Crack Growth in Compressive Stress Fields

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Abstract *— To understand how to analyze Damage Tolerance in an aerospace component loaded in compression one must first obtain correct Fatigue Crack Growth curves. Once the fatigue data curves are correct one could then move forward to understand and develop a method that predicts Fracture Mechanics fatigue lives for designs with high compressive stresses. The investigation yielded ground breaking results that could change the Fatigue Crack Growth data generation standard procedures governed by the ASTM E-647. Also the proposed Design Methodology and Application procedure defined a method to analyze loading conditions with compressive stresses above yield. It is recommended the Compression Pre-Cracking process is standardize and incorporated into the ASTM E-647 procedure by replacing the existing tension pre-cracking process with the proposed Compression Pre-Cracking process. For the Design Methodology and Application it is recommended to validate the hand calculation methodology with experimental results.*

Key Terms *— Compression Pre-cracking, Fatigue Crack Growth, Stress Intensity Factor, Tension Pre-cracking.*

INTRODUCTION

The Damage Tolerance Analysis field was nonexistent prior to World War. Irwin developed the Energy Release Rate concept in 1956 [1] and later on in 1961 Paul C. Paris published the most popular fatigue crack growth model known as the Paris Law or the Fatigue Crack Growth Rate equation. A 1978 study in the U.S. showed an estimated annual cost of $119 billion due to fracture problems in designs. In addition, the study estimated a reduction of $35 billion in losses if the current technology was applied back then. For example, the Liberty Ships used during the WW II sustained fractures on 400 out of the 2700 ships made with 90 of them considered serious and 2 of them broken completely in two [1]. This example shows how the failure to provide the deserved attention to similar cases could cause malfunction of a design or a potential catastrophe like the one just described.

Today, Damage Tolerance Analysis is one of the most important failure modes studied in the aerospace industry and is generally used to predict service life and inspection intervals of designs. Its methodology relies on Fatigue Crack Growth (FCG) data curves generated through laboratory testing and governed by the ASTM E-647 process [2]. The testing principles, a crack growing in a flat plate in a tensile stress field are widely known. Theories correlating the FCG rate with the Stress Intensity Theory have been demonstrated (experimentally) thoroughly and Damage Tolerance is now considered an established engineering discipline. Conversely, although there are several proposed concepts that have been published before [1], [3], [4], [5], [6], and [7] a common or universal theory on how to approach the potential of a crack growing in a fully compressive stress field does not exist. The reason is the Stress Intensity Theory definition assumes a crack does not grow when closed. Some aerospace structures (e.g., aircraft engines) can experience high compressive stresses up to three times the tensile yield strength of the material. Failure to provide the deserved attention to loading conditions like this could cause malfunction of the design or even a potential catastrophe. Understanding how to analyze this problem is vital to the future of aerospace engineering designs since the need for high power machines is pushing the loading envelope to superior loads every day.

The scope of the article is to research publications of laboratory testing on specimens loaded with compression to generate Fatigue Crack Growth (FCG) data curves, compare its correspondent conclusions and recommend the most robust analysis method. The objective is to further the understanding of the effects of the tension pre-cracking versus the compression pre-cracking on the subsequent Fatigue Crack Growth test. The article concludes with a proposed analysis methodology for locations with high compressive stresses.

EFFECT OF RESIDUAL STRESSES

To understand how to analyze Damage Tolerance in an aerospace component loaded with compression one must first obtain the correct FCG curve. This FCG curve can be used to predict fatigue life for designs with high compressive stresses.

The study of a crack growing in compressive loading is relatively new [6] when compared to the study of specimens under tension loading. Focusing in all of the parameters that may affect this topic requires an enormous amount of work, time and budget. The variable selection process for the investigation was made by selecting the Linear Elastic Fracture Mechanics (LEFM) concept as the investigation main macroscopic theory. Currently the aerospace industry focuses on LEFM analysis since most parts are design to operate only in the elastic stress range. The Stress Intensity Theory was selected over the Energy Release Rate concept since FCG data curves are based on the stress intensity equation. FCG data testing is governed by the ASTM E-647 [2] standard procedure which consists of two tests carry out in series: The tension pre-cracking test followed by the FCG test. The pre-cracking testing of the ASTM E-647 procedure plays a major role in the investigation. Different pre-cracking test approaches impact the outcome of the subsequent FCG test therefore the variables selected are a direct function of the pre-cracking tests.

