DAMAGE SEVERITY OF MONITORED FATIGUE LOAD SPECTRA

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Abstract

Many military aircraft are used more severely and over a longer period than originally intended. Consequently, a careful life management, including service load monitoring has become indispensable. This paper describes the development of a simple method to quantify the severity in terms of "potential crack growth" of recorded load spectra. This Crack Severity Index accounts for load interaction effects under spectrum loading.
Crack growth tests under a variety of different load spectra have proved the validity of the CSI-concept. It is shown that the CSI-concept can also be used as a tool in studies to influence fatigue life consumption by operational measures.

I. Introduction

Many Air Forces in the world expect to use their current aircraft considerably longer than originally intended and often far beyond their design service life. As a consequence, a careful life management, including in-flight service load monitoring has become indispensable.
Usually this monitoring includes the determination of service load spectra for one or more structural locations, either from direct strain measurements or calculated from a few recorded flight parameter histories[1].

In order to assess the consequences of changes in usage, resulting in changes in recorded load spectra, it is desirable to have an easy means to quantify the relative damage associated with a recorded load spectrum. In the past, the usual way was to make a simple linear damage calculation, based on Miner's rule assuming a "representative" stress concentration factor k_t and an appropriate s-N curve. The outcome of these calculations turned out to depend very heavily on the assumptions made and did not reflect any load interaction effects. Moreover, current fighter aircraft have been designed for Damage Tolerance: therefore, the amount of crack growth rather than fatigue life defines the severity of a load spectrum.

For the Royal Netherlands Air Force a method to express the severity of recorded stress spectra in terms of "crack growth potential" has been developed, indicated as Crack Severity Index (CSI).

This paper starts with a description of the background and the development of the CSI-concept. Results of a large number of crack growth tests under widely varying load spectra were used to check the validity of the concept. It is shown that the CSI is a reasonably accurate measure to compare the crack growth damage of manoeuvre dominated spectra in aluminium alloy structure. In a general discussion, specific aspects of the CSI-concept are reviewed. It is shown that the CSI can also be usefully applied in studies to influence the fatigue consumption by operational measures.

II. Development of the CSI concept

Stress spectrum: It is assumed that the stress history in a specific structural area has been recorded over a certain period (e.g. half a year). This stress history has been analysed using "Rainflow" counting[2]; the resulting "stress spectrum" consists of n stress cycles i with max stress $s_{max,i}$ and minimum stress $s_{min,i}$.

Crack growth law: The crack growth due to load cycle i is given by:

$$da_i = C(\Delta K_{eff,i})^m = C\left[\beta(a)\sqrt{\pi a}\right]^m(\Delta s_{eff,i})^m$$

a is the crack length, $\beta(a)$ a geometry function and m a material constant. The effective stress range $\Delta s_{eff,i} = s_{max,i} - s_{op,i}$.
The opening stress level s_{op} is independent of crack length.

Spectrum crack growth: Eq. 1 can be rewritten:

$$\frac{da_i}{\left[\beta(a)\sqrt{\pi a}\right]^m} = (s_{max,i} - s_{op,i})^m \qquad (2)$$

or

$$f(a)da_i = (s_{max,i} - s_{op,i})^m$$

with

$$f(a) = \frac{1}{\left[\beta(a)\sqrt{\pi a}\right]^m} \qquad (4)$$

Under the spectrum a crack with length a_b will grow to a_e. Defining the integral of f(a) as F(a), the crack growth can be calculated from:

$$F(a_e) - F(a_b) = C\sum_{i=1}^{n}(s_{max,i} - s_{op,i})^m \qquad (5)$$

In this equation,only the right side includes load-spectrum dependent terms;the left side is purely defined by structural geometry,material properties and crack length. The right side defines the "crack growth potential" of the stress spectrum: two spectra yielding the same value for the "right side term" will cause the same amount of crack extension: this right side term will be called the Crack Severity Index CSI:

$$CSI = C \sum_{L=1}^{n} (s_{max,i} - s_{op,i})^m \quad (6)$$

As the CSI is used to compare different spectra, the value of the constant C is immaterial: In practice, C is chosen so as to yield a CSI = 1 for a "reference" stress spectrum.

The opening stress s_{op}. The magnitude of s_{op} has a major influence on the amount of crack growth, and the determination of a simple rationale for calculating s_{op} is a key element in the CSI-development.

