane stress or a transition between those two conditions. De Koning [2] derived a special equation for the plastic zone. It was based on the Irwin type equation, but it was modified to account for large zones if the stress level approaches the net section yield limit. The plastic zone size is:

$$\frac{D}{a} = \frac{1 - \gamma\left(\frac{S_{max}}{\sigma_y}\right)^2 + \left(\frac{a}{b}\right)^2}{2\left(\frac{a}{b}\right)^2} - \frac{\sqrt{\left[1-\gamma\left(\frac{S_{max}}{\sigma_y}\right)^2 + \left(\frac{a}{b}\right)^2\right]^2 - 4\left(\frac{a}{b}\right)^2}}{2\left(\frac{a}{b}\right)^2} - 1$$

where b is the semi-width of the specimen and γ depends on the state of stress. For plane stress $\gamma = 1/1.32$ and for plane strain $\gamma = 1/9$.

In the model, the crack tip state of stress depends on the size of the plastic zone relative to the thickness. First, the plastic zone size is calculated under plane stress conditions (D_{ss}). If $D_{ss} \geq 0.5t$ (t=sheet thickness) then the plastic zone is supposed to be in plane stress. If $D_{ss} \leq 0.35t$, the plastic zone is supposed to be in plane strain, size D_{sn}. During the transition from plane strain to plane stress ($0.35t < D_{ss} < 0.5t$), the plastic zone size is given by:

$$D = D_{sn} + 2D_{ss}[(D_{ss}/t - 0.35)/0.15]^4 (D_{ss} - D_{sn})/t$$

The overload will be effective as long as the crack tip is between a and ADP = a+D. Also here a is the crack length at which the overload occurred.

During crack growth under variable amplitude loading various plastic zones will be created. If they can affect the crack opening stress in later cycles they must be stored in the material memory (plastic zone history, ADP-values labelled as ADPH with H from history). For example, consider a crack length a_1 with a plastic zone size dp_1. A second plastic zone dp_2 will be memorized if (a_2+dp_2) is longer than (a_1+dp_2). In this case, a new plastic zone penetrates the elastic material ($ADP_2 > ADPH_1$).

Fortunately, not all plastic zones can affect S_{op}, because their effect on S_{op} is overruled by other plastic zones with a higher S_{max} ($S_{max} > SH_{max}$). A higher overload overrules the previous lower overload. The series of overload affected zones is characterized by a decreasing series of S_{max}-values (SH_{max}-values). As a consequence only a limited number of plastic zones must be stored in the material memory.

Selection of Crack Opening Stress in Every Cycle

Two different crack opening occurrences are defined in the modified CORPUS model, i.e. (1) crack opening related to the history stress levels (SH_{max} and SH_{min}, associated with plastic zones created previously) and (2) crack opening related to the current stress cycle ($S_{max,i}$, $S_{min,i}$). The history values are related to overloads (SH_{max}), which produced primary plastic zones, and to dominant underloads (SH_{min}) of the underload affected zones. As a consequence of the concept of the underload affected zone, the dominant (i.e. the highest one) SH_{max} must be combined with the dominant SH_{min}, i.e. the lowest SH_{min} in order to calculate the relevant S_{op} (=SH_{op}) for the current cycle.

The crack opening level induced by the current cycle is determined from $S_{max,i}$ and the successive $S_{min,i}$. This S_{op} is applied in the next cycle only, and only if it exceeds the above SH_{op}.

Interaction of Overloads

As already mentioned in the introduction, overload interaction effects play an important role in the CORPUS model. De Koning recognized that overloads with overlapping primary plastic zones will cause an extra increase of the crack opening level, which will give more crack growth retardation (multiple overload effect). The crack opening stress level for single overload and underload is:

$$S_{op} = S_{max}\,(-0.4R^4 + 0.9R^3 - 0.15R^2 + 0.2R + 0.45) \qquad \text{if } R > 0 \text{, and}$$

$$S_{op} = S_{max}\,(0.1R^2 + 0.2R + 0.45) \qquad \text{if } -0.5 < R < 0$$

where R is the stress ratio (S_{min}/S_{max}). Newman [4] demonstrated that the opening stress level does not only depend on S_{min} and S_{max}, but also on the maximum stress in relation to the yield stress, i.e. S_{max}/σ_y. In Newman's analysis elastic-perfectly-plastic material behaviour was assumed with a kind of an average yield stress: $\sigma_y = (\sigma_{0.2}+\sigma_u)/2$. De Koning [2] defined a correction function h which is a good fit to Newman's results. The correction function h is:

$$h = 1 - 0.2\,(1 - R)^3\left(\frac{S_{max}}{1.15\sigma_y}\right)^3$$

The corrected stress opening level then is SH_{op}. If interaction between overloads occur, this opening stress level will increase due to the multiple overload effect. The opening is increased after each overload until it has reached a certain upperbound. The equations proposed by De Koning will not be reproduced here, since they need a fairly extensive explanation. It includes one material constant δ, which was obtained by analyzing empirical data. A full description is given in [1] and [2].

