Recent Progress and New Challenges in Fracture Mechanics Methods for Rocket Engines

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ABSTRACT

This publication presents how state-of-the-art numerical tools and advanced simulation methods are applied to deal with fracture mechanics problems encountered when designing rocket engines. Three major difficulties of fracture control applied to rocket engines can be found: the importance and impact of displacement-controlled loads such as the ones induced by large thermal gradients, the presence of cracks in highly plastified areas and the difficulty to evaluate an upper bound value of initial crack sizes when performing damage tolerance analysis in small size parts and complex geometries.

A survey of recent advances is presented and areas of future developments are identified:

- The need to use the Extended Finite Element method for crack stability and crack propagation simulation in a more industrial way.
- The evaluation of the usefulness of methods accounting for global plasticity,
- The determination of initial crack sizes in line with the manufacturing processes, the inspection methods and the probability of detection requirements,
- The prediction of crack propagation under varying amplitude load spectra and crack retardation effects,
- The need to perform experimental validations to anchor the progress brought by the new numerical methods.

1. Introduction

Life related issues faced by a rocket engine can be classified as follow:

- Start-up and shutdown cycles; their number is low (typically less than 10 when taking into account ground acceptance tests and the re-start capability for an upper stage engine). However very large thermal gradients inducing thermal stresses are associated with these cycles. This very Low Cycle Fatigue loading can initiate cracks which will subsequently propagate under a mechanical vibratory loading,
- Vibratory loads induced by the dynamic environment of the flight (especially the atmospheric and boost phase of the flight) and of the ground acceptance tests (to a lesser extent),
- High cycle fatigue induced by pressure fluctuations generated by high velocity flows in pumps, turbines and hot gases line components.

The Life evaluation methodology is based both on crack initiation (i.e. fatigue evaluation) and crack propagation from existing or assumed initial cracks.

As opposed to launcher structure mostly submitted to mechanical loads and for which the risk of crack initiation during the service life is normally low, the fatigue evaluation is an essential part of the design of engine components. The fatigue evaluation allows determining areas where crack ignition is highly probable, if not almost certain after a small number of cycles.

Therefore in parallel to crack propagation activities, a large part of research activities related to life prediction is focused on improving the predictive capability of fatigue methodologies.

The specificities of crack propagation problems encountered in rocket engines are:

- Numerous situations where driving loads are displacement controlled with thermal strains being induced by thermal gradients,
- The presence of hot and highly plastified parts where linear elastic fracture mechanics do not apply,
- Complex geometries for pump and turbine components (figure 1),
- Deterioration of material properties by hydrogen embrittlement which induces a loss of ductility and toughness and accelerates propagation rates.

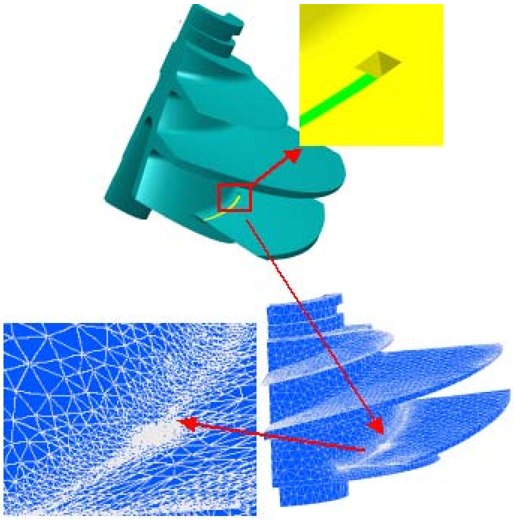

Figure 1 : Crack propagation in an inducer blade

2. Numerical methods

The crack propagation approach currently used in the rocket propulsion community is:

- In a large number of cases, formulae compendium such as the NASA/ESA Nasgrow/ Esacrack computer program,
- Direct assessment of stress intensity factors or J values using finite element meshes. The crack propagation is performed using an iterative approach and re-meshing, accounting for possible angular deviation assessed according to the Sih's angles.

The direct assessment of stress intensity factors is essential in numerous engine crack propagation problems since:

- Loadings are very often displacement controlled and are not adequately represented by the Nasgrow/ Esacrack programs which consider a library of force controlled cases,
- Hydraulic geometries such as the one of an inducer or a turbine blade attachment are often complex and not dealt with in Nasgrow/ Esacrack programs.