The standard tension pre-cracking creates compression residual stresses at the crack tip while the compression pre-cracking creates tension residual stresses at the same location.

It is believed that residual compression stress creates a crack closure or type shielding at the crack tip. When performing the subsequent FCG test the crack starts out closed [7]. Having a close crack tip could result in lower crack growth rates and higher FCG thresholds. These results are considered anti-conservative [7]. Conversely CPC creates tension residual stresses at the crack tip as shown in Figure 1.

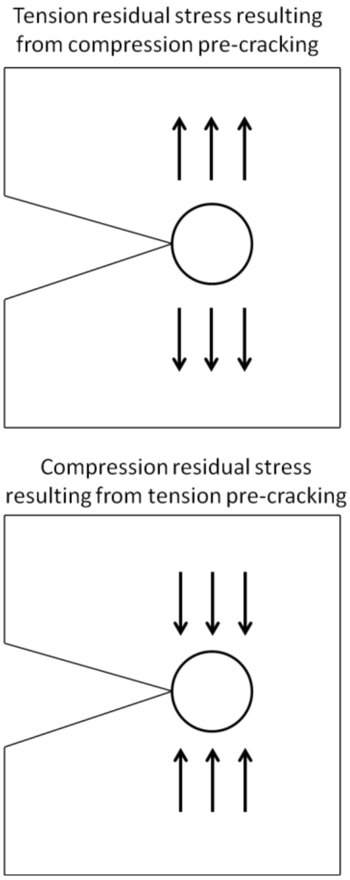

Figure 1
Effects on Residual Stresses by Tension and Compression Pre-cracking

It is believe that tension stresses create a fully open sharp crack tip. When performing the subsequent FCG test the crack starts out with a fully open sharp crack therefore resulting in higher crack growth rates and lower thresholds. Based on the above analysis the variables selected to be analyzed in the investigation are: compression pre-cracking procedure, tension pre-cracking procedure, tensile residual stress, compression residual stress, crack closure, crack growth rate, load history effects and FCG threshold. All other variables are assumed to be fixed for the purpose of the analysis.

FCG DATA CURVES

Load Reduction Procedure: The FCG data E-647 ASTM, Standard Test Method for Measurement of Fatigue Crack Growth Rates, consists of a procedure called the Load Reduction Procedure. The Load Reduction Method was develop by Paris in 1970 [5] to generate data at low values of stress intensity factor ranges and approaching FCG threshold conditions. Its objective is to determine steady state constant amplitude results at constant state ratio without any load history effects. Fatigue crack growth data is typically generated using a load reduction procedure, where the driving force is methodically reduced to a threshold while monitoring the crack growth rates. ASTM Standard Test lists two different methods the Constant K_{max} procedure and the Constant Load Ratio procedure.

Constant K_{max} Procedure: Only the constant load ratio was considered during the investigation since the K_{max} procedure is not applicable [3] for generating low load ratio threshold data.

Constant Load Ratio: The constant load ratio [3] procedure holds the minimum to maximum load ratio constant as the driving force is reduce to threshold. References [3] and [7] shows that recent experimental data indicate the constant load ratio procedure can produce non-conservative results like high FCG thresholds [8], lower fatigue crack growth rates and width/thickness dependent specimens resulting in unsafe designs. One of the primary causes of these high FCG thresholds is the concept of crack closure due to load history effects [6]. High tensile pre-cracking loads can cause remote crack closure or plasticity induced shielding. The shielding effect reduces the crack driving force on the subsequent FCG test resulting in a load history effect caused by the tensile pre-cracking.

STANDARD TENSION PRE-CRACKING

Laboratory testing and specimen configuration standard procedures to generate FCG data curves using tension pre-cracking are governed by ASTM E-647 and consist of two tests carry out in series: The tension pre-cracking test followed by the Fatigue Crack Growth test.

