Fracture control and damage tolerance methods for highly loaded launcher components

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EXECUTIVE SUMMARY

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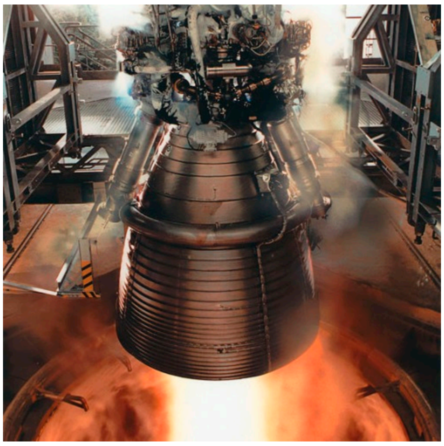

Problem area

Highly loaded launcher components are often designed according to the damage tolerance approach, not taking into account load interaction effects and often using only simple stress intensity solutions. Other problem characteristics often not taken into account include displacement controlled loading and large scale plasticity.

Description of work

The main objective of the ESA project on Fracture control/Damage tolerance methods for highly loaded launcher components was to examine the benefits of more advanced damage tolerance approaches for the prediction of crack growth in highly loaded structural launcher components than the traditional classic damage tolerance approach. The study examined application of load interaction models, probabilistic models and other new methodologies for these types of

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Knowledge area(s)
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structures. The first part of the project consisted of a number of surveys. In the second part verifications of the load interaction models, probabilistic models and other new methodologies were performed supported by some testing.

Results and conclusions

In this paper an overall synthesis of all activities is provided. The tests and analyses show that linear elastic fracture mechanics can be applied to highly loaded launcher components. A schematised life analyses is provided that can be applied to the fatigue design of highly loaded structures.

Applicability

The overall synthesis presented provides a schematised life analyses that can be applied to the fatigue design of highly loaded structures.

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Fracture control and damage tolerance methods for highly loaded launcher components

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Summary

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The main objective of the ESA project on Fracture control/Damage tolerance methods for highly loaded launcher components was to examine the benefits of more advanced damage tolerance approaches for the prediction of crack growth in highly loaded structural launcher components over the traditional classic damage tolerance approach. The study examined application of load interaction models, probabilistic models and other new methodologies for these types of structures.

The first part of the project consisted of a number of surveys. In the second part verifications of the load interaction models, probabilistic models and other new methodologies were performed supported by some testing on IN718.

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Content

Abbreviations

Acronym	Description
CA	Constant Amplitude
EIFS	Equivalent Initial Flaw Size
EPFM	Elastic Plastic Fracture Mechanics
FAD	Failure Assessment Diagram
HCF	High Cycle Fatigue
LCF	Low Cycle Fatigue
LEFM	Linear Elastic Fracture Mechanics
MT	Middle Tension
RAP	Reliability Analysis Program
SET	Single Edge crack Tension
SIF	Stress Intensity Factor
TRP	Technology Research Programme
VA	Variable Amplitude
XFEM	eXtended Finite Element Method

1 Introduction

Fracture control methods are a major concern in the aerospace and aeronautics industry where damage tolerance of structural parts is often demonstrated. Most of the methods have been derived in the framework of linear elastic fracture mechanics (LEFM) from deterministic assumptions, which render them safe in most cases. In that case the fracture process is controlled by the stress intensity factor (SIF). Nevertheless, this approach becomes either not feasible or too conservative to deal with cases that do not fit with the basic non-retardation LEFM framework, such as full plasticity. In such cases, alternative approaches based on costly qualification testing have to be considered to substantiate the fail-safe of the structural parts, i.e. the structure has redundancy to ensure that failure of one structural element does not cause general failure of the entire structure during the remaining lifetime.

During the last two decades, much progress has been made to extend the damage tolerance methods beyond the LEFM framework. One important step was the development of elastic plastic fracture mechanics (EPFM) methods aiming at describing the crack propagation under large scale plastic conditions. Furthermore, nowadays stress intensity factor solutions for complex geometries and loads can be readily computed with finite element method. Another important step was the development of probabilistic approaches that can better handle the inherent scatter in crack sizes and orientation, material properties and loading.

To examine the potential of these new developments, ESA started a technology research programme (TRP) “Fracture control/Damage tolerance methods for highly loaded launcher components”. The consortium consisted of NLR, Snecma and Cenaero.