The available numerical methods for computing K1 or J along the crack tip are the:

- The energy release rate method based on a small variation of the crack size,
- The contour integral method for the direct calculation of J. This method is often associated with the concept of "crack box" in finite element codes, allowing the replacement of an area of the mesh by a block containing a crack,
- More recently a new numerical technique designated as the Extended Finite Element Method (X-FEM) has been proposed. This method is based on the enrichment of the standard FE approximation by discontinuous functions and the asymptotic crack-tip displacement field. Using the "level sets" technique this method allows the calculation of stress intensity factors without re-meshing the crack area.

The flexibility of the Extended Finite Element Method applied to crack propagation allows the simulation of large size crack propagation with crack branching and crack orientation shift in the vicinity of a stress discontinuity (figure 2). This simulation of crack propagation only requires a very limited re-meshing effort.

The Extended Finite Element Method along with the level sets technique also allows to deals with crack propagation problems where changes of topology occur.

In parallel to the X-FEM approach, recent and significant improvements of automatic meshing tools were performed. Based on the achieved progress it is now possible to develop tools that automatically perform re-meshing of the cracked area as the crack is progressing into the structure.

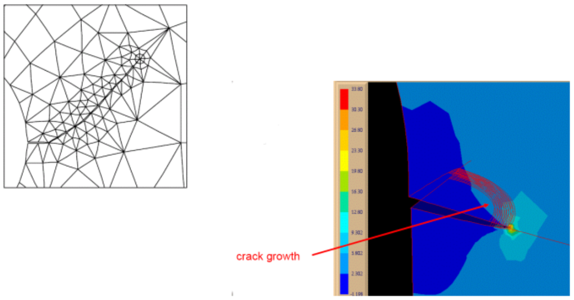

Figure 2 : Prediction of crack orientation shift in a complex stress distribution.

3. Specificities of damage tolerance applied to rocket engines

Similarly to launcher and satellite structure, the damage tolerance approach is based on a dialog between structural designer and non destructive inspection engineers. One of the difficulties of this exchange is the determination of upper bound initial crack size, namely crack size associated with a detection probability of 90 % and a confidence level of 95 %.

Specificities of engine parts may create difficulties when determining an initial crack size associated with a statistical requirement:

- The small size and complex geometry of engine parts,
- The compressive residual stresses precluding cracks from being visible with dye penetrant inspection.

The initial crack size is a driving factor of the life prediction. This is clearly shown by the simple case of a turbopump lug submitted to alternating forces due to the first stage flight dynamic environment. In this example the life to rupture varies almost linearly with the initial crack size: an initial crack size increased by a factor 2 leads to a life divided by a factor 2.

Specific test campaigns should be performed in order to determine Probability of Detection (POD) curves and establish 90 % probability / 95 % confidence detection level. However establishing Probability of detection curve is a long process and only a few examples of such curves exist.

The determination of Probability of Detection was recently performed by Snecma for powder metallurgy.

The steps of this statistical calibration of detection limits are:

- Calibrated particles of four materials, A, B, C, D are dispersed into powder metallurgy specimens,
- Non destructive examination are performed by 5 different operators.

These tests allow to establish a relationship between defect size, Probability of Detection P, Confidence Level CL.

In the above powder metallurgy case, it was shown that a factor approximately equal to 2 exists between the P 50 / CL 50 value (“average value”) and the P 90 / CL 95 value.

As a possible alternative to the determination of probability of detection curves, the possibility of using statistical defects coming from cuts and metallographic examinations is essential to consolidate the knowledge of the most commonly defects to be found in parts, especially welds and castings. The testing and destructive examination of sample parts at regular interval in addition to providing a database of defect distribution can also be a mean to verify the absence of material drift in production.

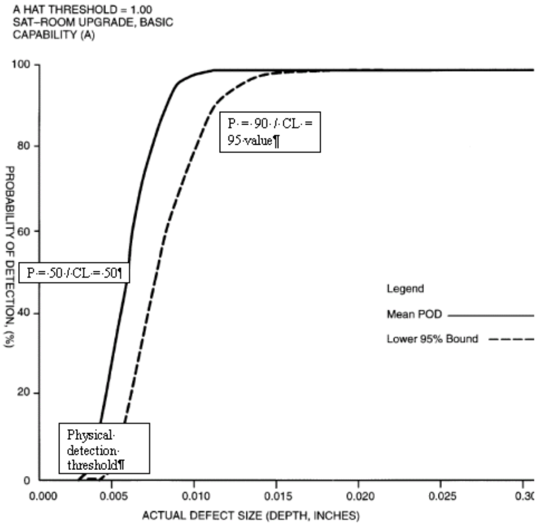

Figure 3 : Typical probability of detection curve provided by MIL HDBK 1823 for a standard non destructive examination method.