In fighter aircraft, the interest is concentrated on the development of relatively short cracks, emanating from initial flaws of say 1.25 mm in usually relatively thick structure. Hence, for cracks of interest plane strain conditions at the crack tip may be assumed.

Under constant amplitude loading, the opening stress s_{op} may then be approximated by the expressions given in Figure 1[(3)]

Under variable amplitude loading, a much more complicated situation exists as the instantaneous opening stress depends on previous load peaks and valleys and their associated plastic zone sizes near the crack tip. This effect of preceding overloads and underloads on the crack opening stress is currently considered as the cause of so-called crack growth retardation under spectrum loading. To study the behaviour op s_{op}, an analysis was made of the s_{op} for typical manoeuvre dominated fighter aircraft load sequences,using the NLR "in house" computer program CORPUS (Calculation Of Propagation Under Service loading)$_{(3)}$. CORPUS is an advanced program for cycle by cycle calculation of crack growth.

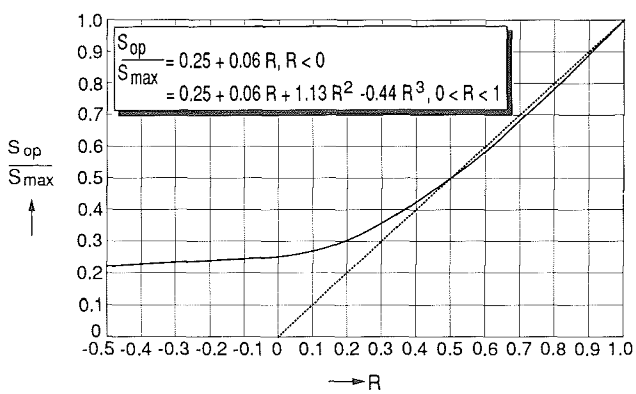


Fig. 1 $\frac{S_{op}}{S_{max}}$ *as a function of* $R = \frac{S_{min}}{S_{max}}$ *for plane strain conditions*

Figure 2 shows typical results for a part of the (relatively long) load sequence analysed. It turned out that after a certain number of flights a "minimum opening stress" has developed, which is purely defined by the highest peak and the lowest valley in the stress sequence: a high load pushes

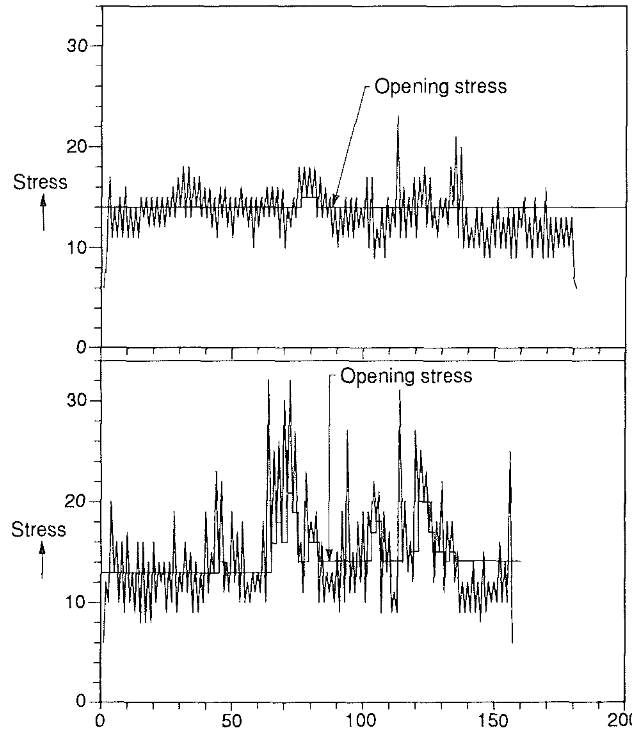


Fig. 2 Opening stress levels calculated with CORPUS for two flights in the analyzed sequence

up the opening stress, thus reducing the amount of crack growth associated with the load cycles coming next. The opening stress is lowered again when a low valley occurs. The "memory" of the overload will end with the advance of the crack tip, when the tip grows out of the plastic zone produced by the overload.

On the basis of the above considerations, the following rationale has been adopted for calculating s_{op}:

$s_{op,i}$ pertaining to stress cycle i is the largest of:

1. $s_{op,i}$ determined for $s_{max,i}$ and $s_{min,i}$ according to Figure 1.
2. $s_{op,min}$ determined for the highest stress occurring in 30 flights, $s_{max,30}$ and the lowest stress in 30 flights, $s_{min,30}$, whereby $s_{op,min}$ is related to $s_{max,30}$ and $s_{min,30}$ according to Figure 1.

