DEFENCE AND SPACE

Computationally Enhanced Probabilistic Fracture Mechanics for AM parts

2021 EASA-FAA Industry-Regulator AM Event

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Fatigue & Damage Tolerance
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Contents

Context

Round robin study with parts provided by commercial AM vendors in order to assess the potential of consolidated settings of process parameters. Primary focus on monotonic strength with additional check on cyclic (fatigue) strength.

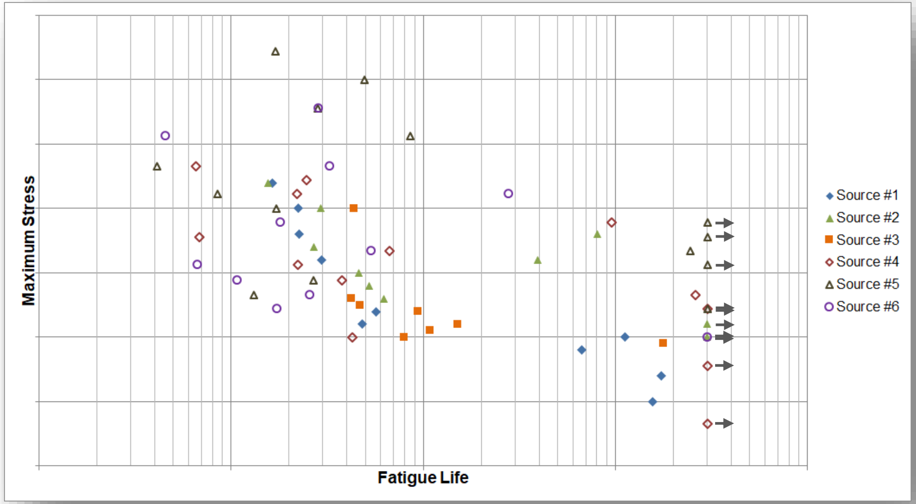
Shared requirements	Degrees of freedom	Tests performed

• Same material (i.e., Scalmalloy)
• Same manufacturing technique (i.e., L-PBF)
• Same coupon geometry specifications (Kt ~ 1)
• Same heat treatment(s)
• Same surface conditions
• Coupon acceptance based on maximum defect size (realistic production conditions)
	• Different machines
	• Different process parameters
		• Monotonic
		  ○ Tensile strength
		  ○ Bearing strength
		  ○ Shear strength
		  ○ Compression
		  ○ Fracture toughness
		• Cyclic
		  ○ Fatigue

Context

Main outcomes:

- Moderate sensitivity of monotonic strength to process parameters. Acceptable vendor-to-vendor repeatability
- Cyclic (fatigue) strength more dependent on process parameters, with significant scatter between sources and within sources, consistent with literature
- **Fatigue failures controlled by defects** (sub-surface / bulk)



More work was needed in at least two fields:

- *Optimised process definition for cyclic behavior in order to maximize the mean results and minimize the scatter*
- *Flexible and robust F&DT methodology capable of getting the most out of the physical developments*

Probabilistic framework

Although several engineering models have been proposed over the past years to address the fatigue failure of additive manufacturing, an in-house F&DT methodology based on the probabilistic life prediction (**probabilistic fracture mechanics**) was preferred in this case.

