A time dependent crack growth law for high temperature conditions

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1 Introduction

Alloys, especially nickel based ones used in the aerospace industry, are continuously being improved to provide greater strength against component failure and also to increase resistance against crack propagation. This involves altering their composition and, under controlled conditions, modification of precipitate and grain sizes. At high temperatures under both sustained and cyclic loading conditions, these microstructural changes interact synergistically with time dependent mechanisms such as creep, oxidation and corrosion and affect the crack growth rate (CGR). The individual effects of environmental conditions such as oxidation and corrosion and microstructural evolution of grain size at high temperatures, are generally difficult to evaluate. In addition, thermo-mechanical testing of large numbers of specimens under a variety of conditions can be prohibitively costly. Attempts have been made over the last few decades by a number of investigators to conduct standardised tests under controlled environmental conditions and compare them with the results obtained in neutral environments such as vacuum or inert gas [1-4]. It has been found that these environmental effects interact and their combined effect is generally greater than if they were considered separately. In this paper a time dependent crack growth law, COMET (Creep Oxidation Microstructure Environment Temperature), is described which considers the effect of these combined processes using a temperature dependent parameter based on an Arrhenius equation. Using this time dependent law in conjunction with a fatigue crack growth law, a finite element based implementation has been developed to carry out detailed 3D crack propagation analysis and simulation of a cracked component under the effect of thermo-mechanical loading at high temperatures.

2 COMET crack growth law

The COMET equation for time dependent crack growth data defines the instantaneous time dependent crack growth rate as:

$$\frac{da}{dt} = D(K)^n$$

Equation 1

where:	a = crack size	t = time
	D, n = material parameters (see below)	K = stress intensity factor

3 Definition of the D parameter

The time dependent mechanisms that are active during the time the component remains at high temperature (also referred to as “hold” or “dwell” time), may include creep, oxidation, corrosion and microstructural evolution of grain size and structures. These time dependent effects interact synergistically and their combined effect is generally greater than if they were considered separately. Also it must be noted that it is not easy or cost effective to determine these effects individually. For example, during the dwell period it is not clear whether the increase in crack growth rate is purely due to creep or due to the environmental interaction involving oxidation and corrosion. The time dependent growth is assumed only to occur when the applied stresses are tensile. Therefore the term D in Equation 1 is evaluated only when K is greater than zero. This is because the crack will be closed when subject to compressive loads and therefore the effects of creep and oxidation will be significantly reduced.

The parameter, D, used to describe time dependent growth rates is temperature dependent. Rate based temperature dependent quantities are frequently defined to vary with temperature based on an Arrhenius equation:

$$D = A\, e^{\left(\frac{-Q}{RT}\right)} \quad \text{which can be written as} \quad D = A\, e^{\left(\frac{-B}{T}\right)}$$ **Equation 2**

where : A, B are material constants; Q is Activation Energy
R is Universal Gas Constant; T is temperature in degrees Kelvin

Q is based on the activation barrier for the synergistic mechanism affecting crack growth. A and B are temperature independent material constants that can be determined experimentally by carrying out isothermal specimen testing at a range of temperatures of interest and preferably with different dwell periods.

4 Calculation of material constants A and B

One methodology for the evaluation of the values of A and B is *summarised* below. This procedure first requires determination of values of the Arrhenius parameter, D, for a range of temperatures.

- At several temperatures, T, over a range of temperatures of interest, crack growth data is obtained experimentally using a trapezoidal waveform loading cycle consisting of ramp up, hold at max, ramp down and hold at min. We refer to the duration of each stage of this cycle using the notation 1.1.1.1, for instance where each stage lasts 1 second. Varying dwells at max load of between 1 second to 3600 seconds or even longer may be used ie 1.3600.1.1. The 1.1.1.1 cycle is referred to as a baseline cycle, due to the absence of a significant dwell this cycle is used to define the time independent response and is assumed not to contain any time dependent crack growth.
- For each temperature (T) plot the curve (log-log) of da/dN vs ΔK which has the contribution from both time independent and time dependent CGRs.
- To obtain only time dependent crack growth data at each temperature, subtract the baseline fatigue crack growth rate from the overall crack growth rate for the tests with a max load dwell time greater than one second. Fit this new data to Equation 1 using a log-log scale to get a graph of log (da/dt) vs log (K) for each temperature.
- From each isothermal curve, extrapolate to K=1.0MPam^{½}, obtain the value of da/dt in ms^{-1} which is equal to D for that temperature. (Note that different specimen tests under the same nominal test conditions will produce scatter and therefore a range of D values can be derived at each temperature. In the following, a single value of D is used for each temperature).
- Thus for each value of temperature (T), we have a value of D from these fitted curves.
- Now to obtain the values of material constants A and B, consider the Arrhenius relationship in Equation 2:

$$D = A\, e^{\left(\frac{-B}{T}\right)} \quad \text{which gives:} \quad \ln(D) = \ln(A) - \frac{B}{T}$$ **Equation 3**

- On a ln-linear scale plot D vs 1/T where T is in degrees Kelvin to fit Equation 3. The intercept of this curve gives the value of A and the slope of this curve is –B.

5 Threshold temperature and blend function

Equation 1 is valid at high temperature i.e. above a threshold temperature, T_{thr}. Below the threshold temperature the value of D (and hence the time dependent crack growth rate) is defined as zero. To provide a smooth transition across the threshold temperature a value T_{blend} is defined such that in the range T_{thr} to (T_{thr}+T_{blend}), Equation 3 is replaced by an alternative definition. The full definition of D as a function of temperature is then:

$$D = 0 \quad \text{for} \quad T \le T_{thr}$$ **Equation 4**

$$D = E\,(T - T_{thr})^F \quad \text{for} \quad T_{thr} < T < T_{thr} + T_{blend}$$ **Equation 5**

$$D = A\, e^{\left(\frac{-B}{T}\right)} \quad \text{for} \quad T_{thr} + T_{blend} \le T$$ **Equation 6**

where E and F are determined by the requirement to match the values of D and dD/dT from Equation 3 at a temperature T_{blend} above the threshold.

6 Acknowledgements

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7 References

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Overview

- Background for high temperature crack growth prediction
- Proposed COMET crack growth law
- Calculation of growth law coefficients
- Application in a combined time dependent and time independent crack growth analysis

Engine environment

- High stress and high temperature environment
  - Stresses and temperatures out of phase i.e. peak values occur at different times
- Crack growth rates are dependent on the combined effect of:
  - Time independent (i.e. fatigue) processes
  - Time dependent (i.e. sustained load) processes

Engine environment

- Aim is to achieve a general crack growth prediction capability which accounts for the time dependent and time independent processes
  - Requires significant investment in specimen testing
  - Understanding of how the time dependent effects contribute to growth during a flight cycle

Time dependent crack growth

- Time dependent crack growth is less well described than fatigue
- It is affected by several factors which interact in a complex manner e.g. :
  - Creep
  - Oxidation
  - Microstructure
  - Environment
  - Temperature

COMET crack growth law

- Specimen testing cannot easily separate the factors contributing to time dependent growth.
- Therefore, the aim of the growth law is to describe the combined effect of these various factors:
  - Creep, Oxidation, Microstructure, Environment, Temperature

COMET crack growth law

- The law must account for the temperature effect on the growth rate as well as the time contribution
- The proposed law is:

$$\frac{da}{dt} = D(K)^n$$

where:
a = crack size
t = time
D, n = temperature dependent material parameters
K = instantaneous stress intensity factor

Temperature effect

- Although this appears similar to a Paris law, the temperature effect is introduced via the D parameter
- Rate based temperature dependency is often based on an Arrhenius equation:

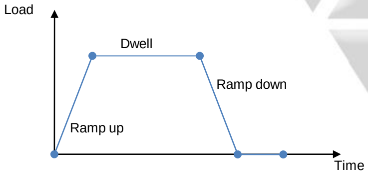
$$D = A\,e^{\left(\frac{-Q}{RT}\right)} \longrightarrow D = A\,e^{\left(\frac{-B}{T}\right)}$$

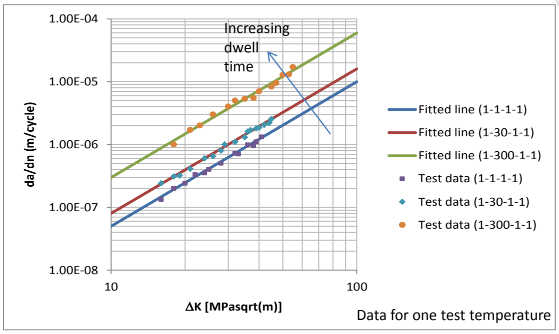
where A is a material constant
Q is Activation Energy
R is Universal Gas Constant
and T is temperature in degree Kelvin

where A and B are temperature independent material properties

Specimen testing

- Isothermal tests using a simple load cycle
- General trends:
  - Increase of growth rate with:
    - dwell time
    - temperature