The above definition implies that a "relevant" CSI-value can only be determined for a stress spectrum covering at least 30 flights: if a CSI has to be determined for a smaller batch of flights, a value for $s_{op,min}$ must be assumed, that means it must be assumed that the specific batch of flights belongs to an overall usage for which the "extremes" of the spectrum are known.

III. Validation of the CSI-concept

In order to validate the CSI-concept calculated CSI-values were compared with results of crack growth tests on simply notched plate specimens, made of 7475 aluminium alloy plate with a thickness of 7.62 mm. A number of these tests were defined specifically for the CSI-validation but the

majority of tests were done as part of the RNLAF F-16 Life Management program. In the following, results of these comparisons will be discussed for a number of the test results that were available.
In these comparisons, the "calculated severity" refers to the CSI value computed for the specific testspectrum (the material constant m was taken as m = 3), whereas the "observed severity" is the inverse of the crack growth life until a = 16 mm as found in test.

Figure 3 presents spectra for some tests done specifically for CSI validation. The "basic" spectrum refers to the wing bending moment of a fighter aircraft. In the spectrum indicated as "omission", all load cycles with a s_{max} lower than the predicted $s_{op,min}$ (49.51 MPa) were omitted. The CSI-concept predicts that this omission will have no influence on the spectrum severity, and this prediction appears to be fully confirmed by the tests.
In the "truncated" spectrum the highest peaks were reduced to 195.45 MPa. The increase in severity by a factor of 1.26 was not fully predicted by the CSI, (factor = 1.08) but it may be noted that in any case the CSI predicted an increase in severity due to truncation, whereas all "classical" non-interaction models would have predicted a decrease!

Figure 4 shows different spectra for one structural location, namely the wing root. One spectrum is indicated as "Design", the other three are recorded spectra pertaining to different usages. At first glance, one would expect the Design spectrum to be much less damaging than the actual service usage, but the tests show that the opposite is true: the Design spectrum is the most severe. It turns out that actually the CSI predicted this effect reasonably well. However, the CSI overestimated the severity of usage 3 compared to usage 1 by 20 percent.

Figure 5 shows spectra for three different structural locations. It may be noted that the Horizontal Tail Spectrum is very different from the others as it is nearly symmetrical around zero stress. The horizontal tail spectrum was found in test to be about 16 times less severe than the wing