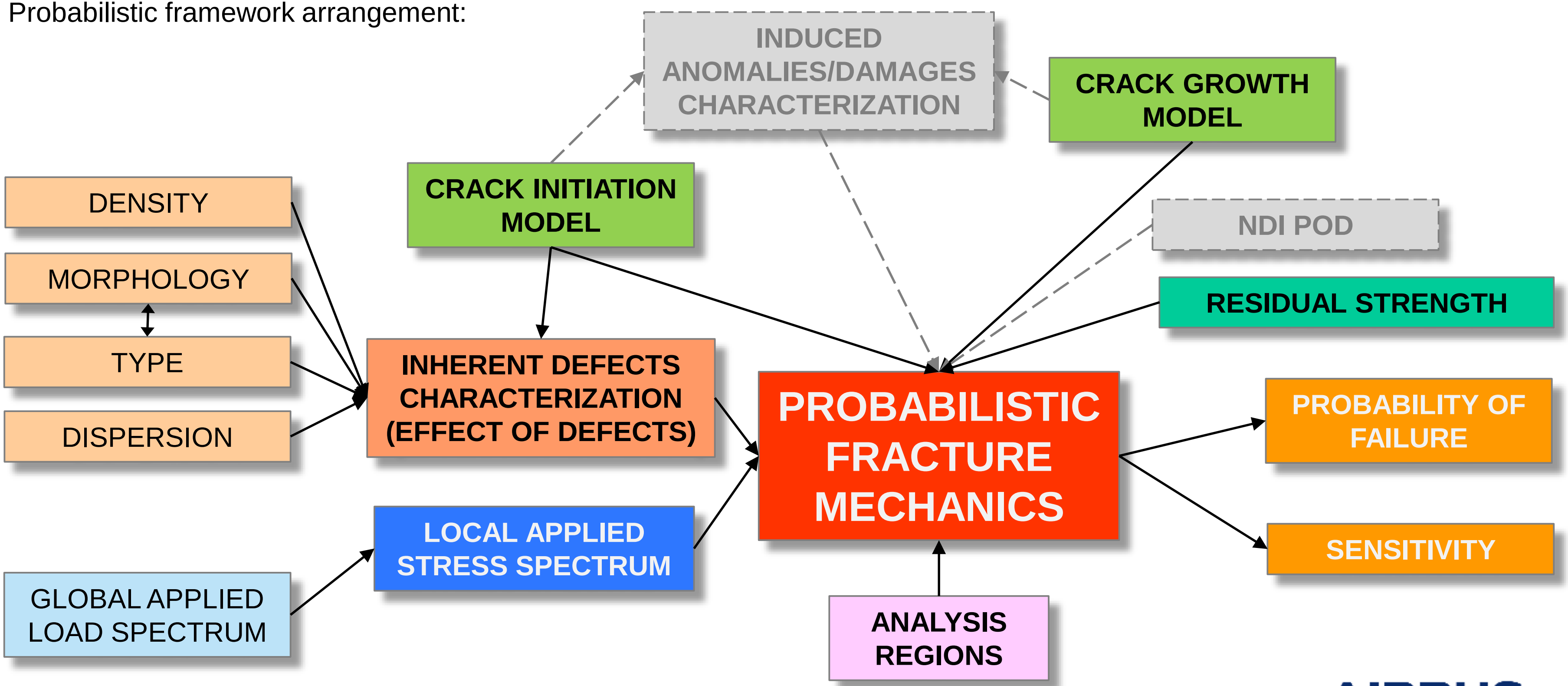
The method addresses the **influences of primary random variables** such as defect type, defect morphology (size and shape), defect occurrence, defect dispersion (i.e., clusters), applied stress, fracture-mechanics-related variables. The global system has been designed to 'learn' through the addition of new test data.

The method has been designed for a double purpose. Today, the main target is the evaluation of the **impact of the different sources of scatter** (e.g., variable occurrence rates of different types of inherent defects), thus supporting the efforts on physical development side. But the modular concept of the probabilistic analysis allows the incorporation of new variables (such as NDI POD or induced damages), so that in the future it will be compatible with the assessment of primary structure as per §25.571, either directly or supporting the evidences associated to eventual simpler ad hoc methods.

The practical architecture of the method is aligned and harmonized with the simulation developments already in use for other applications. These developments enable an **enhancement of the analysis capabilities** with respect to the classical implementation of probabilistic fracture mechanics.

Probabilistic framework

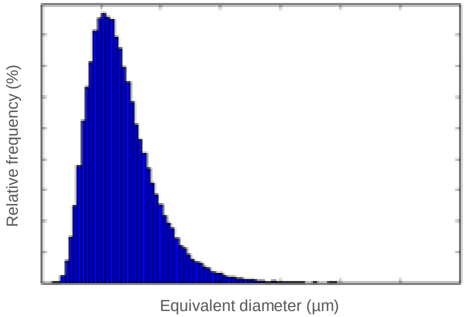
Probabilistic framework arrangement:

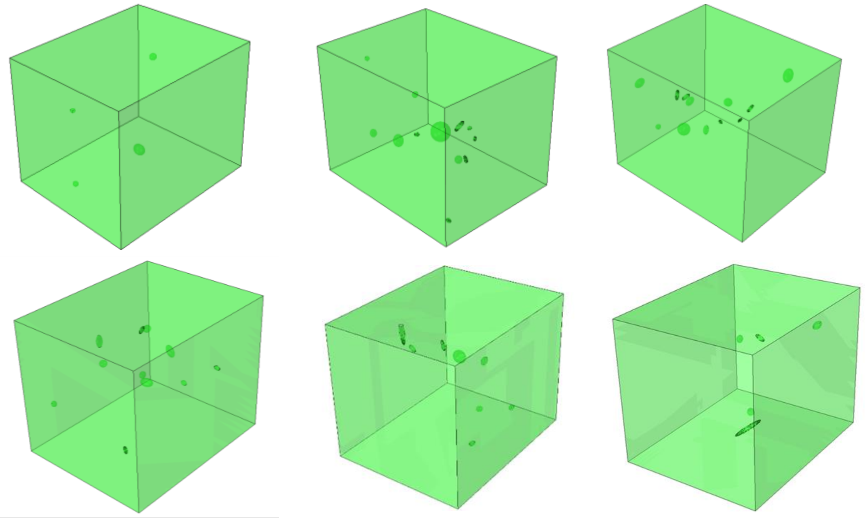


Effect of defects: RVEs

Depending on its morphology and its dispersion (e.g. clusters), the effect of defects on fatigue life will vary in a probabilistic way. **3D characterization of defects has been used** in order to consider all the possible impacts.