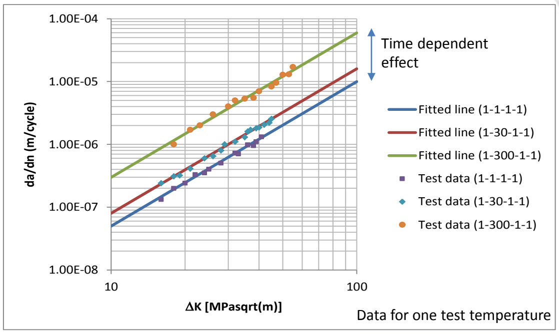




Data for one test temperature

Calculation of A and B

- For a particular isothermal test temperature, subtract the fast cycle (fatigue-only) growth rate from the dwell growth rate
- Repeat for different temperatures
- Result is da/dt and K data



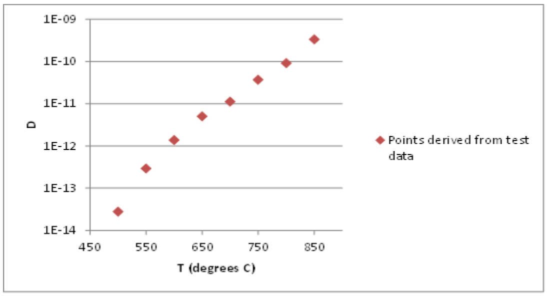
Data for one test temperature

Calculation of A and B

- Fit the da/dt-K data sets for each temperature on a log-log scale to:
  - Intercept gives value of D

$$\frac{da}{dt} = D(K)^n$$

- There will be some scatter
  - Reduce the data to a single D value for each temperature

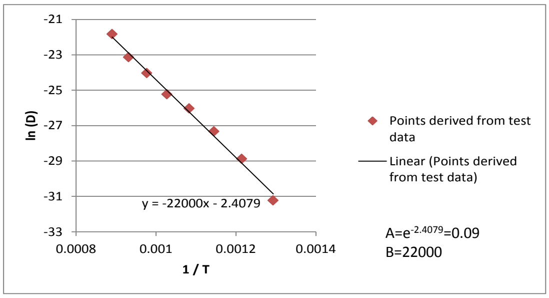


Calculation of A and B

- Use the definition of D:

$$D = A\,e^{\left(\frac{-B}{T}\right)} \longrightarrow \ln(D) = \ln(A) - \frac{B}{T}$$

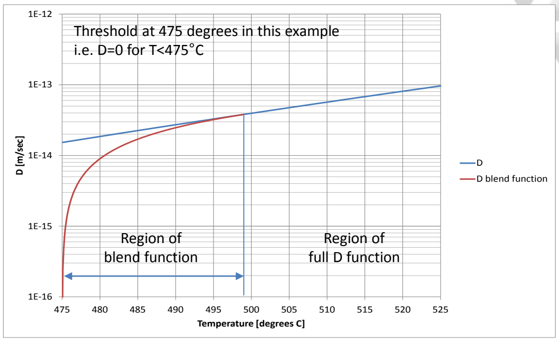
- Plot ln(D) vs 1/T
  - Line fit gives A and B from intercept and slope



$A=e^{-2.4079}=0.09$
B=22000

Temperature threshold & blend

- The temperature must be sufficiently high for any time dependent effect
  - A threshold is defined
  - A blend function is used to smooth the value of D near the threshold



Fatigue crack growth

- Fatigue crack growth is well described e.g. Walker equation $\frac{da}{dN} = C_o\left[\Delta K(1-R)^{(m-1)}\right]^n$
- Coefficients are derived from isothermal testing at a range of temperatures
- Cycle counting and methods for handling temperature changes are required during crack growth calculation

Combined fatigue and time

- Time and fatigue contributions to overall crack growth are often split into two separate components:

$$\left.\frac{da}{dN}\right|_{total} = \sum \frac{da}{dn} + \int_{cycle} \frac{da}{dt}$$

$\frac{da}{dN}$ is the effective overall growth rate for a single flight load cycle

$\frac{da}{dn}$ is the growth rate due to an individual fatigue cycle within the load cycle

$\frac{da}{dt}$ is the instantaneous time dependent growth rate.