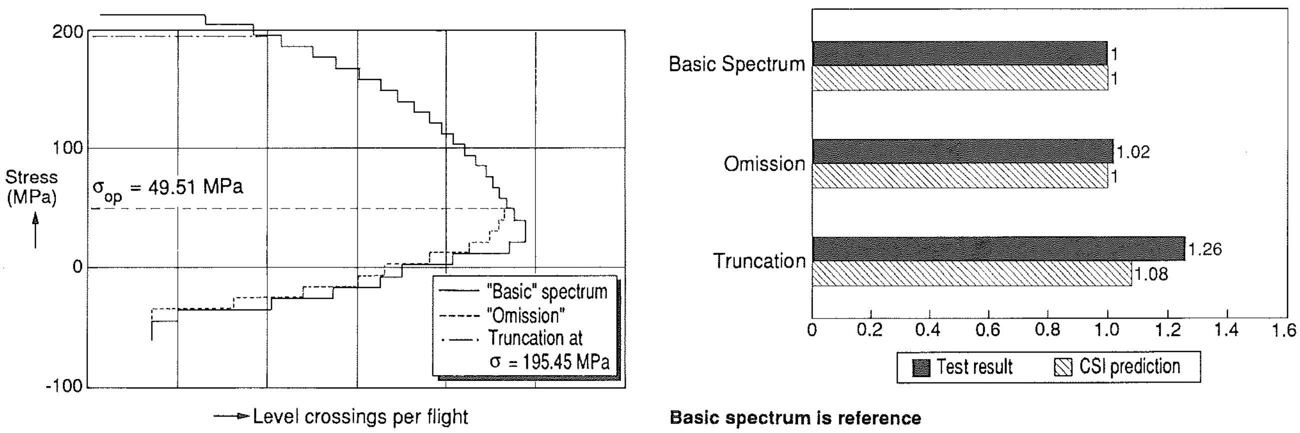


Fig. 3 Predicted and observed effect of spectrum changes on spectrum severity

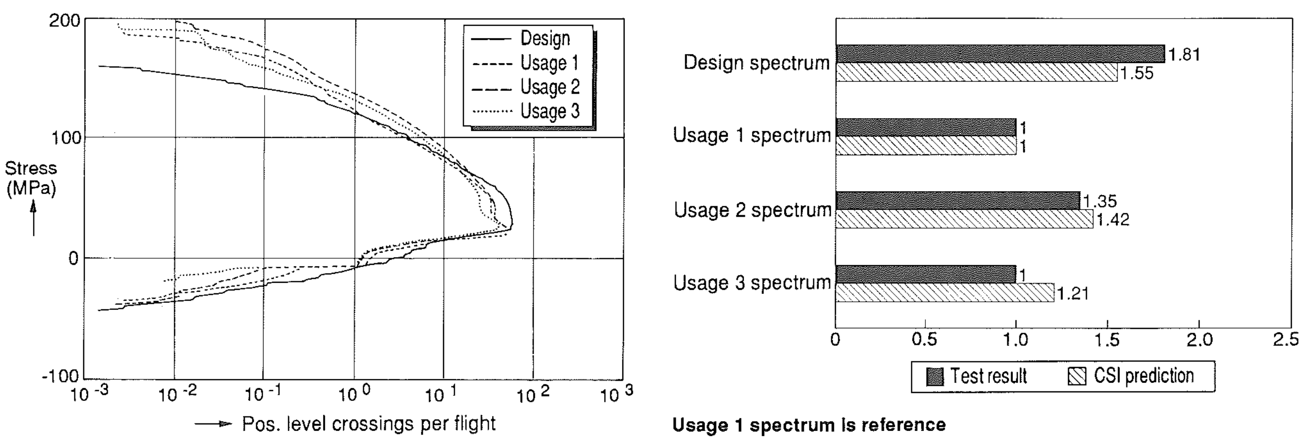
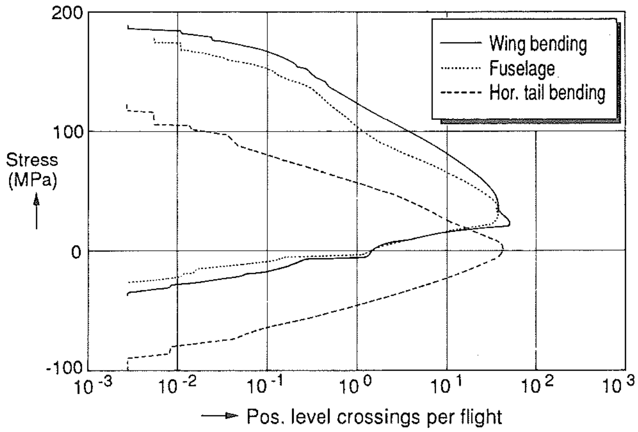


Fig. 4 Comparison of observed and predicted severities for Wing B.M. Spectra pertaining to different usages



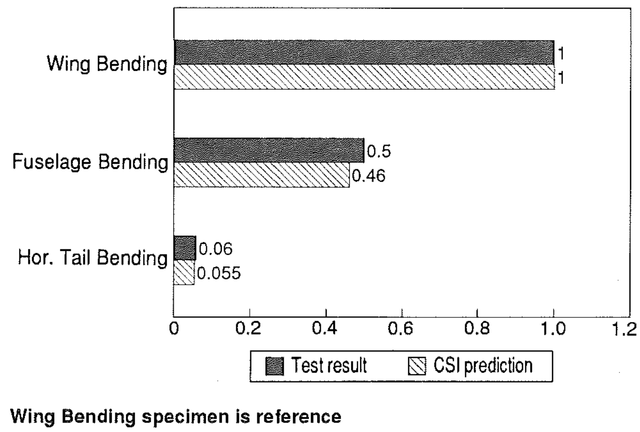


Fig. 5 Predicted and observed severities of spectra for different structural locations

B.M. spectrum. This severity was predicted within 8 percent by the CSI-concept. Undoubtedly, this outcome is remarkably good.