Starting from in-house statistical data for defect population, multiples instances of a Representative Volume Element (RVE) are created.

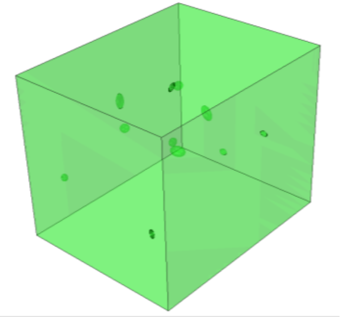


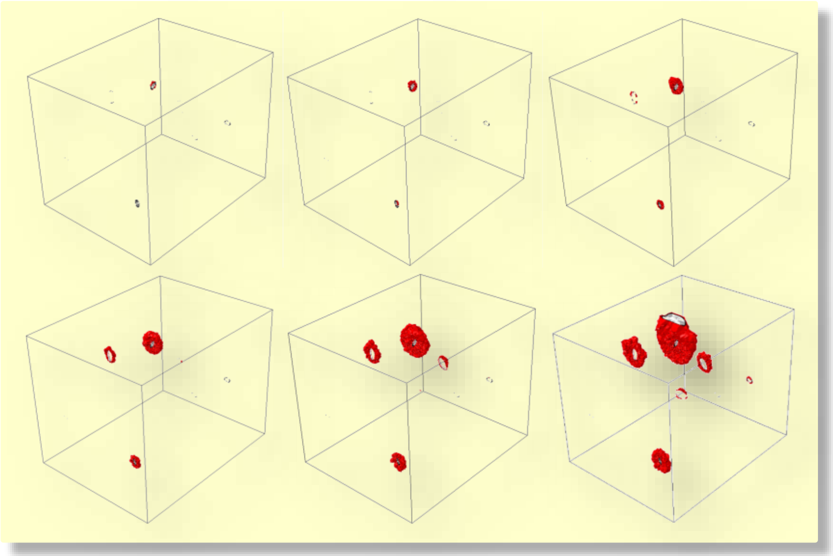


Effect of defects: Porosities

Porosities are simulated using **spheres** and ellipsoids with low aspect ratio. Defects sizes range from the expected non-propagating crack size up to the minimum detectable diameter by the quality control. Several densities are assumed.

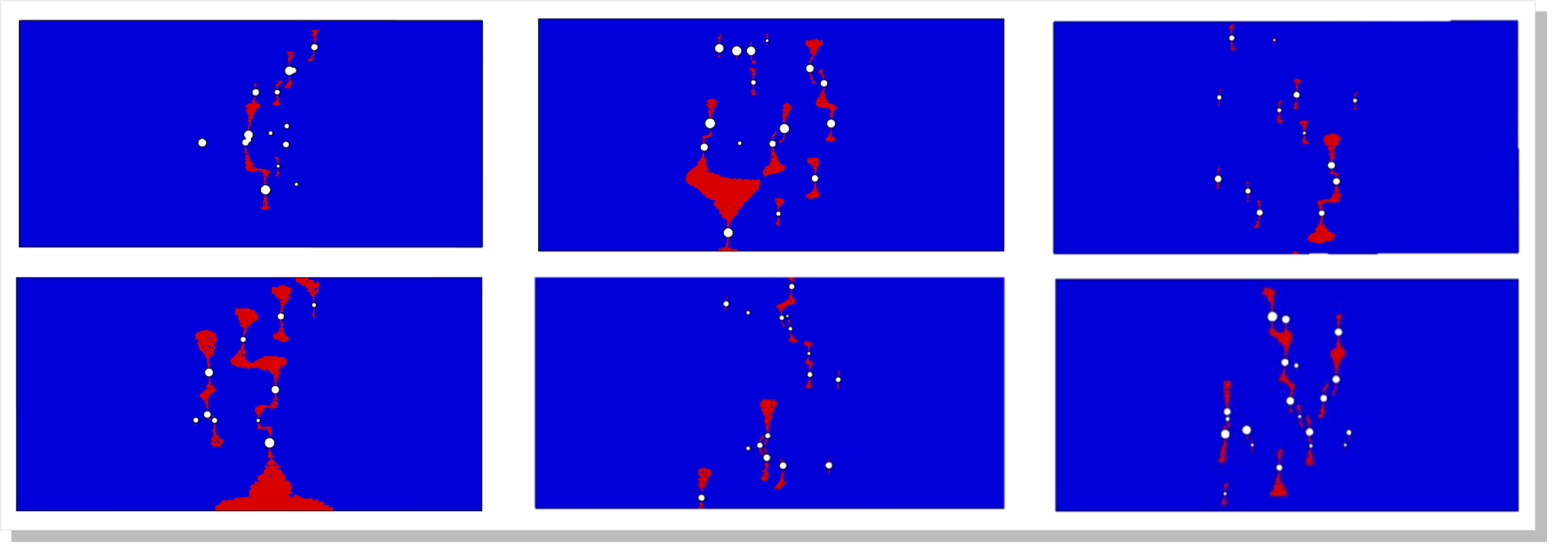
Crack formation life (i.e., the number of cycles required for a defect to form a growing crack) is calculated using **Continuum Damage Mechanics (CDM)**, thus avoiding the need of a traditional analysis based on stress concentration factors. The subsequent early crack propagation is also calculated using CDM, as the associated damage model has been calibrated to reproduce this step also.