Combined fatigue and time

- The crack growth integration process uses a law such as the Walker equation for the fatigue part
- A separate time based law is required for the time dependent part
  - e.g. COMET law

Implementation

- The new COMET law can be used in a spreadsheet analysis of known K and temperature vs time histories
- A general implementation suitable for real components requires a finite element analysis to provide K and temperature histories along a 3D crack front

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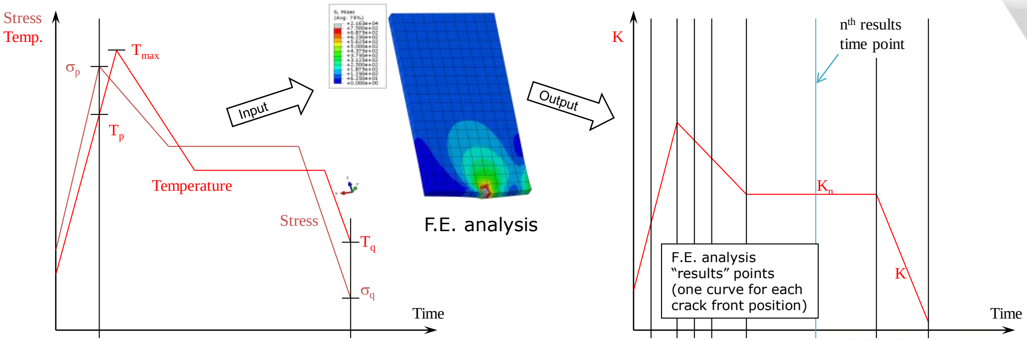
F.E. implementation

- F.E. analysis used to analyse a flight cycle
  - – Produces history of K and T at each crack front node



F.E. implementation

- Crack growth integration scheme uses:
  - K, T histories for time dependent calculations
  - Cycle count or major cycle extraction for fatigue cycle definition(s)
  - Fatigue law and time dependent COMET law
- Output:
  - Growth at each crack front node over the next N flight cycles

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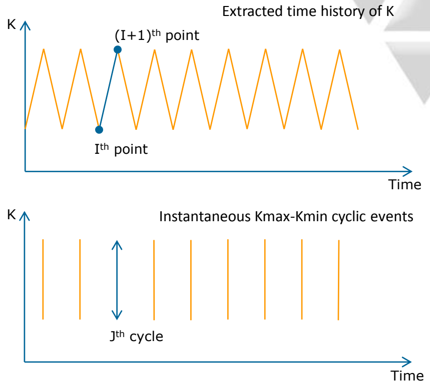
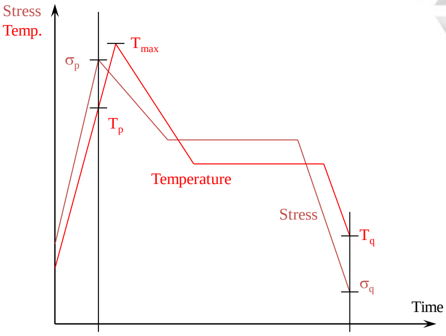
F.E. implementation

- Integration proceeds along time segments
  - da/dt contributions are added to the growth
- Cyclic events are instantaneous da/dn effects within the timeline



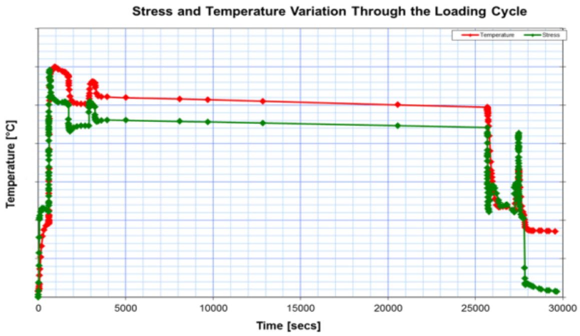
F.E. implementation

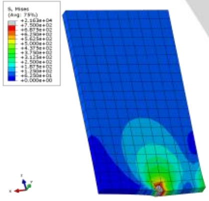
- Temperatures for calculating da/dn:
  - da/dn using the maximum temperature in the cycle (Tmax)
  - da/dn using the actual temperature at Kmax (Tp)
  - Mean da/dn from both of these methods