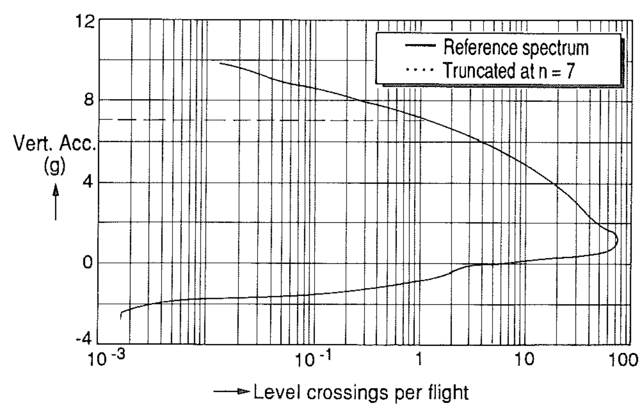
Comparisons for other load spectra, which will not be presented here,revealed equally acceptable results. For a total number of 55 different stress spectra that were studied, the average error in the CSI- prediction was -6.3 percent and the average absolute error was 15.1 percent.

Summarizing, we may conclude that comparison of CSI prediction and test results have shown that the CSI-concept may provide a reasonably accurate means to quantify the relative severity of manoeuvre dominated fighter type load spectra.

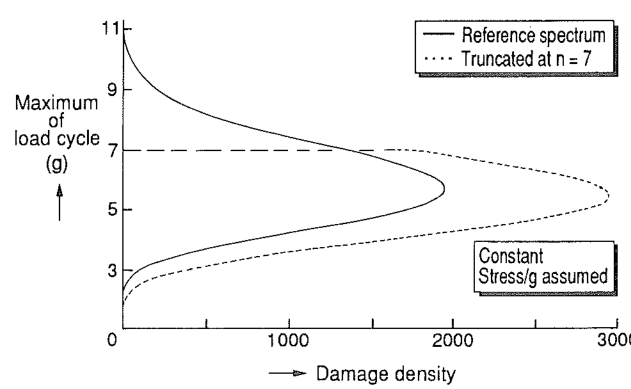
IV. Discussion

The CSI-concept is able to account to a certain extent for load interaction effects by means of the $s_{op,min}$ which is a function of the overall"spectrum shape". It may be recalled that a valid CSI could only be calculated for a batch of at least 30 flights. In other words, a CSI pertaining to one flight can only be calculated if assumptions are made with regard to the overall spectrum of flights to which our specific flight belongs. This may appear as a shortcoming of the CSI-concept but is actually a direct consequence of the load-interaction phenomenon: it must be realized that the damaging effect of a flight is not solely defined by the spectrum content of that flight, but depends on the load sequence that preceded that flight. Any attempt to define damage figures for one flight on the basis of information about the loading history of that flight alone must fail, in case of variable amplitude loadings and structural materials like the common aluminium alloys used in aircraft, which are sensitive for load interaction effects.

The CSI concept is not only useful to quantify the severity of recorded spectra, but can also be used successfully in studies how to influence the loading severity by changes in aircraft operation. Figure 6a shows a typical load spectrum for a fighter aircraft. A study was made of the effect of limiting the maximum obtainable load factor to 7 g on the spectrum severity,on the basis of the CSI concept. Figure 6b shows the "damage density" distributions,that is the contribution of load cycles with a peak at n g to the calculated CSI-value, for the original spectrum and the spectrum truncated at n = 7. Obviously, for the truncated spectrum the damage contribution due to cycles with peaks above n = 7 has disappeared. However, due to truncation of the high loads the opening stress



a) Load spectra



b) Distribution of Damage

Fig. 6 Effect of spectrum truncation on Damage Severity Distribution

$s_{op,min}$ has decreased and consequently the damage of the cycles below n = 7 has drastically increased. As a result, the CSI of the truncated spectrum is 1.18 times larger than that of the untruncated spectrum.

Figure 6b also indicates that most damage is caused by manoeuvres up to between say 4.5 g and 6.5 g and *that loads up to 3 g cause no damage at all.* Consequently, it may be concluded that in order to reduce the fatigue life consumption one should not limit the maximum attainable load factor but efforts should be directed to a limitation in number and magnitude of the manoeuvres in the range of 4.5 g to 6.5 g.

V. Conclusions

1. A simple means to quantify the severity of a measured load spectrum has been defined, which accounts for load interaction effects.

2. The CSI appears to be a reasonably accurate measure for the relative severity of manoeuvre dominated fighter spectra.

3. The CSI can also be used as a valuable tool in studies to influence the fatigue life consumption by operational measures.

VI. References

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