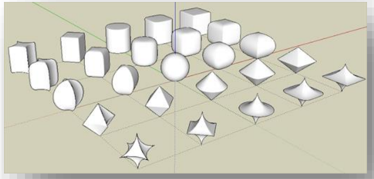
Effect of defects: Clusters

Since the shape of a porosity is approximately spherical, the stress concentration factor of an isolated internal pore is $K_t \sim 2$. This stress concentration will increase when **adjacent porosities** are sufficiently close so that their stress fields interact. Actually, when the distance between two adjacent pores is below a critical distance, they will even spontaneously coalesce. The behavior within clusters of porosities is autonomously reproduced by the probabilistic CDM simulations without the need of any external case-by-case intervention.

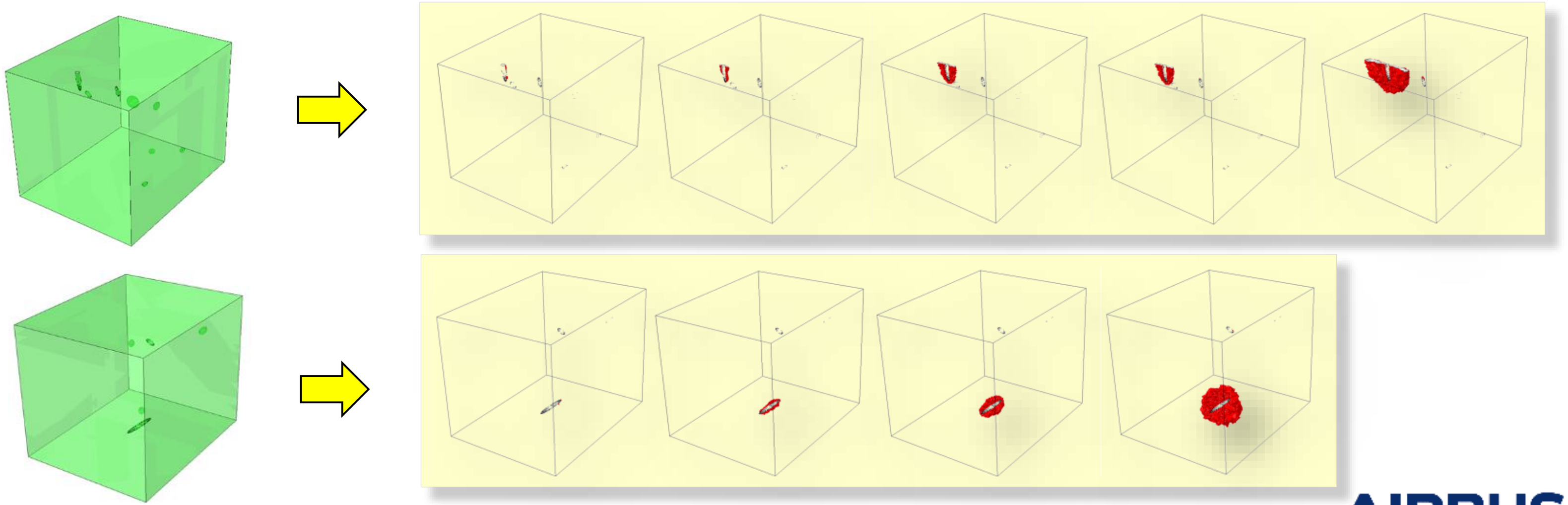


Effect of defects: LoF

In the general case, Lacks of Fusion (LoF) are simulated using **superellipsoids**, thus having the capability of reproducing the wide range of stress concentrations that appear in reality as a consequence of their elongated shape and irregular morphology. However, the most common practical implementation is made through **ellipsoids of relatively high aspect ratio**.

