Development of efficient high-fidelity solutions for virtual fatigue testing

Gomez-Escalonilla, Javier; Garijo, Diego; Valencia, Oscar; Rivero, Ismael
Airbus Defence & Space, Military Aircraft, Getafe, Spain

Over the years, the aeronautical industry has been capable of increasing the safety standards of the airframe while achieving more demanding performance requirements. This success has been based on a duality of analysis and test programs during the development phase, which has been proved as sufficiently effective for airframe certification purposes.

Recent estimations quantify in approximately 10^4 the number of physical tests required for the certification of an airframe structure, from which the tests needed for the check of Fatigue and Damage Tolerance (F&DT) constitute a significant fraction. In contrast, the analysis systems used today are still just sophisticated tools in many cases. Actually, the availability of these tools and methods alone does not guarantee the accuracy of the analysis, as the success of their application is mainly based on the user's capability, training and experience.

However, the current status quo is prone to experience a quick change. The constant improvements in the resources available for analysis are challenging the dependence on testing, thus leading to the conception of a new analysis framework able to treat the fatigue damage phenomenon from a comprehensive and holistic perspective in order to minimize or remove the need of physical testing in the development of aerostructures. This new, ongoing paradigm is called *Virtual Fatigue Testing* (VFT) in modern literature.

VFT should not be understood as just a mere evolution of the current analysis techniques. On the contrary, it is a complete change of paradigm. Thus, the classical analysis is based in many cases on a top-down multiscale approach, based on successive couplings by transference of boundary conditions from upper-level coarse definitions to lower-level refined details. But VFT constitutes a hierarchical bottom-up architecture of numerical models able to act as “building blocks” for the construction of more complex models. By validation of the elemental “blocks”, these can be integrated into more elaborated models without detrimental effect in the accuracy of the numerical predictions. The main requirements that a Virtual Fatigue Testing framework has to fulfil can be summarized as:

- Comprehensiveness (holistic approach)
- Accuracy (very high fidelity)
- Predictive and unconditioned outputs (a priori analysis, no manual input)
- Flexibility (adaptable to bottom-up & top-down strategies)
- Multi-scale capability (multi-fidelity)
- Multi-stage applicability (design development, certification, maintenance program support, analysis of in-service events and assessment of ageing structures)

In this context, this paper presents the work developed by Airbus towards the practical implementation of VFT capabilities for the F&DT analysis of metallic structures. Certainly, a key factor of the eventual success of the VFT is the ability to incorporate models and methods that fulfill all the previous requirements with a reasonable computational cost. A very significant effort is being devoted to select and validate the collection of solutions to be included in the VFT definition, comprising: Finite Element Method (FEM), eXtended Finite Element Method (XFEM), Meshless Methods (MM) −including Element-Free Galerkin Method (EFGM), for example. The associated degradation models (a generalization of the classical fatigue damage models) will be based on the extensive application of the Damage Mechanics (DM) approach for crack initiation, crack propagation and fracture. All the deterministic methods will be extended to probabilistic simulations by means of their probabilistic counterparts (Stochastic FEM, probabilistic DM) combined with Artificial Neural Networks (ANN). Table 1 shows how these methods are distributed throughout the main steps of the F&DT analysis.

Each of these techniques has a vital contribution to the targets of VFT. For example, XFEM and Meshless Methods are aimed to overcome the evident limitations of mesh-based methods (e.g., FEM) in dealing with problems of fracture mechanics, as they have been especially designed for treating discontinuities. Both have become efficient tools for solving crack arbitrary propagation problems, having been tested by Airbus for lead crack and multiple crack scenarios (Figure 1).

Table 1. Comparison of classical vs virtual testing approach.