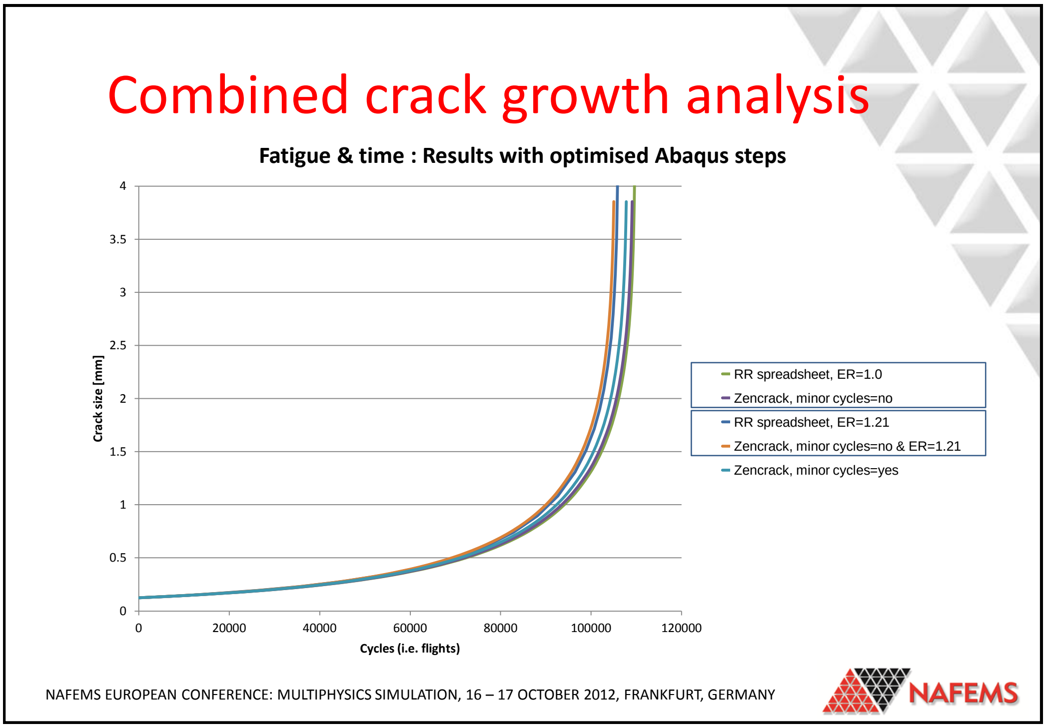


Example

- Simple model to allow comparison with Rolls-Royce in-house spreadsheet methods







Combined crack growth analysis

Fatigue & time : Results with optimised Abaqus steps

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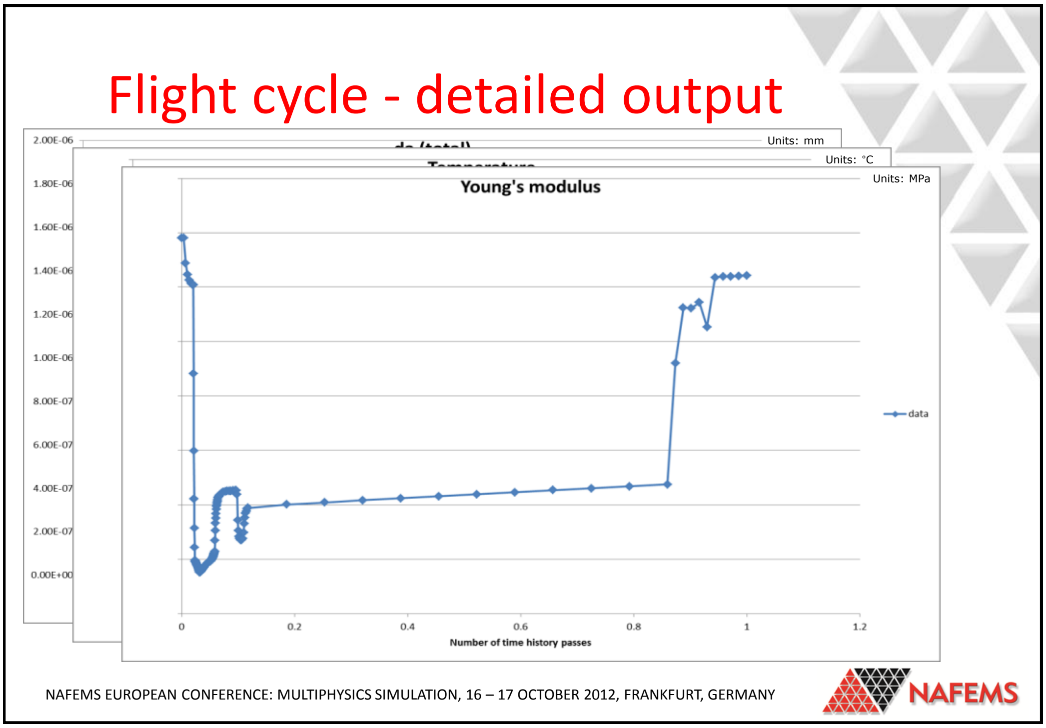