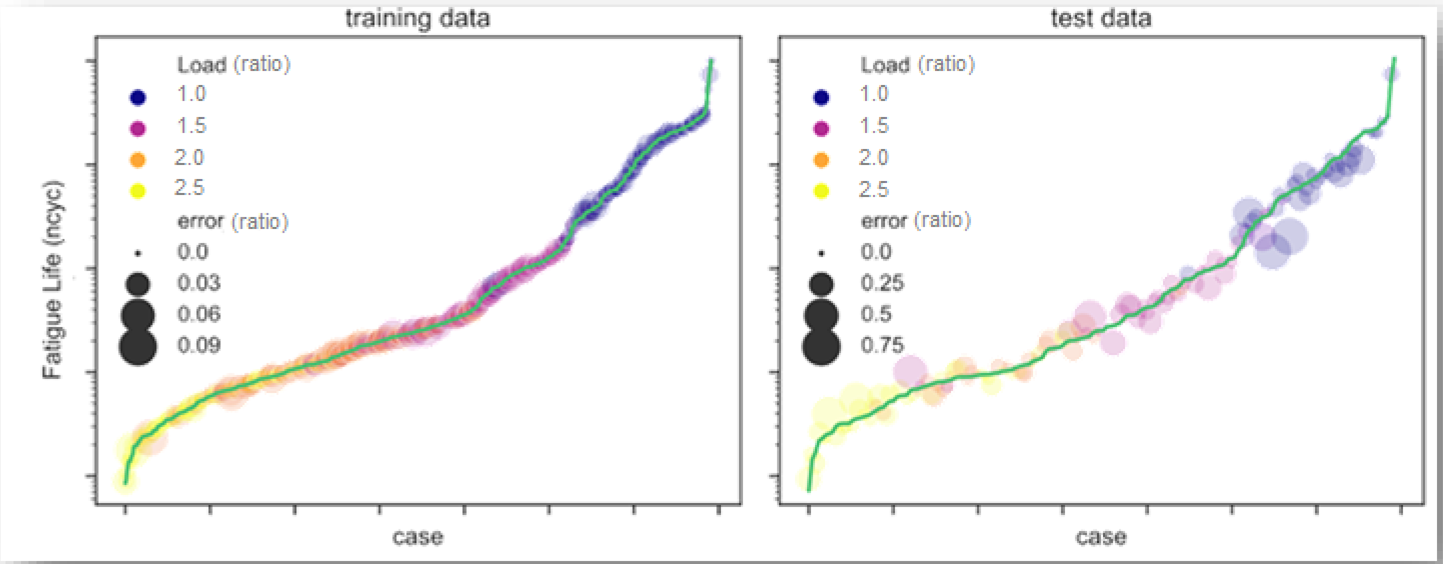


Crack initiation and early propagation are again calculated using **Continuum Damage Mechanics (CDM)**.



Effect of defects: Surrogate models

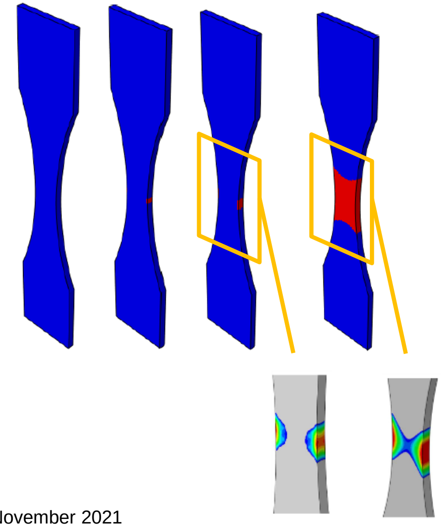
Computational cost associated to the generation of all the needed RVEs is high. A significant improvement can be achieved by using surrogate models. Due to the complexity of the problem, **Machine learning (ML)** are used for this purpose. Among the different ML algorithms evaluated –Random Forest (RF), Support Vector Machine (SVM), etc–, we have observed that the prediction performance of the Gradient Boosting Regressor (GBR) model is the best in this case.