PREDICTION RESULTS

Flight-simulation test results used in this chapter are adopted from different references. It includes results obtained with six spectra, i.e. CN-235 spectrum [5], F-27 spectrum [6], TWIST [7], miniTWIST [8,9], FALSTAFF and MiniFALSTAFF[10], and a simplified flight-simulation loading [11]. Most of the spectra are related to civil transport aircraft, except FALSTAFF and miniFALSTAFF, which are standardized flight simulations for fighter wing structures. The material was 2024-T3 Alclad sheet material, except for the tests with FALSTAFF and miniFALSTAFF, where 2024-T3 bare material was used.

Variables of the test programs were:

- CN-235 : design stress level and truncation level
- F-27 : 12 combinations with different
    - gust spectrum severity
    - ground stress severity
    - design stress level
- TWIST : truncation level
- miniTWIST : ground stress level
- FALSTAFF : design stress level
- miniFALSTAFF : design stress level

The variations of the gust spectrum severity of the F-27 were obtained by increasing or decreasing the ratio between gust amplitudes and the mean stress in flight (S_a/S_{mf}). There are three gust spectrum severities, viz. severe, normal and light. Also three ground load levels were adopted with S_{gr}/S_{mf} vary from -0.5 (severe), -0.234 (normal) to +0.125 (light).

In the miniTWIST and CN-235 tests, the crack increments in the most severe flight (type A) were recorded.

The load sequences used in the simplified flight-simulation loading tests [11] are shown in Fig.2. During one test all flights were equal. There are three types of flights. The mean stress in flight was 80 MPa and the stress amplitude was 40 MPa. Two values of numbers of cycles per flight were used, m=5 and m=100 cycles. The purpose of the tests was to study the effect of periodic overloads and underloads. Furthermore, a load sequence effect might occur in view of the low-high and high-low sequence of the flight profiles II and III respectively.

Prediction results compared to test results are presented in Figures 3 to 9.

DISCUSSION

For most flight-simulation tests the modified CORPUS model and the CORPUS model gave approximately similar predictions, with some noteworthy exceptions. The predictions compared to test results discussed below are those obtained with the modified CORPUS model. Predictions of both models are given if significant differences were found.

Effect of spectrum severity

The effect of the severity of the spectrum is illustrated by the results in Fig.3. It clearly shows an increasing crack growth life if the spectrum becomes less severe. This applies to each of the three ground stress levels. The trend is a logical one, and as shown by Fig.3, the trend is accurately indicated by the prediction model.

Effect of design stress level

The systematic effect of the design stress level is illustrated by Figs 4 and 6 for three different load spectra. The design stress level is represented by either S_{max} of the load spectrum or the mean stress in flight, S_{mf}. It should be understood that all stress levels of the load spectrum are proportional to S_{max} or S_{mf}. As shown by the results, the trend of the effect of changing the stress level was correctly predicted, although an accurate life prediction was not always obtained.

Effect of the truncation level

The effect of truncation of the rarely occurring very high loads of a load spectrum (clipping) has been well known for a long time (survey in [12]). Predictions in Fig.5 confirm this trend, shorter crack growth lives for lower truncation levels. This is the reason why high truncation levels should be avoided in full-scale flight-simulation tests in order to obtain conservative results.

Effect of omitting small cycles

In a gust load spectrum cycles with a small amplitude are quite numerous. If such cycles can be omitted from a test, saving of testing time is considerable. MiniTWIST was derived from TWIST by a drastic reduction of the small cycles. The average number of cycles per flight is 100 for TWIST and 15 for miniTWIST. It leads indeed to a shorter testing time, but the crack growth life in flights is increased about 2 times. The small cycles of TWIST were still damaging. This trend agrees with predictions (results not presented here).

In Fig.6 a comparison is made between FALSTAFF and miniFALSTAFF. In miniFALSTAFF about 50% of the smaller load excursions are removed by a rain-flow procedure. The predictions indicate a negligible effect on the crack growth life in agreement with the test results.

Effect of the ground stress level

The ground stress level (S_{gr}) in a wing, as compared to the mean stress in flight (S_{mf}), is dependent on the aircraft configuration (engines, landing gear, fuel tanks) and the rib station. As shown by Figs 3 and 7, a more severe ground stress level can imply a significant reduction of the crack growth life. This trend is predicted by the modified CORPUS model, but not always by the CORPUS model; see next paragraph.

