ADVANCES IN INDUSTRIAL APPLICATIONS OF DAMAGE AND FAILURE APPROACHES

Stéphane Mahdi

Airbus Operations SAS, 360 Route de Bayonne, M25-1, 31060 Toulouse Cedex 9, France

Keywords: Damage, Failure, Simulation, Virtual Testing

Abstract

Developments in engineering structure analysis often refer to virtual testing capabilities; a technology allowing for the screening and the early assessment of innovative materials and design principles. It shall be recognized that an enabler for the extensive use of this technology is in the implementation of physical approaches, allowing for accurate predictions in the damage and the failure of airframe structures. It is therefore essential to ensure that the development of physical models meet the constraints of the structure analysis requirements. Industrial applications of damage and failure approaches are discussed in this paper.

1 Context

1.1 Structure Analysis and Airframe Sizing Process

The composite airframe sizing process [1] is initiated with the combination of design configuration and the loads derived from a global finite-elements model (GFEM). The sizing is addressed through the development of calculation methods that are either analytical or numerical through local finite-elements models. This dual approach allows for fast sizing computation, analysing all configurations (geometries and load cases) as well as refined analyses of selected critical ones. Verifications and validations are typically performed on a wide variety of experimental tests at several structural scales, from coupons to components.

The calculation methods and associated allowable are thus defined from model development and experimental evidences covering all levels of the test pyramid. This building block approach is robust, although complex to manage in case of late change in concepts or introduction of new technologies. The challenge therefore lies in developing processes that allows for both cost and weight savings, satisfying the structure requirements, set from the certification specifications.

Latest developments address trade-offs in complexity and in accuracy:

- Enabling optimisation process for efficient design/calculations loops,
- Allowing some flexibility and adaptation of generic principles to specific configurations,
- Being foolproof with respect to the complexity of the simulation and the number of users.

Multi-level simulations, representative of the structural scales and employing the principle of sub-modelling, are now common in order to anticipate with respect to complex physical phenomena. State-of-the art allows for full detailed multi-components simulations.

1.2 Physically-based Damage and Failure Simulations

Calculation methods are typically simple, based on classical progressive failure analysis, and adapted to the need for fast or detailed sizing (e.g., based on traditional limit, interactive, point/volume stress or strain and energy release rate criteria, etc.).

The advent of efficient Multi-Level simulations in structure analysis processes is showing opportunities for implementation of “physically-based” approaches, in order to complement the physical validation. The aim is the mimic of the physic of the deformation, damage and failure processes, whilst avoiding the use of semi-empirical calibrated data. These allow computing Failure Loads, as well as to some extent to track the relevant damage predictions with respect to change in design variables.

Replacing semi-empirical approaches with physically-based ones aims at enabling:

- ✓ Virtual extension / exploration of the design space.
- ✓ Rapid assessment of materials and design principles, allowing new concepts.
- ✓ Reducing reliance on expensive and costly tests.
- ✓ Being right first time, with ultimately more decisions based on simulation results.

The potential of these advanced models will be illustrated through recent Airbus applications.

2 Progressive Damage Analyses

2.1 Industrial requirements

High-fidelity simulations require that intrinsic damage and failure processes are firstly understood, and secondly modelled and identified in a synergetic manner. Composites develop diffuse (e.g., micro- decohesion and cracking) or discrete (e.g., macro- failure and delamination) damage that interact with each others. Failure results from a complex process, which is a characteristic of a given material set, process, stacking sequence etc.

Failure analyses shall address ‘first-ply’-failure in the laminate (FPF), considering all possible failure modes, a “physical” scheme of ply discounting and failure progression, after FPF and last, but not least, a definition of ultimate laminate failure.
Physically–based Progressive Damage Analyses describe the progressive deformation, damage and failure mechanisms occurring, in a representative structure element, and are thought to be accurate and predictive. A plethora of approaches developed in-house or by key Institutions or University are now reaching a significant level of maturity and were assessed in the context of an industrial sizing process. It is not the aim of this discussion to review merits of each. Today, so-called meso-scale models, enhanced with micro-scale information, seem to offer the best compromise in terms of adherence to physical processes and control of computational solutions and results.

It shall be noted at this stage that a key parameter for industrial acceptance of a physical model is the extent of sizing criteria covered, and to what degree of fidelity (i.e., robust and physical). But not only, as the industrial context naturally implies constraints such as having a high computational robustness (the calculation runs, each time, and provides the correct results), ease of integration and adaptation capabilities, community acceptance as well as ease of identification and validation to name but a few. The fulfilment of these criteria may in fact constitute a significant step into the definition (or adaptation) of the physically-based progressive damage analysis.

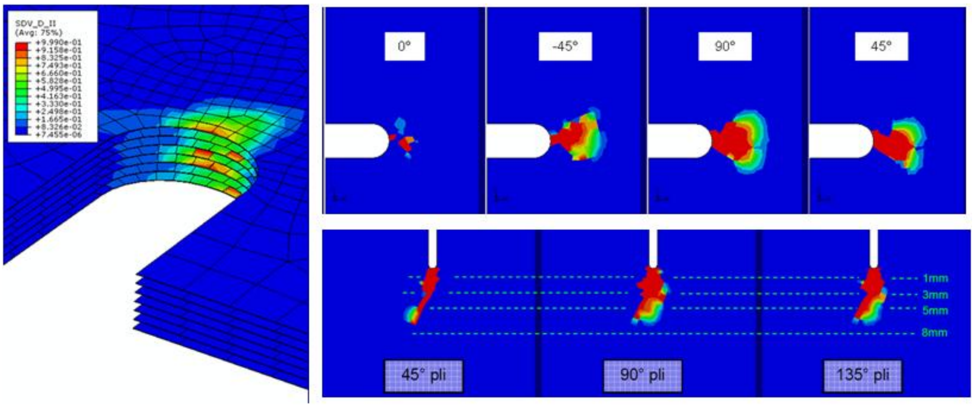
The industrial requirements can be summarized as:
- From one set of tests for the identification of the Deformation, Damage and Fracture parameters,
- Reach high-fidelity predictive capabilities, of considered technologies, over all range of industrial and non-conventional design criteria,
- Satisfying the Structure Analysis requirements.