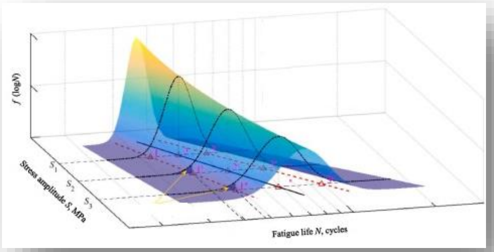


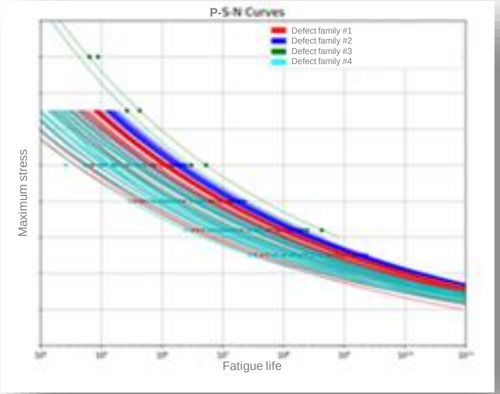
Effect of defects: P-S-N curves

Once characterized the RVEs, the effect of defects is condensed on **probabilistic S-N curves** (P-S-N curves), linked to different 'defect families' (i.e., combinations of variables such as morphologies or densities). These curves will feed the damage models to be used at part level.

The P-S-N curves also enable the analysis of aspects well known in reality such as reduction of fatigue mechanical properties and, particularly, the substantial scatter observed as a consequence of sub-surface or bulk defects, even under almost identical process conditions.







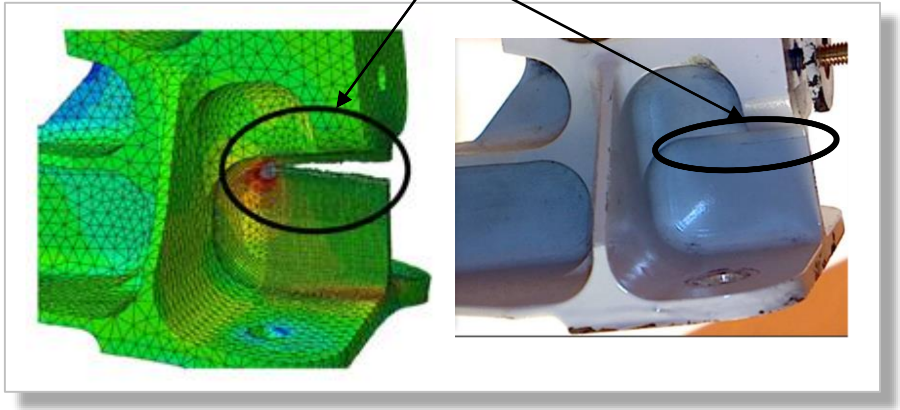
Crack growth model

Macroscopic crack growth assessment derived from a failed porosity or Lack of Fusion is based on an in-house version of the **eXtended Finite Element Method (XFEM)**, which allows the simulation of 3D crack growth paths without the need of explicitly calculating stress intensity factors.

This technique is also applied to the propagation of crack-like defects, for which crack initiation life is assumed negligible.

XFEM has been validated over the years for a wide range of analytical cases and real scenarios, such as those linked to in-service events of conventionally manufactured parts.

Correlation between simulation and reality



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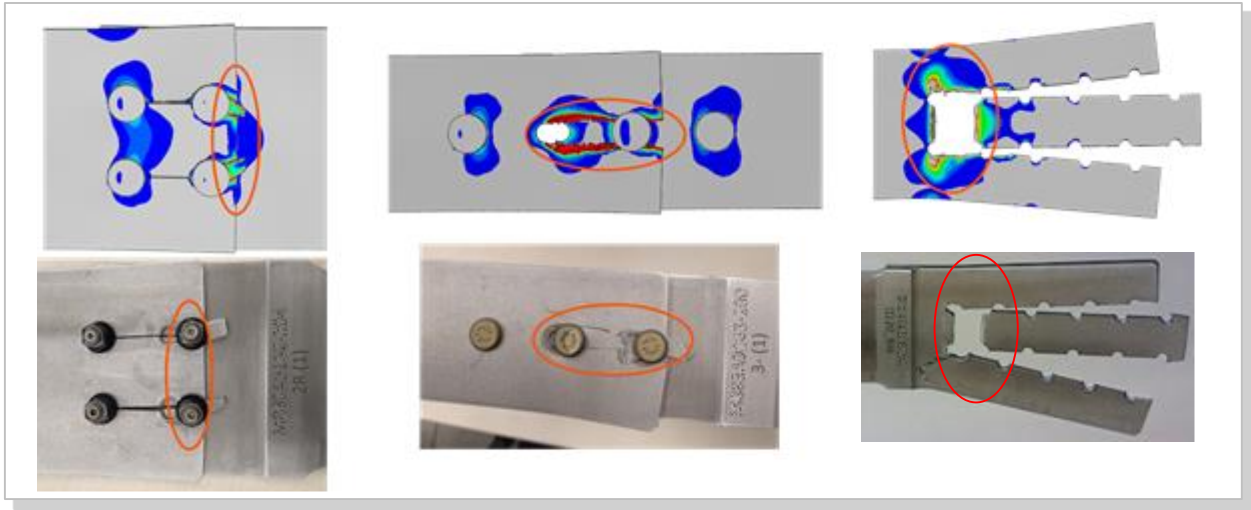
Residual strength

Residual strength is evaluated using an in-house implementation of **Continuum Damage Mechanics (CDM) for the simulation of ductile fracture**, avoiding again the need of the evaluation of the classical criteria (fracture toughness failure, net section yield, etc).