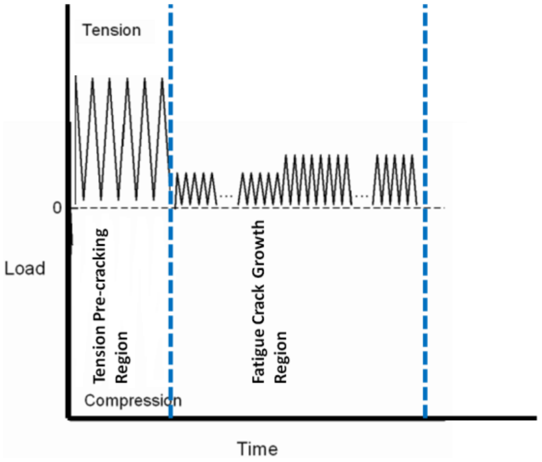

Figure 2

ASTM E-647 Test Consists of the Tension Pre-cracking and the Fatigue Crack Growth Test

The procedure is shown in Figure 2. For full details of the ASTM E-647 procedure see [2]. The purpose of the tension pre-cracking is to grow a crack in the notched region by applying high magnitude tensile loads for short period of cycles. The pre-cracking is followed by the FCG test in which lower magnitude tension loads are applied for longer periods of cycles as shown in Figure 2. Its significance is based on, fatigue crack growth rate expressed as a function of crack tip stress intensity factor range, da/dN versus ΔK, which characterizes the material resistance to stable crack extension under cyclic loading [2]. After notching the specimen the standard E-647 process requires tension pre-cracking the specimen in order to grow a crack in preparation for the subsequent FCG test. Figure 4 shows both the notching and the crack grown in the specimen. The minimum required crack growth Δa is shown in (1).

$$\Delta a = \frac{3}{\pi}\left(\frac{k_{\max}}{\sigma_{ys}}\right)^2 \tag{1}$$

References [3], [5], [8], and [7] all agree that using tension pre-cracking to generate FCG data curves is anti-conservative due to load history effects caused by the compressive residual stress product of the tension loading.

COMPRESSION PRE-CRACKING

In the last 10 years CPC has gain new interest as a possible alternative procedure for generating FCG data with minimal load history effects. An ASTM standard procedure for the compression pre-cracking test does not exist. A specimen configuration example is shown in Figure 3. For compact tension C(T) specimens there are two different ways of applying the compressive loading.

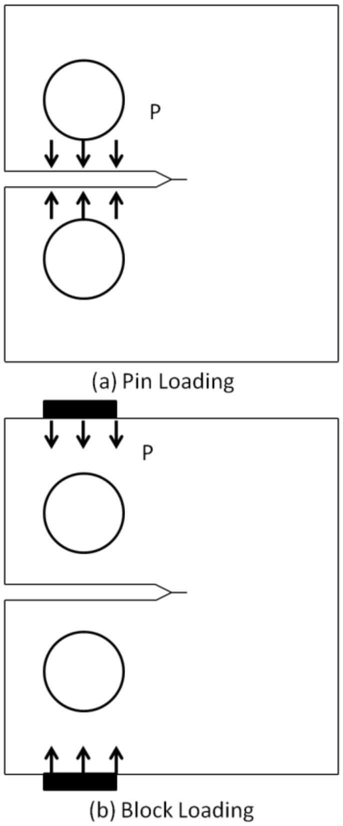

Figure 3
Methods of Loading Applied for Compact Specimens

Figure 3 shows the (a) Pin Loading and the (b) Block loading standard set ups. The Block Loading method is the preferred specimen set up since it limits the risk of cracking the holes and invalidating the analysis.

There are three different pre-cracking methods that have been developed [6]: CPCA or Compression Pre-Cracking Constant Amplitude, CPLR or Compression Pre-Cracking Load Reduction, CPCK or Compression Pre-Cracking Constant ΔK. The three procedures are plotted and shown in Figures 5 and 6. Only the CPCA method was analyzed in the article.

After performing the CPCA procedure a crack must be grown until satisfying the crack extension criteria (2) or (3):

$$\Delta c = 0.5 \times h_n \tag{2}$$

$$\Delta c = 3(1-R)\rho_{cp} \tag{3}$$

Where h_n is the notch height *R* is the stress ratio and ρ_{cp} is the calculated compressive plastic zone size from (4):

$$\rho_c = \left(\frac{\pi}{8}\right) * \left(\frac{K_{cp}}{\sigma_{ys}}\right)^2 \tag{4}$$

Where K_{cp} is the stress intensity factor and σ_{ys} is the yield stress of the material. Figure 4 shows the crack extension Δc is a function of the notch height h_n. References [6] and [8] recommends the crack extension to be 2-4 plastic zones away to eliminate the influence of tensile residual stresses caused by compressive yielding.