Comparison between predictions of CORPUS and the modified CORPUS model

As pointed out before, the CORPUS model and the modified CORPUS model gave similar results in most cases. However, this is not true if a rarely occurring negative gust load is a more severe down load than the frequently occurring ground load. This condition occurred in the F-27 tests with a "mild" ground stress ($S_{gr}/S_{mf} = +0.125$); see Fig.3c, and in the miniTWIST tests with $S_{gr}/S_{mf} = 0$ (Fig.7). The predictions of the CORPUS model are indicated by a black dot. The CORPUS model gives a significant underestimation, contrary to the modified CORPUS model. Actually, this kind of comparative result was the argument for developing the modified CORPUS model as discussed before.

Effect of load sequence

Load sequences variations were applied in the simplified flight-simulation tests (Fig.2). The modified CORPUS model predicts a negligible difference between load sequences II and III. That is in agreement with the test results, see Fig.8. However, the CORPUS model predicts a systematic effect if there are 100 cycles in a flight. The life is significantly shorter for sequence III with the OL at the end of the flight. The different predictions of the two models are caused by different S_{op} developments due to the underload affected zone in the modified CORPUS model.

Crack increment in the most severe flight

In some tests the crack increment Δa in the most severe flight (type A) could be determined by measuring the crack length at the beginning and the end of the flight. Results for miniTWIST and CN-235 shown in Fig.9 indicate that the measured increments were significantly larger than predicted for those severe flights. The underestimation of the prediction does not have a significant influence on the predicted crack growth life, because the more severe flight is a rare occurrence. However, it shows a weakness of the prediction model. This is discussed in more detail by De Koning et al.[13] (see also [14]).

Quantitative accuracy of the predictions

The quantitative accuracy of the individual predictions was quite good for a fatigue prediction as illustrated in Figs 3 to 8. The average ratio of predicted crack growth life and test life was 0.87 for the modified CORPUS model (85 test results, including results for 7075-T6) with a standard deviation of 0.182. For CORPUS the average ratio was 0.89, practically the same value as for modified CORPUS, with standard deviation of 0.275, which is significantly higher than for modified CORPUS.

Non-interaction predictions (Miner approach)

The non-interaction prediction model is by far the most simple model, because it ignores any effect of previous load cycles. There is no material memory. In each cycle Δa is calculated with $\Delta K = C\Delta S\sqrt{\pi a}$ and ΔS following from S_{min} and the directly following S_{max}. It is a kind of a Miner approach, because the Minter rule also ignores effects of previous load cycles. For the flight simulation tests with a gust spectrum the average prediction to test result was 0.21 for 2024-T3 specimens (29 test results). It illustrates that large interaction effects did occur. For 7075-T6 (20 test results) this ratio was 0.45, a higher value associated with smaller interaction effects in the lower ductility alloy. For the manoeuvre spectra the average ratio was 0.45 (2024-T3 results only), which also indicate less effective interaction effects. It is associated with the effect that manoeuvre spectra have relatively more high amplitude cycles and less low amplitude cycles.

One trend is extremely poorly predicted by the non-interaction procedure, i.e. the effect of the truncation level. According to the non-interaction concept a lower truncation level leads to a negligible increase of the crack growth life, whereas in reality it implies a significant life reduction as shown by test results and is in agreement with the model predictions.

CONCLUSIONS

Test results on fatigue crack growth in 2024-T3 sheet material under flight-simulation loading were compared to predictions with the modified CORPUS model in the previous chapter. The main conclusions are summarized below:

1. Empirical trends of the effects of test variables are correctly predicted. It includes the effects of the gust severity of the spectrum, the design stress level, the truncation of rarely occurring high loads (clipping), the omission of small cycles, and the ground stress level.
2. Although the CORPUS model also predicts most trends in a similar way, the effect of rarely occurring severe negative gusts combined with a not severe, but frequently

occurring ground load is not correctly predicted by the CORPUS model. Modified CORPUS gives correct predictions also for this case.

3. A load sequence effect in simplified flight-simulation tests was predicted by CORPUS, whereas modified CORPUS predicts this sequence effect to be absent. The latter prediction is in agreement with the test results.
4. The crack extension in the rarely occurring most severe flight was poorly predicted by both the modified CORPUS and the CORPUS model.
5. The quantitative accuracy of the modified CORPUS model was generally good. Non-interaction predictions gave insignificant underpredictions and misleading indications on the effects of test variables.

REFERENCES

[1] Padmadinata,U.H.,"Investigation of crack-closure prediction models for fatigue in aluminum sheet under flight-simulation loading", Doctor Thesis, Delft Un. of Technology, 1990.