4. Elasto-plastic fracture mechanics

For hot and highly plastified parts of propulsive systems such as the regenerative circuit wall of combustion chambers, gaz generator wall, nozzle extension skirt, the damage tolerance demonstration may not be feasible by linear analysis. In these cases the use of elasto-plastic fracture mechanics can be considered. The “J–delta a” approach is already in use in the nuclear industry for very ductile materials such as austenic stainless steel.

The steps of “J–delta a” analysis can be summarized as follow:

- Elasto-plastic calculations using a finite element model with a representation of the crack are performed in order to calculate the J integral value along a contour surrounding the crack with an incrementation of the loading (P1,P2,P3,…). These calculations are performed for several crack sizes, (a1, a2...),
- The J integral calculations are plotted in a “J=f(a)” diagram and superimposed to the “J-delta a” material curve obtain with normalized samples.

Establishing the “J-delta a” material curve is an essential and complex part of this approach. It relies on the use of appropriate standards such as ASTM E 1820 and ISO 12135.

The benefit brought by the “J-delta a” approach for rocket engine and the difficulty of implementing it are still to be investigated.

The current approach which is used when linear fracture mechanics do not apply or when the geometry is too complex, is to perform component tests.

5. Use of engine and component tests

When linear fracture mechanics analysis is not applicable or when the analysis is too complex, the use of development engine tests or component tests are necessary to perform the life justification. Post-test examination of these parts after endurance engine or component tests is essential to understand the crack growth mechanisms:

- Presence of fatigue striations,
- Type of fracture surface (ductile or brittle).

6. Load sequence

As mentioned before, the major types of loading encountered by engine components are:

- Pressure and thermal cycles due to start-up and shutdown cycles,
- Dynamic loading due to structural vibration in flight,
- High cycle fatigue due to internal pressure fluctuation at a very high frequency.

Fortunately in many cases, for a given part, only one type of loading is the driving one, while the others account for a small part of the damage or the crack propagation contributor.

However there are cases where variable amplitude loading should be combined. It is known that well-defined high loads early or at regular intervals in the fatigue load spectrum of the structural items can reduce the growth rate of cracks. Taking this effect into account would improve the predictive capacity of the current approach when evaluating the combination of thermal cycles and vibratory loads for instance.

7. Crack stability analysis

In addition to crack propagation issues which were emphasized in the previous paragraphs, crack stability analysis is also a major issue for rocket engines.

The very high loading of some major components along with the need to limit the mass budget sometimes leads to situations where rupture margins are limited and small initial cracks could be unstable once loaded.

Such situation implies to perform crack stability verifications and to document it in the justification files.

In practice, the numerical tools and methods discussed before also apply for the crack stability verification. The principle is to assess the stress intensity factors and to compare them to the toughness of the material (accounting for possible impact of the environmental conditions on that material characteristic). Elasto-plastic fracture mechanics as described in § 4 may have to be used.

8. Typical examples of crack stability and propagation problems

The SPAR (“Support Palier Arrière”) is a part of a hydrogen turbopump that simultaneously plays two roles: a turbine exhaust duct and a rear bearing support. The damage tolerance analysis of the SPAR is typical of a displacement-controlled problem. Since the vanes are thinner than the outer casing and have a much smaller thermal inertia, a large temperature gradient occurs between casing and vanes during transients. The mechanical loading it-self due to loads from the bearing and pressure differential across vanes is small compared to thermal stresses.

The justification of the TEG (nozzle gaz inlet manifold) guide vane is a typical example of the justification of a complex geometry component submitted to the dynamic environment of the atmospheric part of the flight. In parallel to the analysis, component tests were performed to study the crack initiation and propagation across the vane.