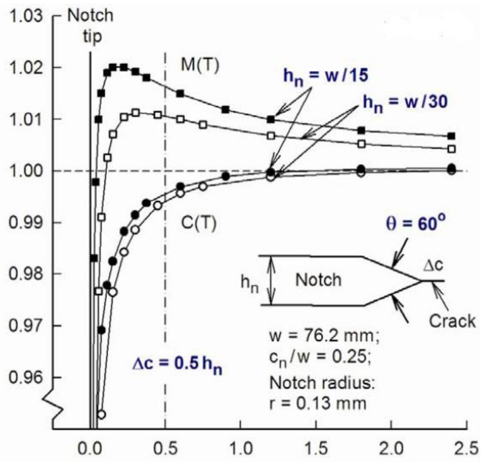

Figure 4
Standard Compact Tension Specimen Parameters

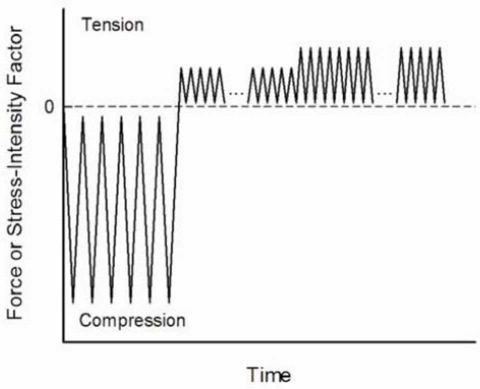

Figure 5
CPCA or CPCK Loading Sequences

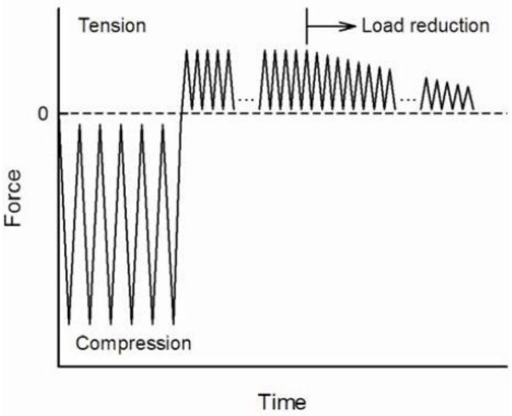

Figure 6
CPLR Loading Sequence

Figures 5 and 6 show the CPCA, CPCK and CPLR sequences in graphs of force versus time. The graphs show a high force magnitude in the compression region when compared to the subsequent fatigue tension region. The compression pre-cracking purpose is to grow a crack in the notched region by applying high magnitude compressive loads for short period of cycles until the crack arrests. The pre-cracking is followed by the FCG test in which lower magnitude tension loads are applied for longer periods of cycles as shown in both figures 5 and 6.

Compression Pre-Cracking Constant Amplitude [6]: The procedure calls for compression pre-cracking the specimen followed by applying constant amplitude loading or constant stress ratio as illustrated in Figure 5. The crack must be grown several (2-4) compressive plastic zone sizes to eliminate the effects of the V-notched and the residual tensile stress. Once the crack starts growing the stress ratio, R, should be hold constant. Only the data beyond the crack extension criteria in (2) or (3) is valid.

Figure 7 shows the results conducted for five different tests including CPCA and the traditional ASTM Load Reduction for Titanium Ti-6AI-4V specimens as published by [6].

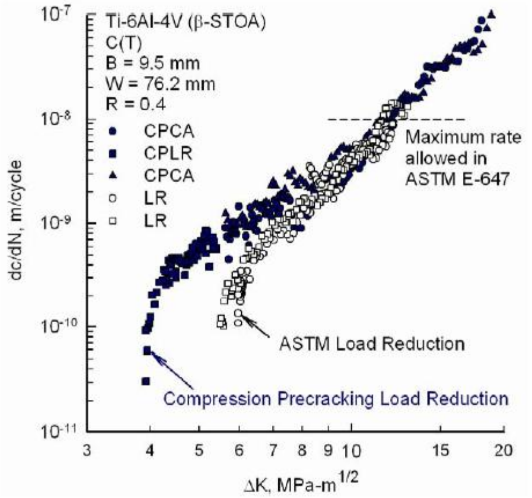

Figure 7
CPLR Test Results vs. Traditional ASTM Load Reduction Method

These results showed a large difference in the threshold and near threshold regimes. The CPCA test shows higher crack growth rates and lower FCG threshold values than the ASTM LR test. Reference [8] quotes test results for other materials (7050-T7451, 7075-T7351, Ti-6AI-4V STOA, and β-STOA, A36 Steel and INCONEL 718) exhibiting the same behavior.