[2] De Koning, A.U. and Van der Linden,H.H., "Prediction of fatigue crack growth rates under variable loading using a simple crack closure model", Proc. 11th ICAF Symp., Noordwijkerhout. May, 1981, paper 2.6. Nat.Aerospace Lab. NLR, Amsterdam.

[3] Elber,W.,"The Significance of Fatigue Crack Closure". Damage Tolerance in Aircraft Structures, ASTM STP 486, 1971 ,p.230-242.

[4] Newman Jr.,J.C.,"A crack closure model for predicting fatigue crack growth under aircraft spectrum loading". ASTM, STP 748, 1981, pp.53-84.

[5] Padmadinata,U.,"CN-235 load spectrum study in fatigue crack propagation", Delft Un. of Tech., Fac. of Aerospace Eng., Report LR-510, 1987.

[6] Van der Linden,H.H.,"NLR test results as a data base to be used in a check of crack propagation prediction model. A GARTEUR activity", Nat. Aerospace Lab. NLR TR 79121, 1979.

[7] ProvoKluit,J.C.,"Significance of crack closure for crack growth in 7075-T6 and 2024-T3 Al-alloy under flight simulation loading with different truncation levels", (in Dutch), Master thesis, Delft Un. of Tech., Fac. Aerospace Engineering 1978.

[8] Padmadinata,U.H.,"Sequence effects of high-amplitude loads in the most severe flights of mini-TWIST on fatigue crack growth in Al-alloy sheet material", Delft Un. of Tech., Fac. Aerospace Eng., Report LR-493, 1986.

[9] Padmadinata,U.H.,"Sequence effects of high-amplitude loads in the most severe flights of miniTWIST with a light ground stress level", to be published.

[10] Vlutters,A.M.,"Crack growth flight simulation tests with FALSTAFF and shortened version, miniFALSTAFF, at two design stress levels", Master thesis, Delft Un. of Technology, Fac. Aerospace Eng.,1982.

[11] Misawa,H. and J.Schijve,"Fatigue crack growth in aluminium alloy sheet material under constant-amplitude and simplified flight-simulation loading". Delft Un. of Tech., Fac. Aerospace Eng., Report LR-381, 1983.

[12] Schijve,J.,"The significance of flight simulation fatigue tests", Proc. 13th ICAF Symp., Pisa 1985. EMAS, Warley 1985, pp.71-170.

[13] Koning,A.U.de and Dougherty,D.J.,"Prediction of low and high crack growth rates under constant and variable amplitude loading", Fatigue crack growth under variable amplitude loading. Elsevier, 1988, pp.208-217.

[14] Schijve,J.,"Fundamental aspects of predictions on fatigue crack growth under variable-amplitude loading. Theoretical concepts and numerical analysis of fatigue. Proc. Conf. Birmingham, May 1992, EMAS 1992, pp.111-130.