ANALYSIS TOPIC	DETERMINISTIC		PROBABILISTIC	
	NUMERICAL FRAMEWORK	DEGRADATION MODEL	NUMERICAL FRAMEWORK	DEGRADATION MODEL
Crack initiation	FEM Meshless methods	Damage mechanics for fatigue damage	Stochastic FEM Stochastic MM	Probabilistic DM for fatigue damage + ANN
Crack propagation	FEM XFEM Meshless methods	Damage mechanics for crack propagation	Stochastic FEM Stochastic XFEM Stochastic MM	Probabilistic DM for crack propagation + ANN
Residual strength	FEM Meshless methods	Damage mechanics for fracture	Stochastic FEM Stochastic MM	Probabilistic DM for fracture + ANN

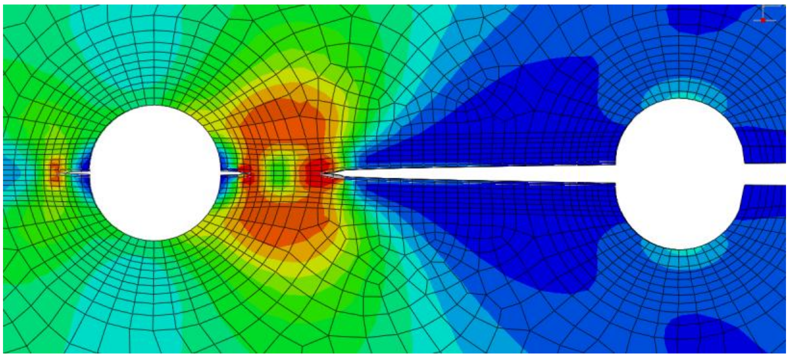
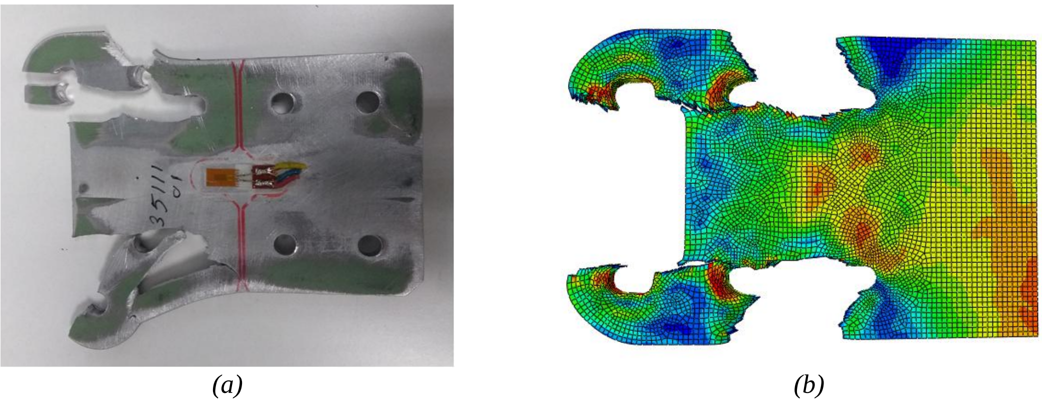


Figure 1. Application of XFEM to the analysis of Widespread Fatigue Damage scenarios.

On its turn, the theory known as Damage Mechanics is ideally suited for the analysis of engineering problems associated to strength, such as fatigue failure or ductile fracture in residual strength. This theory takes into account the gradual material degradation or deterioration of the materials when subjected to cyclic loading (fatigue) or critical static load (residual strength). Figure 2 shows the application of DM to a blind validation of residual strength testing in which failure load was predicted with less than 2% error.



(a) (b)

Figure 2. Comparison between (a) real residual strength test and (b) equivalent residual strength test.

Finally, the Stochastic Finite Element Method (SFEM) is an extension of the classical deterministic FEM to the solution of problems with uncertainties in the mechanical, geometric and/or loading properties. This method, along with their equivalent applications to XFEM and Meshless Methods, has received an increasing attention over the last decade mainly due to the spectacular growth of computing power rendering possible the efficient treatment of large-scale problems.

Keywords: damage mechanics, finite element analysis, stochastic, meshless methods