Figure 7 clearly showed that there is a difference in results between standard ASTM E-647 tension pre-cracking and compression pre-cracking. References [6], [3], [5], [9] and [7] all agree that FCG thresholds are lower for compression pre-cracking meanwhile crack growth rate data is higher making the standard ASTM E-647 standard test anti-conservative.

CRACK CLOSURE

This behavior called crack closure is caused by the load history effects on the specimen. Currently in North America the threshold crack growth regime is experimentally defined by the ASTM Standard E-647 which has been shown to exhibit anomalies due to the load reduction test procedure [7]. The test induces remote closure which slows down the crack growth and produces high threshold [7]. There are several types of reasons that causes crack closure including: Oxide, Fretting, Debris, Closure, Crack Surface Roughness, and Plasticity induced closure. Reference [7] test results for Titanium and other materials shows large differences between the standard ASTM 647-E load reduction method and the compression pre-cracking constant amplitude test results in the threshold region for low levels of stress ratio. At higher stress ratios the differences between the two methods is smaller. Therefore the main variance in materials is large crack threshold and lower FCG rates at low stress ratios due to the remote closure effects. The load reduction test has shown [7] to induce high crack closure loads, during the test the crack surface displacements are decreasing as the crack gets longer which causes crack surface contact and therefore activation of several closure mechanisms. Crack closure is sometimes characterized by the darkening of the fatigue surfaces in the near threshold surfaces [10]. Compression pre-cracking has shown to remove the crack closure effect from the testing by starting the subsequent FCG test with a fully open sharp crack.

Carefully analyzing Figure 7 reveals the importance of updating the ASTM E-647 procedure to include the latest compression pre-cracking load reduction procedure in [7]. The graph shows the FCG curves for Ti-6AI-4V have a Δ k threshold of about 4 $(MPA\text{-}m)^{1/2}$ for the CPCA while the ASTM LR shows a Δ k threshold of about 6 $(MPA\text{-}m)^{1/2}$. This difference in threshold means that if the designer uses the data from the ASTM LR procedure to assess the design for Fracture Mechanics Failure Criteria the analysis will predict a higher life than what the structure can withstand. The crack will start to grow at lower Δ k, therefore the part will fail before the predicted design cycles causing a design malfunction or perhaps a catastrophe. Using this FCG data curves for designing is anti-conservative. In the other hand, evaluating the design using the CPCA data curves is at worst conservative while producing a safe design from the fracture stand point.

At low levels of ΔK at what will be the region 2 (see region 2 in Figure 8) of the Paris curve, the FCG rate or da/dN is significantly higher for the CPCA than for the ASTM LR.

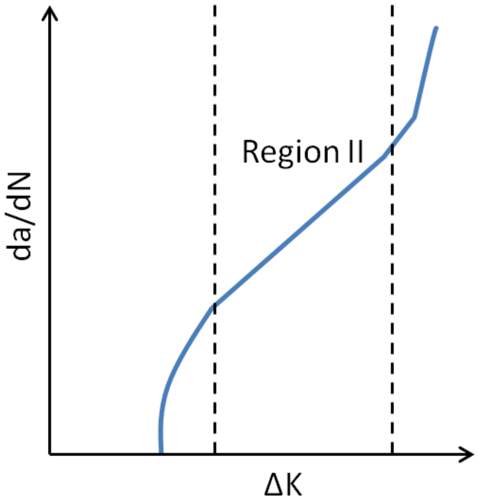

Figure 8
Typical Fatigue Crack Growth Curve

This is a significant problem since a design based on the crack propagation of the ASMT LR test will propagate at lower speed than what the material really predicts when comparing to the rates produced by the CPCA procedure. Once again using the ASTM LR data is anti-conservative, in this case from the FCG rate standpoint.

DESIGN METHODOLOGY AND APPLICATION

The CPCA curve (Region 2) generated experimentally in Figure 7 was replicated in Figure 9 (curve in blue) with hand calculations using the Stress Intensity Theory. Replicating the curve required assuming zero residual (CPC) stress during the FCG test since [6] and [9] state that fatigue data is only valid when the fracture is 2-4 plastic zones away from the plastic zone. The hand calculations have a max error of 15% at the curve lower end (as expected) when compared to the Experimental Results. This difference is due to fact that the Paris Law parameters “C” and “m” had to be approximated [11].