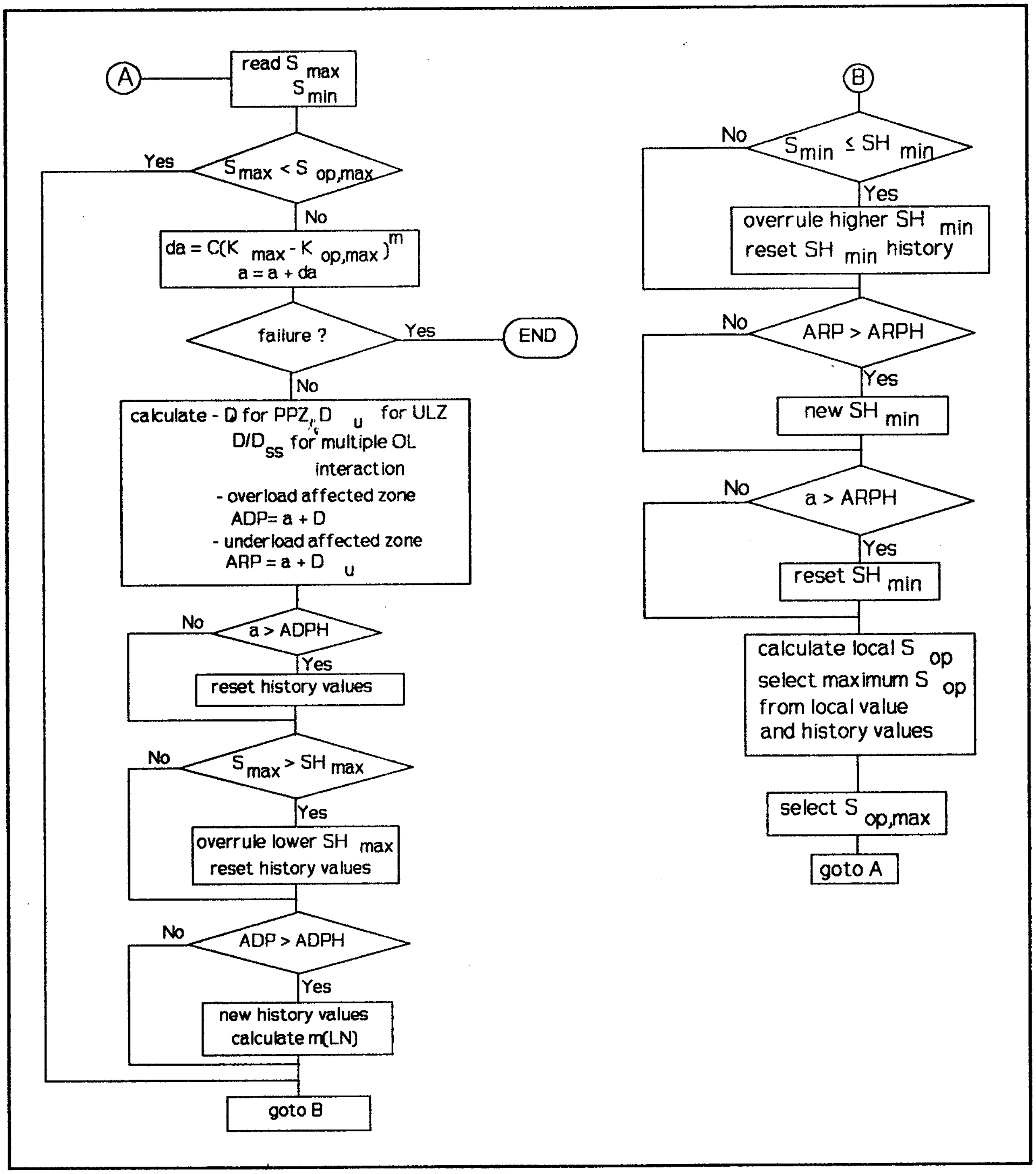


Fig.1 Flow diagram of the Modified CORPUS Model.

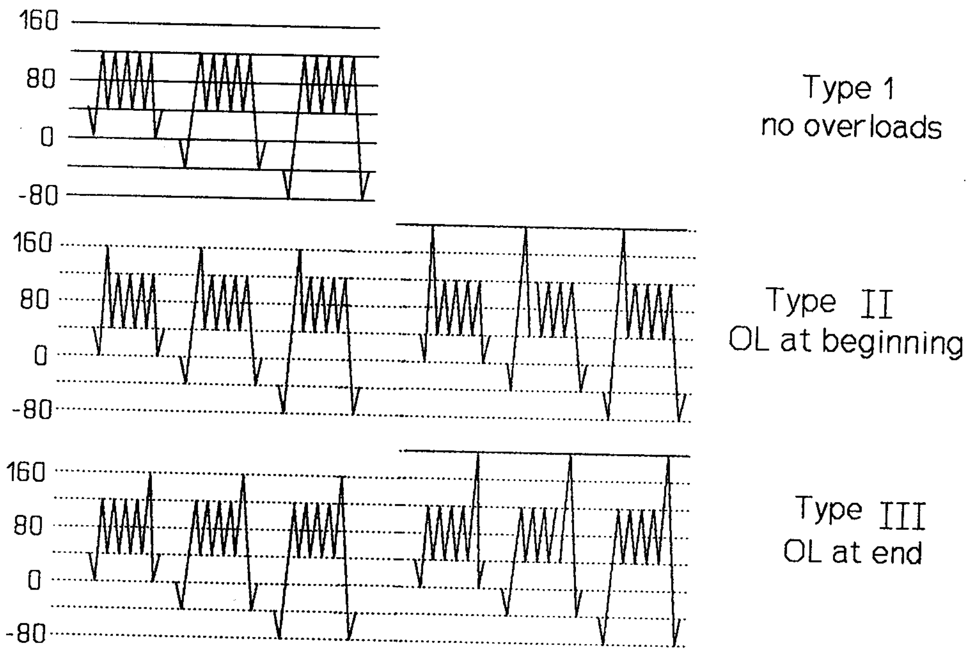


Fig.2 Load sequences of simplified flight-simulation tests with 5 cycles per flight (m = 5). Also tests with m = 100.