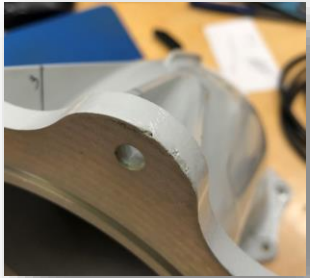
As in the case of crack growth, the application of this technique has been validated against theoretical models and real test results for multiple configurations of conventionally manufactured parts with induced macroscopic defects yielding complex stress fields.

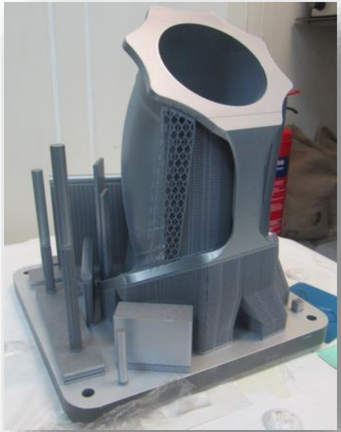


Analysis regions

In a general case, there is a correlation between surface/bulk defects and process parameters and scanning strategies. Therefore, the occurrence of defects **cannot be considered as totally random** throughout the volume of the part.

Surface and bulk defects can also be linked to other design/manufacturing factors, such as the arrangement of support structures.





Analysis regions

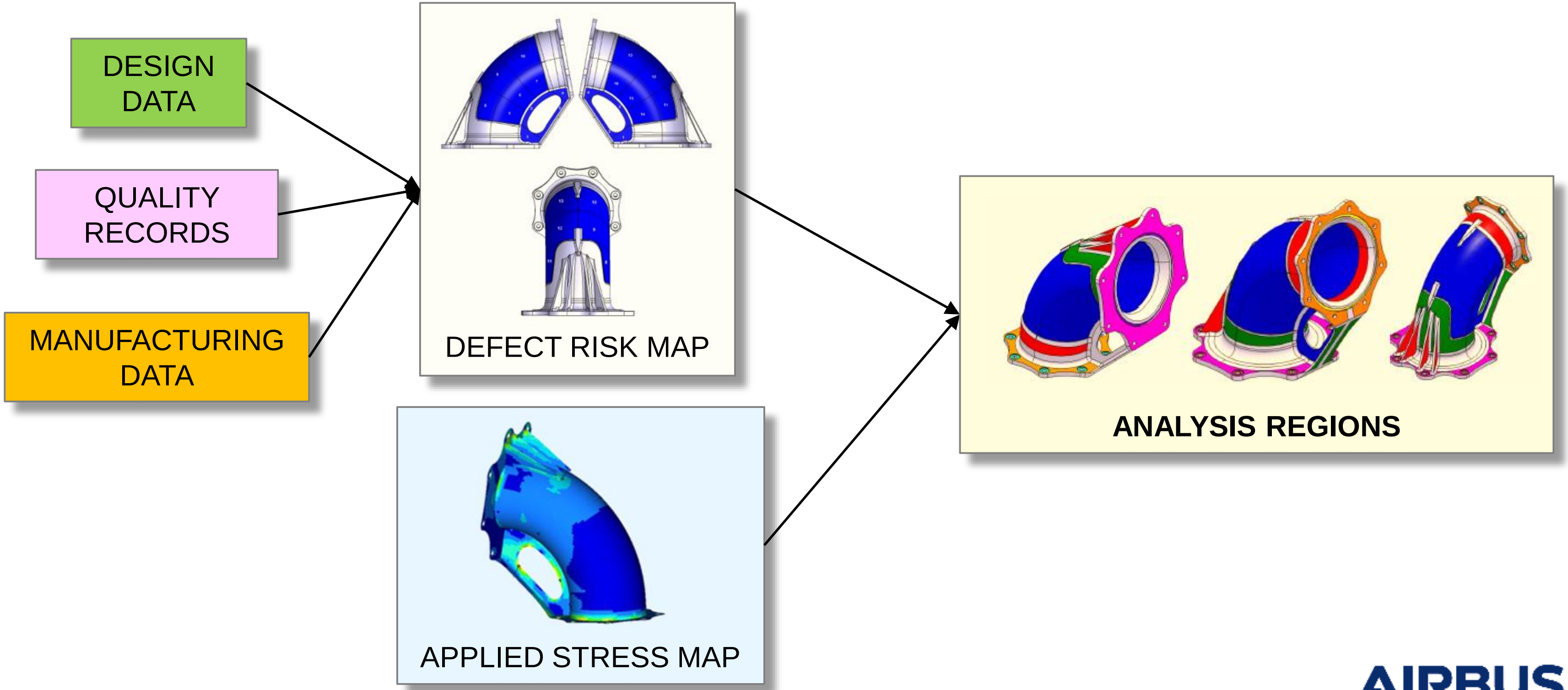
This observation leads to the development of the concept of '**analysis regions**'. An analysis region is that volume of the component to be analyzed in which the probability of a defects family is reasonably homogeneous and the applied local stresses are relatively uniform. This implies that the whole region can be represented by a selected analysis location that condensates its criticality.