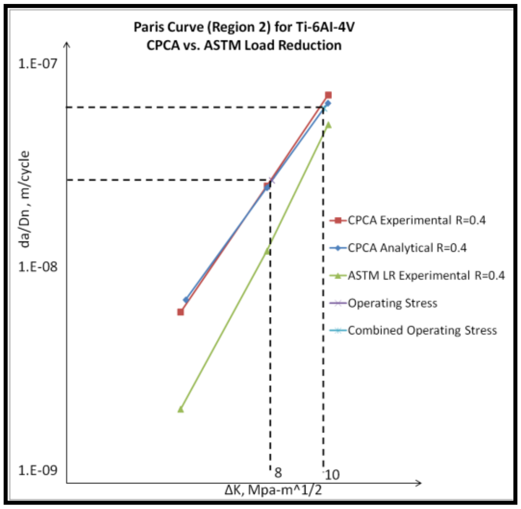

Figure 9

Paris Curve (Region 2) Comparing CPCA Experimental Results (red) vs. CPCA Analytical Results (blue)

Both variables are a function of the experimental set up, cannot be calculated with a parametric equation and were not provided in [6]. Still the equation gave good correlations and is within acceptable limits (about 8%) at the curve higher end, where the design stands in terms of ΔK. The ASTM LR test curve was also included in the chart to make the comparison between curves easily. Equations (5), (6) and (7) were used to calculate the ΔK considering a single edge notched tension panel specimen. Variables C and m were approximated to 3×10^{-11} and 3.33, respectively with typical values in the 4×10^{-11} and 3.11 range [11].

The problem presented in Figure 10 is a typical engineering design task: a flange made of Ti-6Al-4V radially loaded producing critical stresses at the flange fillet. Analyzing the design for Fracture Mechanics requires understanding the problem loading condition through time.

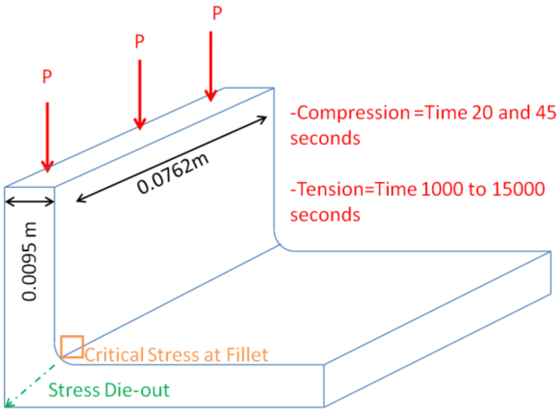

Figure 10

Geometry and Load Description of the Fracture Mechanics Problem

Table 1 shows the flange loaded radially in both tension and compression at a constant temperature T. The compression time corresponds to the 20 to 45 seconds interval while the tension period occurs from 1000 to 15000 seconds. The direction of load *P* in Figure 10 is arbitrary since the loading direction is defined by Table 1. Yield strength for AMS 4928 Ti-6Al-4V at a constant temperature T is 931 MPa [7]. The assumed stress die-out starts at the fillet inside fiber and ends at the outside fiber as stated by the green arrow in Figure 10. A standard normalized die-out with a maximum stress magnitude of 1.00 at the fillet inside fiber was assumed as shown by the orange square in Figure 10.

Table 1
Design Stress vs. Time Data

Operating Stresses vs. Time			
Time (s)	Operating Stress (Mpa)	Residual Stress (Mpa)	Combined Operating Stress (Mpa)
20	-1034	124	-910
45	-828	124	-703
1000	28	124	152
12000	276	124	400
13500	448	124	572
15000	172	124	297

It is interesting to highlight all the tension operating (tension) stresses are below the yield strength of the part while one of the compressive stresses is above the yield condition. Analyzing the part using the Stress Intensity Theory, the compressive stresses will be ignored since it assumes a crack does not grow when closed. The objective of the proposed analysis approach is to demonstrate that applying the Stress Intensity Theory to this specific problem yields none conservative results.