Snecma provided representative examples of fracture mechanics issues encountered on hardware demonstrators or during the development phase of highly loaded rocket engine components. Thirteen examples were selected from the development phase of the main stage engine - Vulcain-2, the demonstrator Vulcain-X and the development phase of the upper stage Engines - HM7 & VINCI. The main characteristics observed in highly loaded launcher components are included in the thirteen examples, such as: (combined) LEFM and EPFM condition, type of loading (load-control and/or displacement control), source of load (mechanical or thermo-mechanical), combined LCF and HCF, multi modes (combined mode I, II and/or III) loading, complex (crack) geometries and loading, stress redistribution due to crack advance and residual stress fields that can result after for instance welding.

The thermo-mechanical load often causes a displacement-controlled type of loading and is related to a small number of cycles (LCF, start/stop cycle of an engine). A characteristic load spectrum for highly loaded launcher components for a main stage cryogenic engine is depicted in

Fig. 1, showing a combined low cycle fatigue (LCF, inertia, pressure and temperature loading) and high cycle fatigue (HCF, engine and launcher dynamics) spectrum. The first three LCF cycles are one or two acceptance and tuning tests and a possible aborted launch. The fourth is the launch itself. The HCF is more severe during the launch.
This characteristic load spectrum of combined LCF and HCF loading was applied in the fatigue crack growth tests and analyses performed in this study in combination with displacement-control, which is the dominant load form.

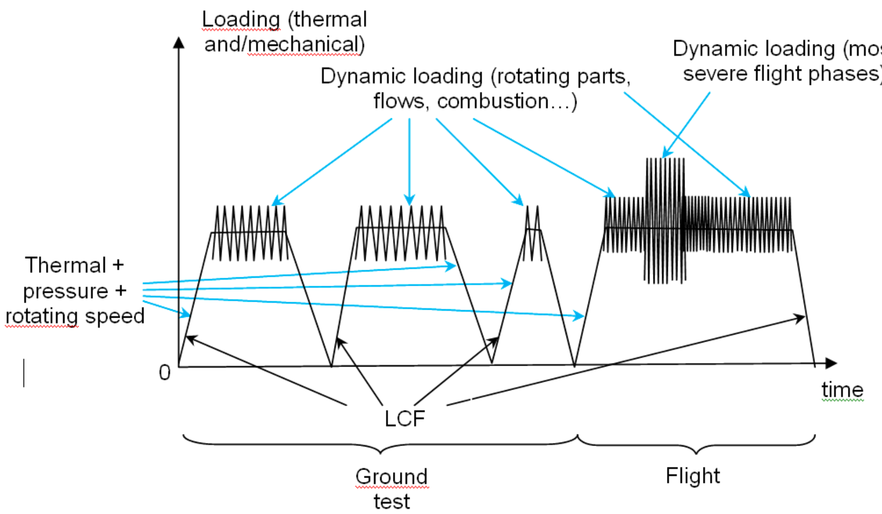

Figure 1. Typical launcher component load spectrum for a main stage cryogenic engine.

Cenaero provided an overview and verification of new methodologies that concentrated on the applicability of the eXtended Finite Element Method (XFEM) in predicting stress intensity factors. NLR provided an overview and verification of the load interaction models and probabilistic methods for crack propagation, supported by a test program.

2 Load interaction models

Fatigue crack growth under variable amplitude loading is generally slower than under constant amplitude loading due to retardation effects. In fatigue crack growth predictions, this effect is included as a retardation model. These models were developed for airframe loads. For highly loaded launcher components the overloads are much higher and other effects are also important. Thus, different retardation models may exist that provide better crack growth predictions than the current models do. For this reason, a literature survey was performed for developments in the field of retardation modelling with a special focus on retardation models that can improve crack growth predictions for highly loaded launcher components.
The models can be broadly divided into yield zone models (Wheeler, Willenborg), crack closure models and the strip yield models. A comparison of these models shows that none of them performs well in all cases. More recent developments are two-parameter models [1], which state that the crack growth rate depends on K_{max} and ΔK and all other effects can be attributed to residual stresses. Plasticity induced crack closure is said to be of minor importance by these models. A second recent development is the time-derivative model [2], which describes fatigue crack growth as a time derivative and not as a function of a cycle. Two of the main advantages are that it removes the need for cycle reconstruction (e.g. rain flow counting) and that it fits better with other fundamental physical models such as the equilibrium equations and advanced material models. A third popular approach is developed at DSTO [3], which essentially uses variable amplitude spectrum data and a Frost-Dugdale crack propagation law to predict fatigue crack growth under variable amplitude loading. The main advantage is that the model shows good predictions from very small up to medium sized cracks, without using any highly complex crack propagation and/or retardation model. For high loads in ductile materials the EPFM approach is used. This approach replaces ΔK with ΔJ as crack propagation parameter. It can give better results when the plastic zone size is large and then predicts faster crack growth. Finally, full finite element analysis can be used to predict retardation but this is only computationally feasible for academic calculations. Issues related to such FEM analyses are when to perform node release to simulate crack advance, a rule is needed to determine how fast the crack propagates, and how correct the plasticity model at the crack tip is.