Today, the determination of analysis regions is made through a **manual process**, as engineering judgement is key for the interpretation of heterogeneous sources of information including manufacturing reports, quality records, design data and stress analysis simulations (stress fields and impact on fatigue).

It is noted that the nature of the **integration between Design, Manufacturing, Quality and Stress** needed for the evaluation of the analysis regions (and, in general, for the assessment of additive manufacturing materials) implies an adaptation of the current process used in conventionally produced components. The update resembles the interaction needed for welds or castings, but is more intensive in additive manufacturing.

Analysis regions

Analysis regions determination process (notional):

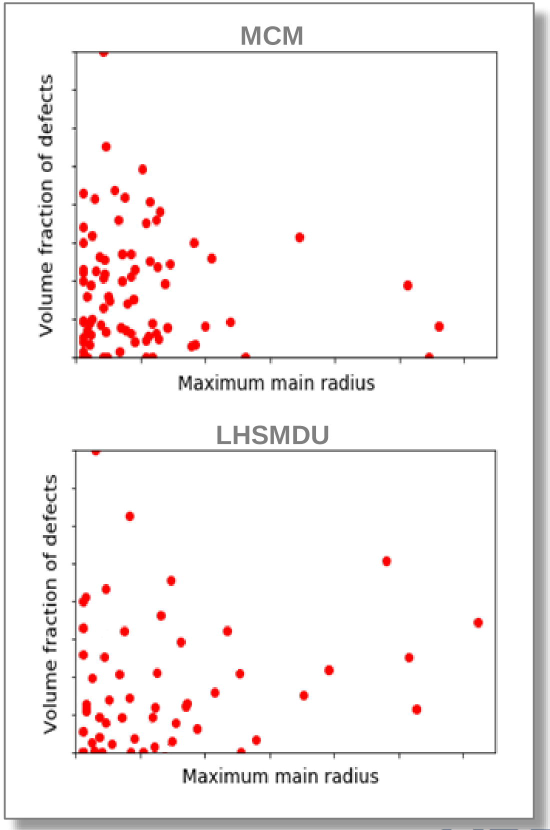


Probabilistic simulation

Due to its conceptual and algorithmic simplicity, Monte Carlo method (MCM) constitutes the backbone of Probabilistic Fracture Mechanics analyses. However, the **computational cost associated to MCM can be very high** to achieve reliability predictions like the one associated to our probabilistic framework.

The use of analysis regions alleviates this cost by reducing substantially the number of calculations and, as such, can be considered as a main contributor to the computational efficiency. However, further savings in the computer process time can be achieved acting over the MCM itself.

The first step in this direction has been made introducing techniques such as **Latin Hypercube Sampling with Multidimensional Uniformity (LHSMDU)**, which keeps the computational cost under acceptable levels for parts with relatively simple geometries. Other improvements will be incorporated in the future when needed for the analysis of more complex parts.



Conclusions

A probabilistic methodology has been developed to quantify the risk of failure associated with defects in additive manufactured parts under cyclic loading.

The method is based on computational enhancements intended to provide the capability of simulating complex interactions between defects (Continuum Damage Mechanics, CDM), crack growth in complex geometries inherent to additive manufacturing (eXtended Finite Element Method, XFEM).

This additional capability implies also a higher computational cost, so that an improvement in the overall computational efficiency –via Machine Learning (ML)– is needed.

An updated cooperation between Design, Manufacturing, Quality and Stress is needed in order to precisely define the mix of contributors potentially leading to a fatigue failure of a part. Despite all the automations introduced elsewhere in the method, this part of the process is retained as fully manual so far.

Further work is in progress to add new variables to the framework, optimize of the Probabilistic simulation (i.e., improved Monte Carlo methods) or to implement a Verification & Validation (V&V) process of the overall method, among other fields.

Thank you