As stated throughout the article, compressive stresses above yield create tensile residual stresses. Reference [4] quotes 10-35% potential residual stresses for Titanium. Assuming a 12% residual stress for the highest compressive stress in Table 1 yields a residual stress of 124 MPa. Conservatively linearly combining the residual stress with the operating stress yields a maximum combined operating stress of 572 MPA. Figure 9 plots the ΔK and da/dN values calculated with (5), (6) and (7) for both the max tensile Operating Stress of 448 MPa and the max tensile Combined Operating Stress of 572 MPa.

$$f(\frac{a}{w}) = \frac{K*B*\sqrt{W}}{P} \qquad (5)$$

$$f(\frac{a}{w}) = \frac{\sqrt{2\tan(\frac{\pi a}{2W})}}{\cos\frac{\pi a}{2W}} * [0.752 + 2.02(\frac{a}{W}) + 0.37(1 - \sin(\frac{\pi a}{2W}))] \qquad (6)$$

$$\frac{da}{dN} = C(\Delta K)^m \qquad (7)$$

The da/dN for the operating stress is 2.61×10^{-8} while the da/dN for the Combined Operating stress is 5.88×10^{-8}, clearly indicating that the combined stress case is worst. If only the operating stress will have been used as the input for the facture analysis in the analysis, the component had the potential to fail before the predicted design cycles since in reality the crack growth rate of the problem is higher than suggested. Moreover, calculating the FCG rate using the ASTM LR curve instead of the CPCA curve would have produce even worst anti-conservative results.

CONCLUSIONS

The investigation yielded ground breaking results that could change the FCG data generation standard procedures governed by the ASTM E-647. This procedure establishes tension pre-cracking as the certified process to be used when growing a crack at the start of a FCG test. Researched articles [6], [3], [5], [9], [7] and [12] yielded similar results; tension pre-cracking the specimen could produce load history effects in the subsequent Fatigue Crack Growth test producing a FCG curve with lower crack growth rates and higher FCG threshold which are considered anti-conservative. This load history effects can be diminished by designing and implementing a standard procedure which substitutes the standard tension pre-cracking by the compression pre-cracking (CPC) test proposed in the article. Compression pre-cracking the specimen enables the subsequent Fatigue Crack Growth test to start with a fully open crack, contrary to what happens during the Tension pre-cracking procedure. The procedure is a conservative one at worst.

The proposed analysis methodology states when analyzing loading conditions with compressive stresses above yield one must calculate the correspondent tension residual stress. Then linearly add it to all the cycle stresses before calculating the correspondent fracture life. Otherwise the resulting analysis will be considered non-conservative.

RECOMMENDATIONS

It is recommended the CPC process is standardize and incorporated into the ASTM E-647 procedure by replacing the existing tension pre-cracking process with the proposed CPC process. The FGC material curves generated with the CPC procedure shall be then incorporated into the existing Fracture Mechanics structural analysis codes in order to provide the software with the updated material fatigue curves. Both recommendations allow moving the Fracture Mechanics analysis from an anti-conservative approach to a conservative one. For the analysis methodology, it is recommended to validate the hand calculation results experimentally.

FUTURE WORK

On the future work 1, as mentioned above using the CPC method to generate FGC data curves could be conservative at worst. This conservatism could drive higher costs and prevent future optimization of the design (like weight reduction). It will be interesting to understand the amount of conservatism involved in the procedure and reduced it to the minimum. Updating the procedure could be concentrated on the fact that articles have quote the necessity to grow the crack 2-4 plastic zones away in order to achieve good data. Finding the exact number of plastic zones required could remove some conservatism from the analysis.

On the future work 2, reference [3] mentioned that load history effects from the CPC affected the FCG curve results even after the 2-4 plastic zones. This is due to the permanent displacements caused be the residual stresses at the outer surface of the specimen. It will be interesting to understand if this is really true as it has the potential to invalidate part of the CPC process.

This article enabled the comparison of several published articles regarding the results of their compression pre-cracking procedure versus de traditional ASTM E-647. The comparison showed similar results even between different articles and authors. There is a strong feeling among the field experts that FCG data should be generated through compression pre-cracking. The investigation provides substantiation that could help change the ASTM procedure by providing data for a high volume of specimen tests. Also there are recommendations for 2 different potential future works that could yield several articles for the University.

In addition the proposed analysis approach provides an alternative and conservative procedure to consider high compressive stresses when analyzing a part for Fracture fatigue live; something that is not possible when using the standard Stress Intensity Theory.

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