A further issue with applying LEFM for launcher structures is that a large scale plastic cycle can cause residual stresses. These can be determined using an elasto-plastic finite element model and subsequently be incorporated in the crack propagation analysis. This is called plastic shakedown in NASGRO/ESACRACK [4]. Large scale plasticity can also be added to strip yield type of models by modifying the plastic stretches. It was experimentally observed that retardation effects decrease for higher loads, presumably because the crack is always open.

Thermal gradients introduce additional complexities in predicting crack growth. The thermal gradients firstly introduce residual stresses. These can be determined using a finite element model and then be incorporated in the crack propagation analysis. Secondly, crack growth rates depend on temperature and thus the crack propagation constant for the local temperature should be used. Related to this is the oxidation of the crack tip causing faster crack growth at high temperatures, depending on the time (either frequency or hold times). Finally, retardation effects are sometimes found to be significantly smaller at high temperatures. High temperature effects were not further studied in the current work.

2.1 Experimental results

The main questions to answer during this part of the project were whether the LEFM approach can still be applied for crack growth after fully plastic conditions at stress levels remaining near yield and whether significant load retardation effects are present due to load spectra consisting of a limited number of high load cycles with HCF cycles superimposed, experienced by typical launcher components.
The loads applied in many existing experimental data sets differs from the ones experienced by highly loaded launcher components, where loads are experienced well above the yield limit of the material and often under displacement control caused by the differences in thermal expansion in launcher structures. Therefore, a limited number of load and displacement controlled crack growth tests, with typical strain load spectra as experienced by launcher components, were performed on material with similar quality and heat treatment as applied by Snecma. The material used was Nickel based superalloy Inconel 718, which is a widely applied material for engine and launcher components. Furthermore, the material availability is reasonable and reference data is readily available in the NASGRO database against which the current experimental results are compared.

Load controlled constant amplitude (CA) baseline spectra were applied to middle tension (MT) specimens, without and with large scale plasticity cycle, consisting of a maximum stress of 800 MPa for R ratios: 0.2, 0.5, 0.65, and 0.8. The large scale plasticity pre-cycle up to 1.3% total strain in spectrum was applied before the starter notch was inserted in the specimen.

Large scale plasticity displacement controlled constant amplitude or variable amplitude (VA) spectra, including a large cycle up to 1% total strain, were applied to single edge crack tension (SET) specimens. The VA spectra consisted of a repeated LCF cycle (representing the loading due to the temperature profile during an engine start/stop) with a superimposed HCF random spectrum of 1000 cycles according to a Rayleigh distribution representing a typical dynamic load generated with ESALOAD [5]. The HCF spectrum was repeated 5 times per LCF cycle.
The CA crack growth rate versus effective stress intensity factor range is depicted in Fig. 2 showing a similar Paris-like crack growth rate for all load spectra and R-ratios.