Flight cycle - detailed output

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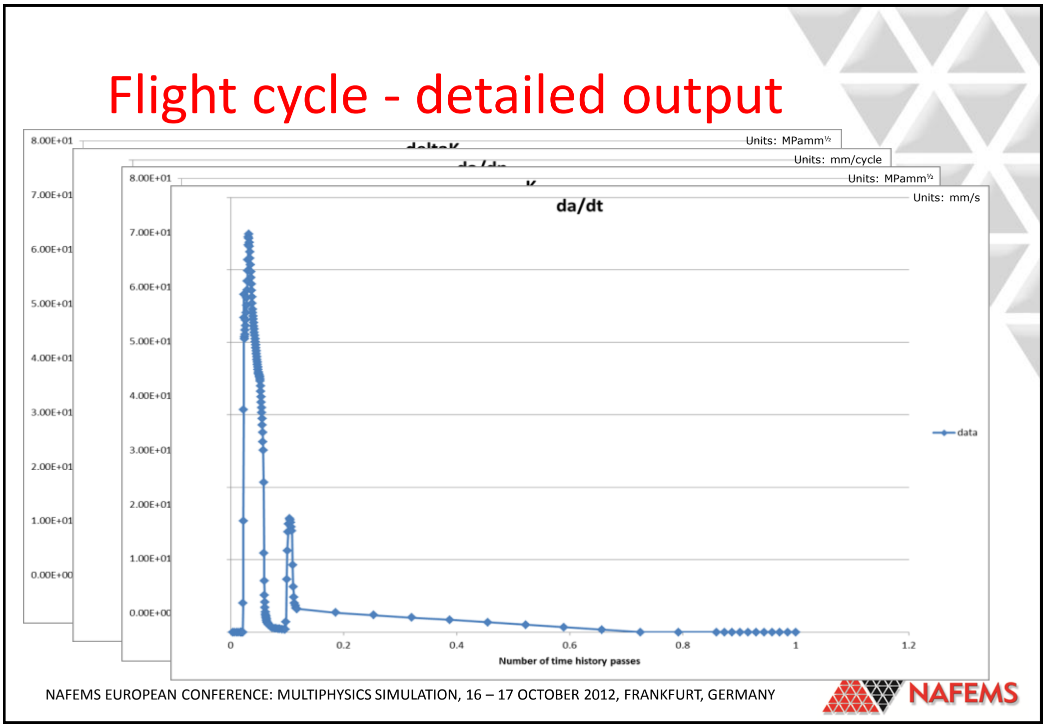