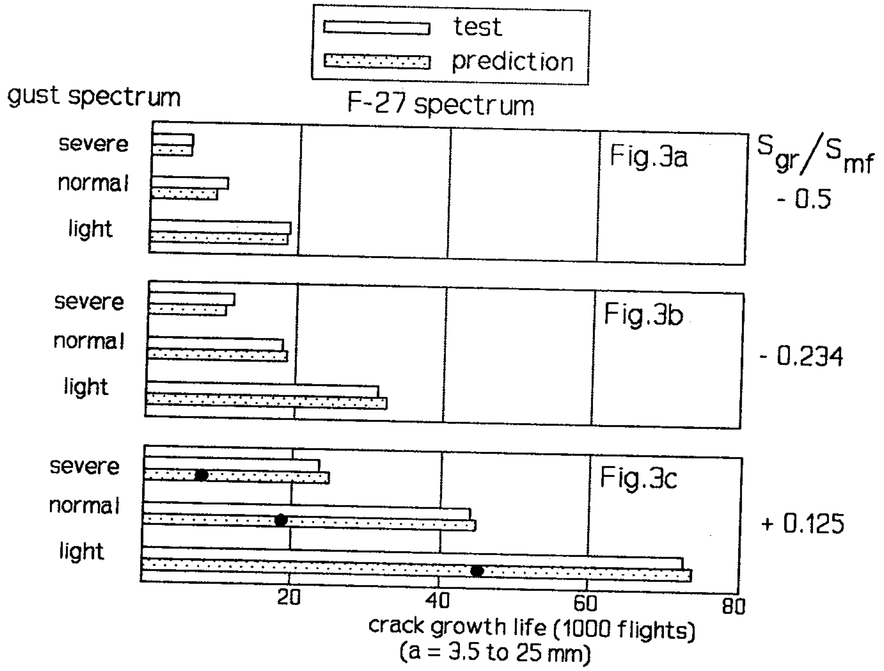


Fig.3 The effect of the gust spectrum severity and the ground stress on the crack growth fatigue life. Comparison to modified CORPUS predictions (Some predictions for CORPUS ●).

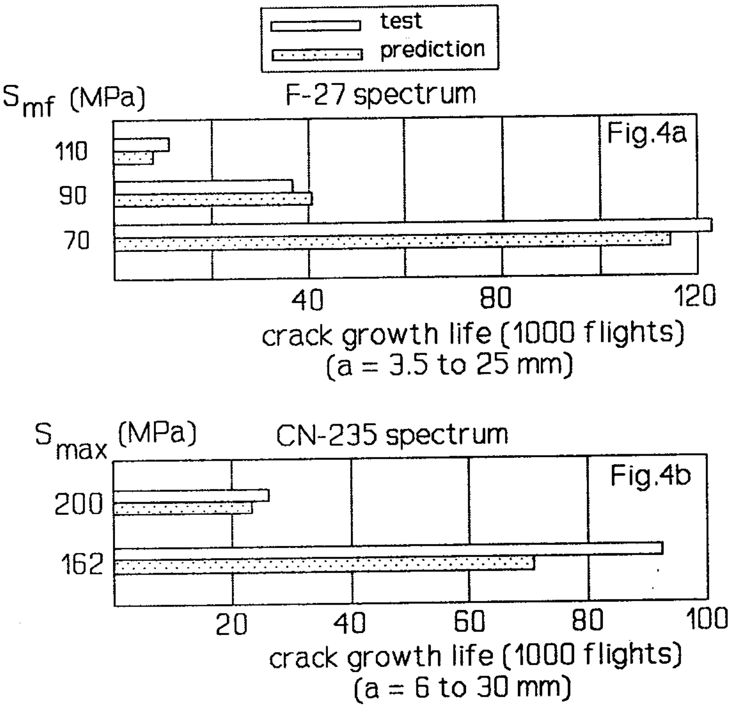


Fig.4 Effect of the design stress level on the crack growth fatigue life, compared to predictions.

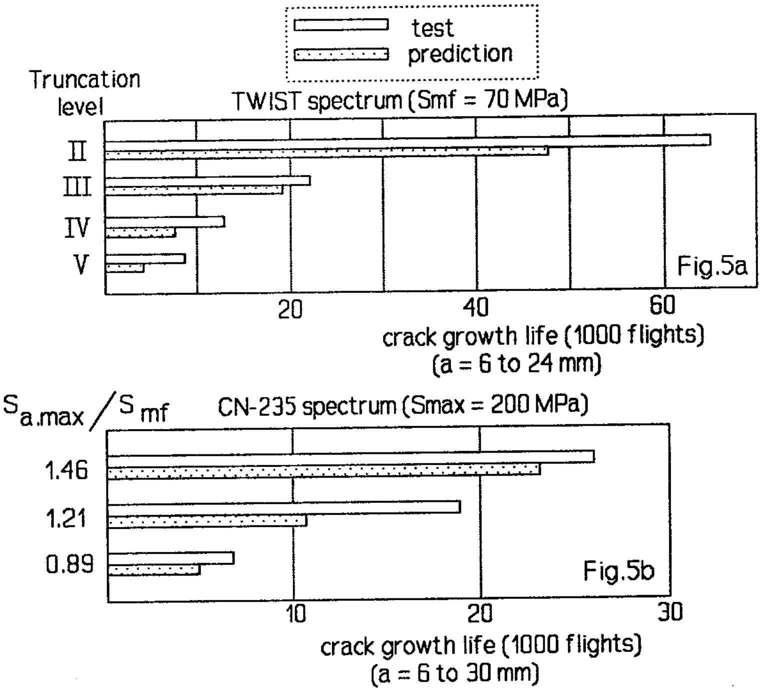


Fig.5 Effect of truncating high gust loads (clipping) on the crack growth fatigue life. Comparison to predictions.