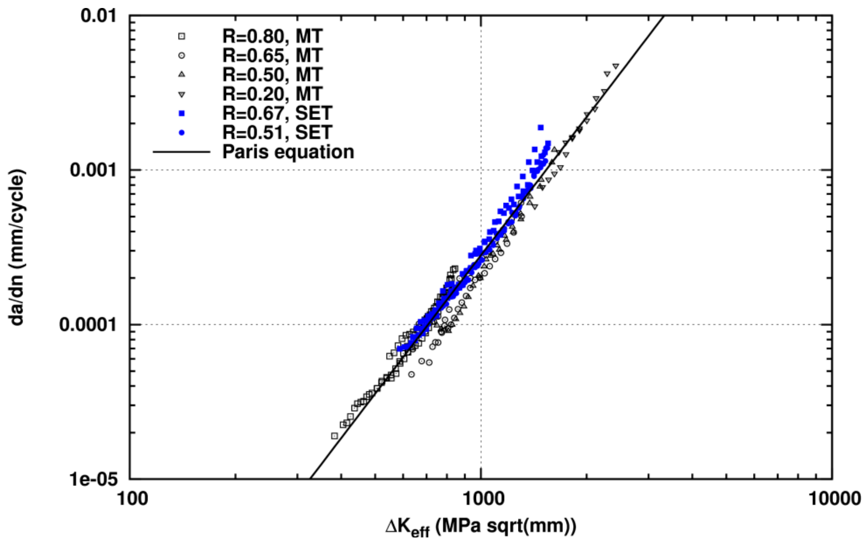

Figure 2. Comparison of the moderate load and high load constant amplitude fatigue crack growth data.

Hence, with the MT and SET CA tests the question could be positively answered that LEFM (stress intensity factor solutions and corresponding crack growth equations) can still be applied for life prediction at these high load levels. With the SET VA tests the load interaction effects at these high load levels were examined. The LCF cycle is repeated here as well to arrive at a more realistic design spectrum and to introduce additional load interaction effects.

It was observed that slanted crack growth (single or double shear) occurred for the large scale plasticity SET specimens loaded by the CA spectra, while the specimens loaded by the VA spectra showed square (flat) crack growth only. An example is show in Fig. 3.

Figure 3. Fracture surface of CA loaded SET specimen, from right to left showing the notch, the pre-crack, the slanted fatigue crack and the final rupture surface.

It occurred that the test frequency could play a role in the fatigue crack growth rate due to possible crack jumping. Two additional tests were defined, one constant amplitude test and one variable amplitude spectrum test at a four times lower test frequency. It turned out that the test frequency had a significant effect, which was supported by additional fractography of the fracture surfaces. A lower test frequency fracture surface showed much more dimples indicating unstable static crack growth (crack jumping) resulting in a lower crack growth life. For more details the reader is referred to [6].

3 Probabilistic models

Traditionally, the life of a structure is determined by means of a deterministic fracture mechanics analysis where all the model parameters have a single value and the outcome of the analysis is single valued as well. Either the design is rejected (“unsafe/failure”) or accepted (“safe/survival”). In reality the life of a structure shows considerable scatter, due to initial defects, variability in loads and material properties. The uncertainty inherent in the deterministic model is compensated for by introducing scatter and safety factors.
These uncertainties in a crack growth analysis can be fully accounted for by means of a probabilistic fracture mechanics analysis. Random variable models treat the uncertain model parameters as random variables by assigning a distribution function to each of them. This is by far the most applied method in probabilistic fracture mechanics. The most important sources of scatter (variability) are the initial flaw size a_i, the crack growth parameters C and n and the load spectrum. Beside these, the variability in fracture toughness K_c might also be important. If a considerable part of the load spectrum yield crack growth rates around the threshold then the variability in the threshold stress intensity range ΔK_{th} might become important as well. A very limited amount of statistical data is generally available to properly describe the various distribution functions.
The initial flaw size, being one of the most important random variables, is very difficult or even impossible to characterise. Some alternative strategies have been developed to circumvent these problems, such as the so-called equivalent initial flaw size (EIFS) concept, which is based on backward crack growth analyses of detected cracks according to a fixed master (mean) curve to the start of the usage life, yielding a statistical dataset on which an EIFS distribution can be determined. Issues with this approach are that the obtained initial crack sizes are not real cracks and can be extremely small. Moreover, the obtained crack size distribution depends on the applied crack growth model and can in principle not be transferred to other locations in the structure (i.e. experiencing a different load spectrum or geometry) or to other components of the same material.

The distribution functions for the crack growth parameters C and n can be determined from a sufficiently large set of crack growth curves from identically tested specimens. Only a few of these datasets exist. A normal distribution is appropriate to characterise the variability in both ln(C) and m. Both parameters show a strong correlation that can be approximated by a linear relationship.

$$lnC = \alpha + \beta m \tag{1}$$

The deterministic model with assigned distribution functions to the model parameters requires special probabilistic methods to solve. A large number of probabilistic methods have been developed in the past decades and even recently. The most well-known and simple method is the Monte Carlo method, but it is very inefficient especially when dealing with smaller probabilities of failure (< 10^{-3}), which is in general the case for engineering structures. Much more efficient methods, such as FORM, SORM and importance sampling (IS) methods, e.g. ADIS, ARBIS, MCS_IS, have been developed in the past decades to improve efficiency [7].