2.2 State-of-the-Art

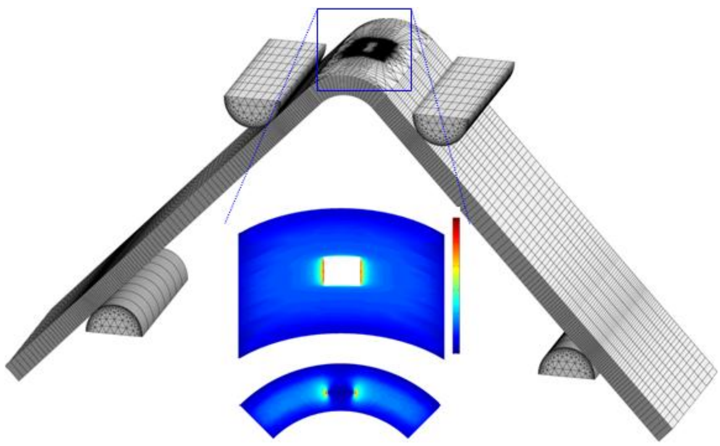
Progressive Damage Analyses, in-house or developed with key partners, have been used in sensitivity studies of design principles, and for the sizing of selected design features. These include plain/open-hole scale effect simulations, skin-stringer panels under impact, disbonding and delamination studies, panel notch strength and toughness, corner unfolding with and without characteristic defects etc. Typical examples are shown in figure 1.

Analysis of Large-Damage Capability [1]:

Analysis of Notch Strength and Toughness,



Analysis of Effect of Defects on L-angles:



Disbonding and Delamination Studies :

Figure 1. Examples of application of progressive damage models to structure sizing

2.3 Perspective

These case studies allowed developing a deep understanding of the use of advanced models. Noted successes over the years include the calculation of in-plane and out-of-plane features as well as high-strain gradient areas, but there are still challenges ahead for large-scale implementation into sizing processes. Interestingly, it is the success and the rapid acceptation of these novel approaches that highlighted potential improvements in order to realize necessary return from investments.

Firstly, the bridge for assessing the effects material, technology and process changes have on the structure performance still need to be confirmed. Indeed, each *significant* change in constituents, impregnation or processing route need capturing into the physical model(s) and consequently also to be characterized. A mixed micro-/meso-model approach is typically followed in order for the predictions to be sensitive to these effects.
However, the scalability of scale-specific models is often limited, meaning that it may be consuming to exchange information between the models. In addition, advanced models often require scale-specific interpretation of model parameters, from scale-specific physical tests. As a consequence, identification and validation of the different model sensitivities may require large and complex experimental test campaign to be run, and the specific interpretations require significant skilled resources, imparting the development time and cost. This remains to be balanced with the potential savings that can be made with screening innovative material and process concepts.
It results that there exists potential for standardization and guidance of some tests for the measurement of non-equivocal deformation, damage and fracture parameters, to be considered at the same time as the development of *integrated* multi-scale models.

Secondly, if real achievements are noted for the simulation of some design criteria, this cannot yet be said for features having complex damaging failure modes (e.g., coupled in- and out-of-plane damage). Indeed, highly non-linear, or coupled, damaging behaviour are particularly challenging even for the most elaborate advanced models.
The emphasis shall be on the robustness of the calculation approaches, i.e., Numerical robustness (obtaining a correct solution without computational penalties) and Physical robustness (reaching consistency and understanding of calculated internal data).

Last but not least, and to be fully effective, there is an industrial need to have the possibility to include in the simulation the effect of (process-specific) defects, stochastic and durability. In this context, covering the full set of design criteria, for a technology such as pre-impregnated unidirectional tapes, with an integrated suite of physically-based models is a good challenge.

3 Drivers for current developments

The development of Progressive Damage Analyses is being made taking into account the requirement of the sizing process, allowing for a reduction of development time and costs:

- modelling with confidence the deformation, damage and fracture processes with a unique set of model parameters for all criteria,
- developing a set of synergetic approaches having computational costs adapted to the need (i.e., trade-offs between accuracy and computational cost),
- bridging the scales, allowing for a validation at all level of the test pyramid.
- implementation in robust tools for extended enterprise deployment (Plug and Play).

4 Conclusions

The increased use of simulation technology facilitates airframe developments.

Virtual Testing aims to explore innovative concepts by simulation in lieu of costly and time consuming details tests.

Multi-scale analysis, when completed with physically-based deformation and fracture simulations, becomes a sizing tool allowing screening and early assessment of innovative designs. Industrial applications are reported.

References

[1] Schenker A., Vidal S., Risse, L. and Mahdi S. Aircraft Composite Structures – from In-Depth Testing To Physical Modelling in *Proceeding of 16th International Conference on Composite Structures, ICCS 16, Porto, (2011)*