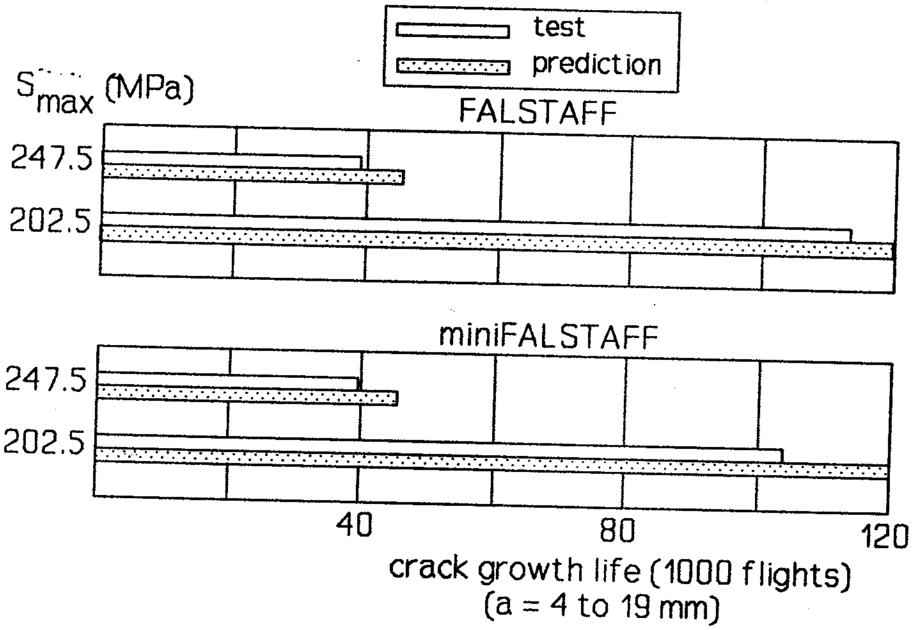


Fig.6 Effects of the design stress level and omitting small cycles on the crack growth fatigue life. Comparison to predictions.

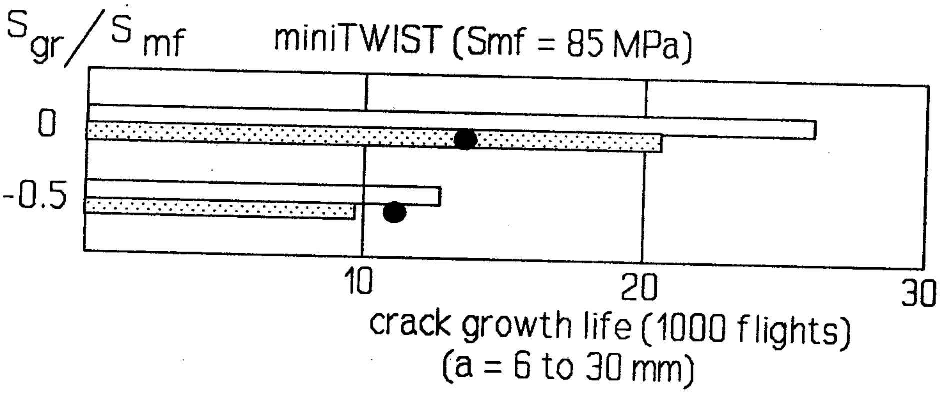


Fig.7 Effect of ground stress level on the crack growth fatigue life. Comparison to the modified CORPUS and the CORPUS predictions (●).