The main questions addressed in the verification of probabilistic methods were how to incorporate probabilistic methods in fracture mechanics and what the applicability is of a probabilistic fracture mechanics approach. To do so, a probabilistic framework was created, using the deterministic tool NASGRO and the general purpose NLR in-house probabilistic tool RAP++ schematised in Fig. 4. The framework was demonstrated by performing a number of probabilistic analyses on the displacement controlled single edge crack tension (SET) specimen as tested within this project to examine numerical aspects and to provide answers to various sub-questions such as: what are the most important scatter sources?; what is the preferred probabilistic method to apply?; what is the influence of the selected type of distribution function?; how can such an approach be applied to improve the current damage tolerance predictions?; what is the computational effort?; what are the pitfalls and open issues?. The main answers of which are discussed in the next section.

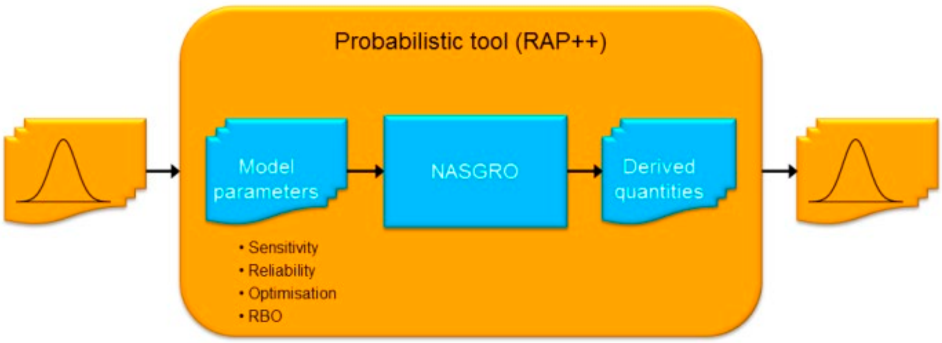

Figure 4. Schematised probabilistic fracture mechanics framework.

4 Overall synthesis and way forward

Two of the main questions to be answered in this TRP study were whether the LEFM approach still can be applied for highly loaded launcher components, experiencing crack growth after fully plastic conditions without global yielding afterwards, and whether load retardation effects experienced in typical launcher component spectra can be predicted with current retardation models. From the experimental and numerical analyses performed in the study it can be concluded that LEFM can still be applied for highly loaded launcher components experiencing fully plastic conditions. Due to the high loads and corresponding high R-values limited load interaction is experienced and therefore a non-interaction crack growth model suffices, supported by the analyses not showing significant difference between a non-interaction and load interaction model. A conservative life estimation can therefore be obtained with NASGRO/ESACRACK for such components.
Possible failure in the first LCF-cycle in the spectrum, causing the large scale plasticity, should be checked independently. This is not covered by the fatigue crack growth analysis and can be done easiest by a failure assessment diagram (FAD) analysis to check survival of the component, which was studied in another recent ESA TRP study [8]. The current FAD procedure is based on a load-control and does not cover displacement-control. A contract within the above TRP study has been awarded to study extension of the FAD approach to displacement-control, regularly experienced in highly loaded launcher components.

In general, a FAD and subsequent NASGRO/ESACRACK LEFM crack growth analysis suffice for estimating the component life for highly loaded launcher components. The LCF temperature cycle in launcher components can cause a displacement-controlled load contrary to a more general load-controlled situation. Currently, only a very limited number of basic displacement-controlled stress intensity solutions are available in NASGRO/ESACRACK. For cases for which a SIF solution is lacking, it can be computed for various crack lengths by means of finite element or boundary element analysis. The SIF table resulting from such analyses can easily be imported in NASGRO/ESACRACK. Within this TRP study only finite element analyses have been examined for this purpose since it is much more versatile and can make use of existing models of the component. To compute the SIF, traditional crack-tip elements or the new XFEM approach can be applied. For basic crack geometries, such as those included in NASGRO/ESACRACK, crack-tip elements are still recommended since they provide a more stable and accurate solution. For more complicated loads and geometries, for example turbine blades; dents; multiple cracks or complex shaped cracks, XFEM is the only feasible approach to determine the SIF solution. Due to the advance in FEM capability in this area over the past years, it nowadays is possible to quickly

generate the SIF solution for realistic loads and component/crack geometries, which allows a (much) more accurate life prediction.
Generation of a number of additional displacement-controlled SIF solutions for basic geometries is recommended to be included in NASGRO/ESACRACK to facilitate launcher design.