Flight cycle - detailed output

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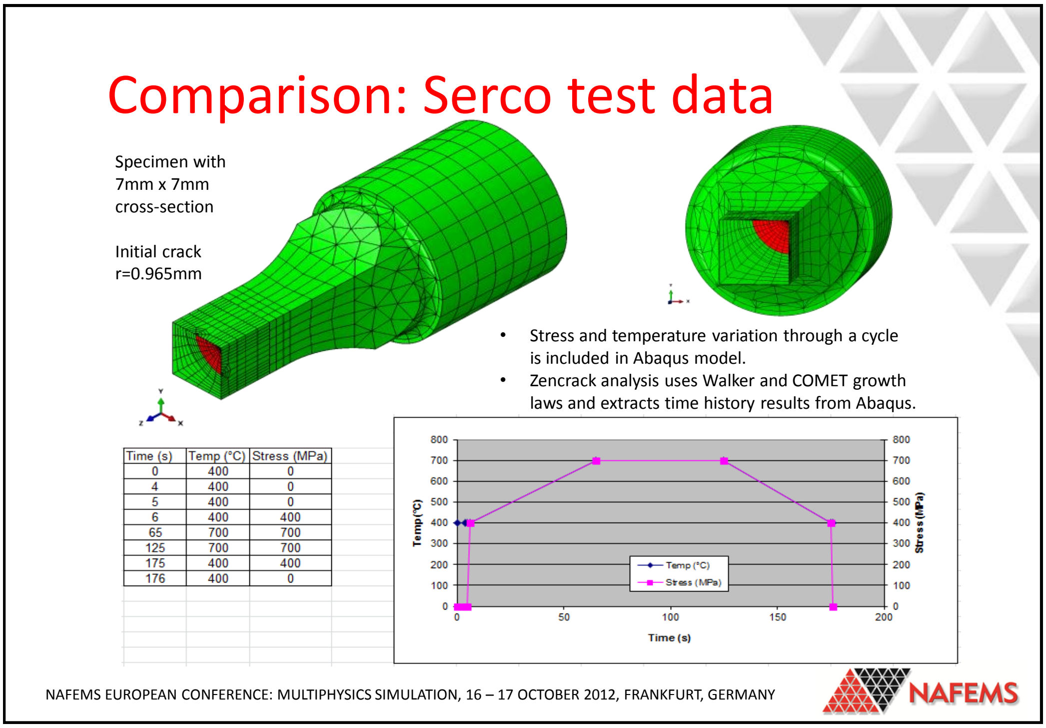

Comparison: Serco test data

Specimen with
7mm x 7mm
cross-section

Initial crack
r=0.965mm

- Stress and temperature variation through a cycle is included in Abaqus model.
- Zencrack analysis uses Walker and COMET growth laws and extracts time history results from Abaqus.

Time (s)	Temp (°C)	Stress (MPa)
0	400	0
4	400	0
5	400	0
6	400	400
65	700	700
125	700	700
175	400	400
176	400	0

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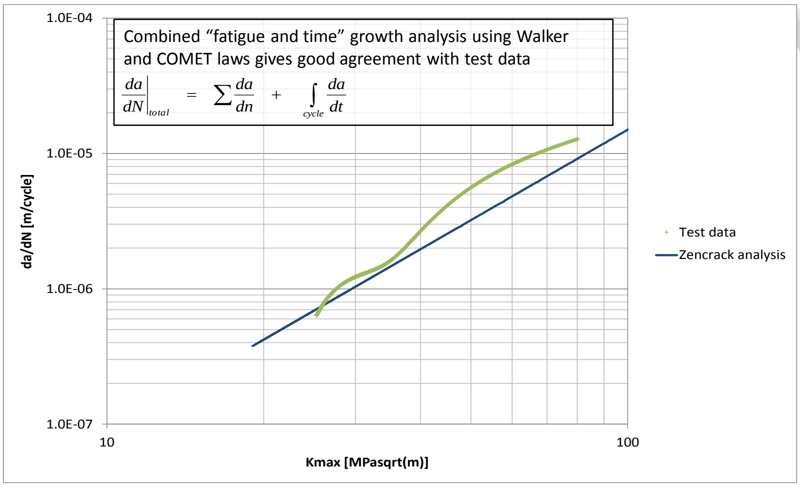
Comparison: Serco test data



Combined “fatigue and time” growth analysis using Walker and COMET laws gives good agreement with test data

$$\left.\frac{da}{dN}\right|_{total} = \sum \frac{da}{dn} + \int_{cycle} \frac{da}{dt}$$

Summary (1 of 2)

- Isothermal test data at different temperatures has been used to define a time dependent crack growth law, COMET
- The growth law incorporates the effects of several physical processes that affect crack growth at high temperature
- Crack growth due to time dependent and independent processes can be calculated using COMET and existing fatigue laws

Summary (2 of 2)

- Existing Zencrack code was enhanced including:
  - COMET crack growth law
  - Detailed “full cycle” fatigue-time analysis capability
    - K, T histories from f.e. analysis
    - Options for cycle count use of major cycle only
    - Options for temperature handling during da/dn calculations

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