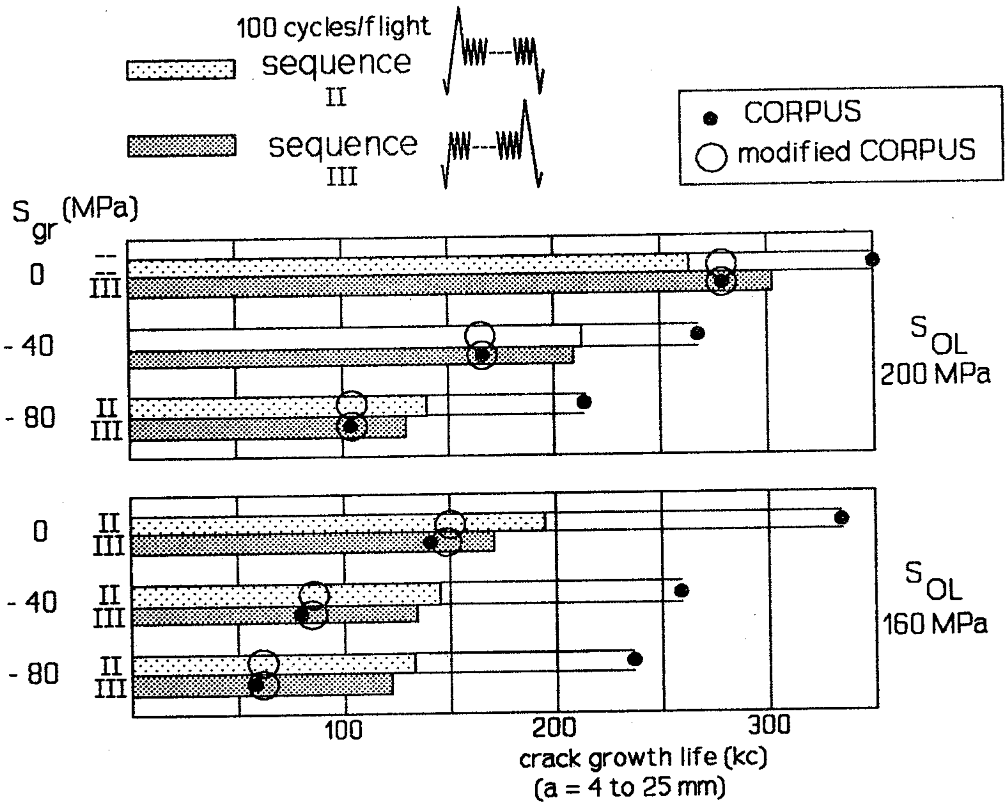
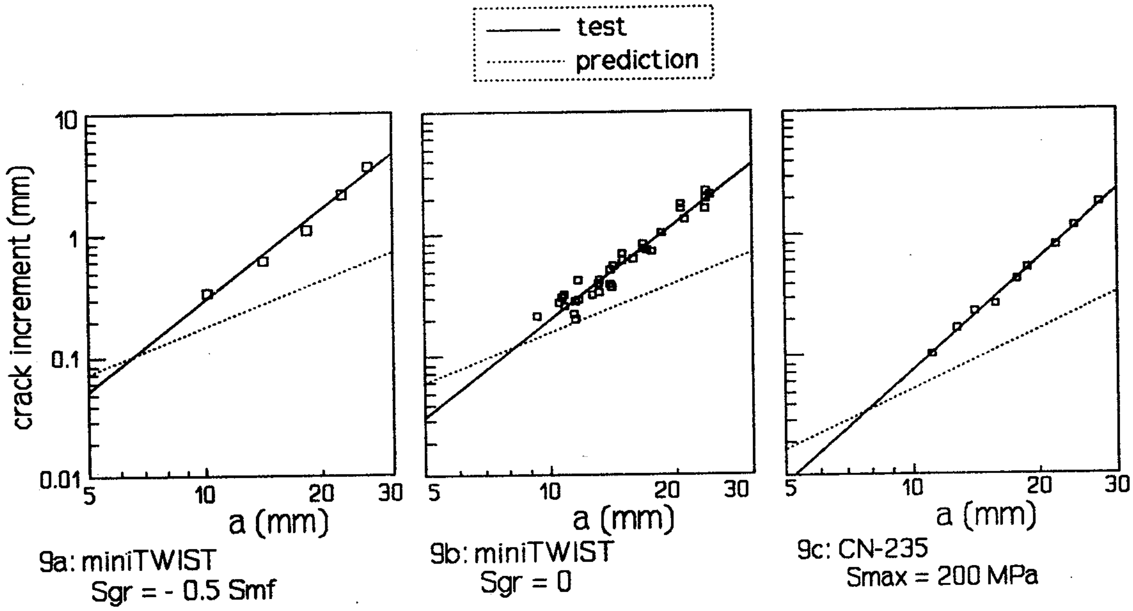


Fig.8 Effects of overload stress level, S_{gr} and the load sequence on the crack growth fatigue life. Comparisons to predictions with the modified CORPUS and the CORPUS model (●).



9a: miniTWIST
Sgr = - 0.5 Smf

9b: miniTWIST
Sgr = 0

9c: CN-235
Smax = 200 MPa

Fig.9 Crack growth increments in the most severe flight A. Test results and predictions.