For both the traditional crack-tip elements and the new XFEM approach a J-integral computation is performed from which the (mode I, II, and III) SIF solution is derived. For an elastic material the J-integral, traversing in an anti-clockwise direction from one crack plane to the other, is equal to the energy release rate G. It is not straightforward to compute stress intensity factors from a known J-integral for mixed-mode problems. For instance, an interaction integral method can be applied to compute the stress intensity factors for a crack under mixed-mode loading. A relation between the three crack opening modes for a homogeneous, isotropic material is given by:

$$G = (1-\nu^2)\left(\frac{K_I^2 + K_{II}^2}{E}\right) + (1+\nu)\frac{K_{III}^2}{E} \tag{2}$$

It can be applied to extract the individual stress intensity factors. It is also valid for an interfacial crack between two different isotropic linear elastic materials. It is not valid for any other material type. Currently NASGRO/ESACRACK can only handle mode I SIF solutions, which suffices in most cases. Nevertheless, in more realistic cases with more complex geometries and loads significant mode II and/or mode III SIFs may result, for instance the observed slanted crack growth in the experiments performed within this program showed a combined mode I and mode III SIF solution. Taking into account mixed mode solutions in the crack growth analysis may occasionally improve the accuracy of the prediction, but requires an extension of NASGRO/ESACRACK.

Apart from the J-integral, the value of the so-called T-stress can be computed. This T-stress is related to the higher-order-term of the stress equation and represents a stress parallel to the crack faces. The sign of the T-stress determines the stability of mode-I cracking for straight crack paths, cracks with T < 0 are stable in this mode while those with T > 0 will curve off from the initial crack plane. Small plastic zones in actual specimens can be predicted more accurately by including the T-stress as a second crack-tip parameter.
The J-integral in combination with the T-stress, computed from linear elastic material properties, plays an important role in mode-I plane strain elastic-plastic crack-tip fields as well. The more negative the T-stress becomes, the greater the reduction of hydrostatic tensile stress (triaxiality) ahead of the crack tip. It was found that when the triaxiality is high, indicated by a positive T-stress, the crack-tip field can be described by the so-called HRR-solution (Hutchinson, Rice and

Rosengren) and strongly depends on the J-integral. For a reduced or negative T-stress this is no longer true. The HRR-solution plays an important role in the elastic-plastic fracture mechanics (EPFM).
In principle the T-stress is only valid for homogeneous, isotropic linear elastic materials and is calculated using the linear elastic material properties, but it is usually used with the J-integral calculated using the elastic-plastic material properties of the body. The T-stress obtained from a linear analysis can therefore be used to indicate EPFM conditions.

Related to this, it is possible to compute the J-integral in case of significant plasticity (EPFM) by means of a non-linear finite element analysis. As indicated before, application of EPFM requires the computation of ΔJ instead of J in LEFM, which might be non-conservative in cases with significant plasticity at the crack tip. This currently is not possible in commercial FE packages and needs a different implementation. Since the ΔJ-integral computation is a post-processing step, this can even be done outside the finite element program.

LEFM is well founded compared to EPFM, being a simple one parameter (J-integral or SIF) approach that is independent from the stress history (reflected by the path independency of the J-integral), this contrary to EPFM which is path dependent. This restricts the current one parameter EPFM approach to monotonic loading and prevents unloading or even strain softening. Hence, crack growth is in principle not allowed since the HRR J-integral formulation is only theoretically valid when no or little unloading occurs. It can be applied to determine crack initiation or structural failure due to monotonically loading. Nevertheless, it can be applied to analyse the first LCF load cycle, as an alternative to the FAD analysis.
The EPFM capability included in NASGRO/ESACRACK is limited to a few crack geometries and load cases. No displacement-control cases are yet available. Hence, a more extensive review of capabilities and shortcomings of the current NASGRO EPFM module is recommended. Validity of application of EPFM in the crack growth phase, including unloading, needs to be examined.