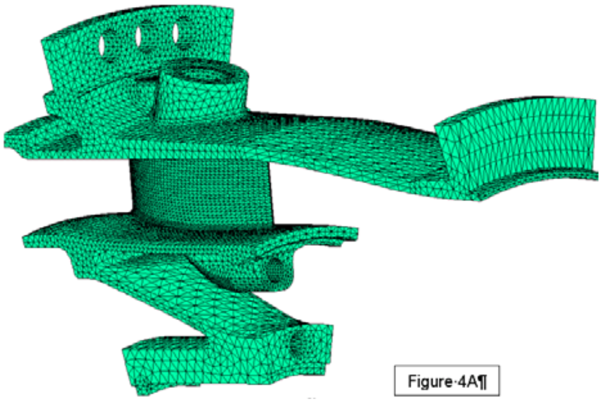

Figure 4 : crack stability analysis in a SPAR vane

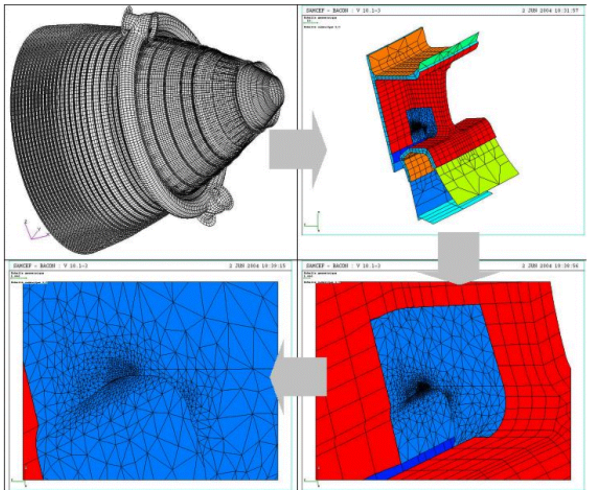

Figure 5 : Crack propagation analysis in a guide vane of the nozzle gaz inlet manifold .

9. Validation

Whereas huge improvements have been performed in the last decade in the field of numerical simulation of crack propagation, especially thanks to the development of the Extended Finite Element method, much less attention was paid to the validation of these methods by experimental test campaigns. Such gap between numerical capabilities, knowledge of physical phenomena and assurance that numerical tools are able to represent them should be reduced in the future.

Most of the validation work performed along with the development of the recent simulation methods for crack mechanics relied on purely numerical activities:

- The comparison with analytical solutions for very simple cases,
- The comparison with classical FEM results in seldom cases,

- Estimations of errors associated with the numerical techniques used to solve the mathematical problems.

Additional activities should be performed in order to provide confidence that numerical advanced tools have the capability to correctly represent observed physical behaviour of structures. Such work would be based tests representing loading situations and geometries found in rocket engines: large thermal gradients, highly plastified structures, etc… Such an approach is already applied to validate High Cycle Fatigue models using high bi-axiality test specimens for instance. The results of these test would benefit other field of the aerospace industry faced with similar loading and structure configurations.

The results of such experimental campaigns would lead to the identification of future model improvements. The improvement of crack propagation models in a multi-axial and varying stress field could be one of them.

10. Conclusion

Fracture mechanics activities applied to rocket engines fulfil the needs of an increasing demand for reliability, for faster developments and better knowledge of the design margins.

Three major difficulties of fracture control applied to rocket engine have been highlighted:

- The importance of displacement-controlled loads in numerous situations where thermal gradients are the driving factor of the structural design, as well as the inadequacy of current calculation tools to correctly represent them,
- The situations where cracks extend in highly plastified areas and where linear fracture mechanics are not applicable,
- The difficulty to evaluate an upper bound value of initial crack sizes when performing damage tolerance analysis in small size parts and complex geometries.

In order to cope with these difficulties, the objective of future development activities can be summarized as follow:

- The need to facilitate the use of direct stress intensity factor and J value, and the simulation of crack propagation through direct Finite Element calculations. The application of the Extended Finite Element to crack propagation issues fulfils this objective,
- The evaluation of the usefulness of the “J-delta a” (crack extension approach) already in use in the nuclear industry when linear fracture mechanics are not applicable,
- The consolidation of the determination of initial crack sizes through Probability of Detection activities applicable to engine configurations or a more extensive use of past experience allowing to establish defects catalogues,
- The prediction of crack propagation under varying amplitude load spectra and crack retardation effect may usefully complement the previous improvements,
- The need to perform experimental validations to anchor the increased prediction capabilities brought by new numerical methods.