The above procedure is schematically depicted in Fig. 5, where a linear FE analysis is performed to compute an unknown SIF solution (K_I) in case of LEFM and a non-linear FE analysis to compute an unknown ΔJ solution in case of EPFM. Most of the open points related to the examples analysed by Snecma can be solved if such a procedure is operational.

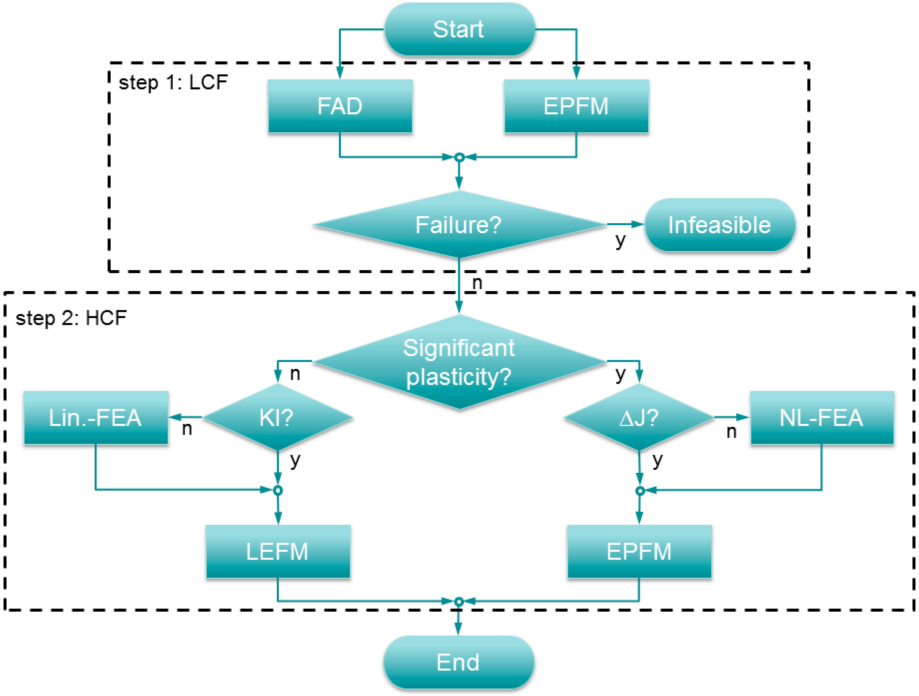

Figure 5. Schematised life analysis procedure for highly loaded launcher components.

So far, the discussion relates to the deterministic fracture mechanics problem, where scatter is taken into account by means of factors on the model input and output. In this project a probabilistic fracture mechanics approach was successfully demonstrated in combination with NASGRO/ESACRACK, with a general probabilistic tool RAP++ that allows for a very generic and versatile probabilistic analysis. In principle such a tool can be applied to compute the probability of failure (POF). However, often insufficient information exists on dominant scatter sources to accurately characterise the distribution functions, especially the tails. The most dominant scatter sources are in general the initial flaw size, the crack growth data and the load. Especially, information of the initial flaw size distribution is lacking and might be impossible to acquire due to measurement constraints and available components which is especially true for spacecraft with limited production numbers. Nevertheless, performing probabilistic fracture mechanics analyses can be very beneficial and is therefore recommended. A probabilistic sensitivity analysis, requiring approximate distribution functions only, shows how sensitive the design is for changes in its model parameters. In this way the most important scatter sources, the cause of potential problems, can be identified and modified to make the design more robust. Furthermore, it can reveal dangerous combination of model parameters causing so-called outliers, which show a response of the system away from the majority of the solutions. Understanding these combinations can contribute to a more robust design as well.

In case insufficient data exists to accurately describe the important distribution functions, application of probabilistic methods might be more appropriate by looking at relative probabilities, i.e. changes in POF, for instance to examine changes in the design, materials, operating conditions, maintenance practices and design rules.
The additional computational effort of probabilistic runs is often limited since a fracture mechanics analysis is not computationally demanding in general.
An easy to use dedicated interface for NASGRO/ESACRACK can reduce the hurdle to perform probabilistic fracture mechanics analyses. For more details the reader is referred to [9].

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