Finite Element Modelling of Very Large Composite Aircraft Wings

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Abstract

We present a methodology for structural simulation of very large composite structures. The methodology does not assume the use of a specific failure model, but rather focuses on establishing a framework that enables failure analyses on full-wing models with a complexity comparable to real wings in large passenger aircraft. We show that it is possible to analyse very refined wing models up to complete failure.

1. Introduction

Modern composite structures, such as aircraft wings, are typically very complex structures 10s of meters long (**Error! Reference source not found.**). This is the scale at which design engineers insist that numerical damage models are required, with the constraint of being as accurate as possible.

The damage tolerance of these large structures is often the consequence of damage processes that become unstable at very small ply-level scales of o(0.1 mm) (**Error! Reference source not found.**). Researchers therefore often insist that damage models need to be developed at this scale, with the constraint of being as scalable as possible.

There is a wide gap between the two positions described above, and the outcome is that failure models for composites, including those available in commercial software, tend not to be readily usable for the design and analysis of very large composite structures (such as an entire aircraft wingbox).

However, to enable multiscale analyses, hot-spots need to be identified at the large scale. This paper demonstrates this, as well as proposing, detailing and verifying a viable alternative multiscale composite material model failure assessment methodology.

Figure 1: Very large aircraft wingbox (Airbus A350) [1].

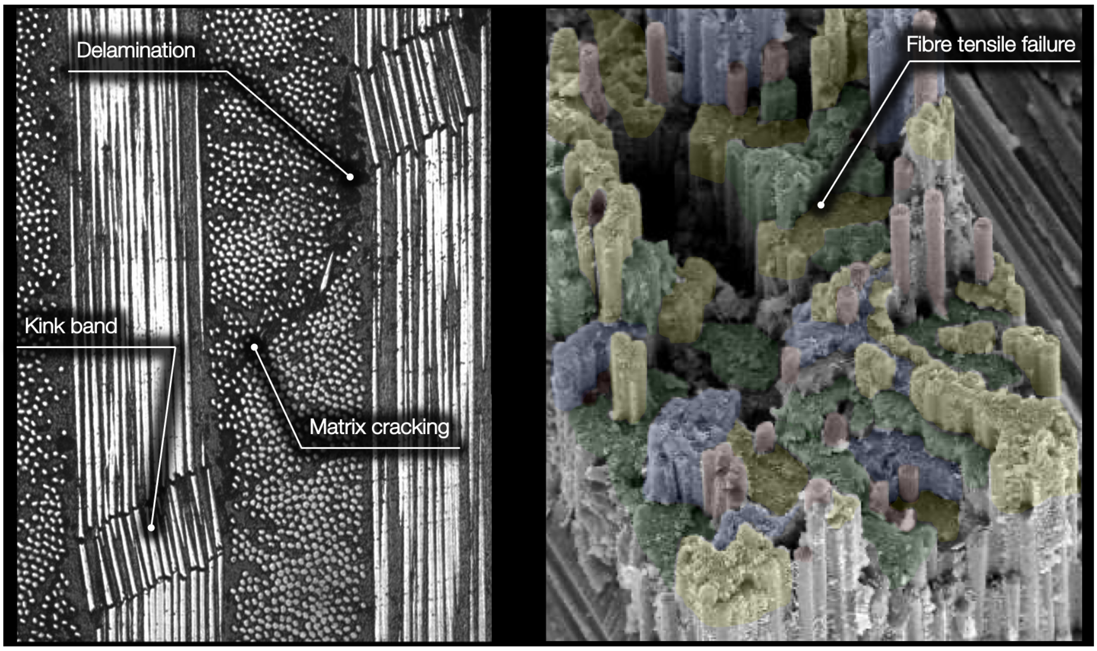

Figure 2: Typical failure modes in composites at the ply scale [2].

2. Modelling framework for very large models

We propose a framework (**Error! Reference source not found.**) whereby high-value data is calculated directly in the HPC cluster during the analysis, and the design engineer only needs to render high-value data suitable for decision making, including identifying hot-spots for sub-modelling [3-6]. So that these hot-spots are modelled using the exact same material models regardless of the scale and material idealisation in the analysis, the implementation of material models does not assume any specific interface (**Error! Reference source not found.**).

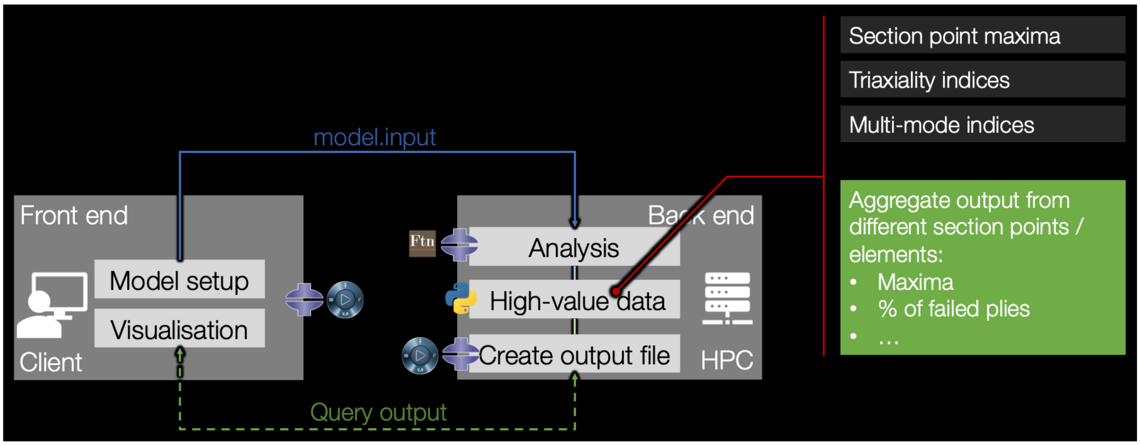

Figure 3: Modelling framework designed around the need to extract high-value data in HPC [4].

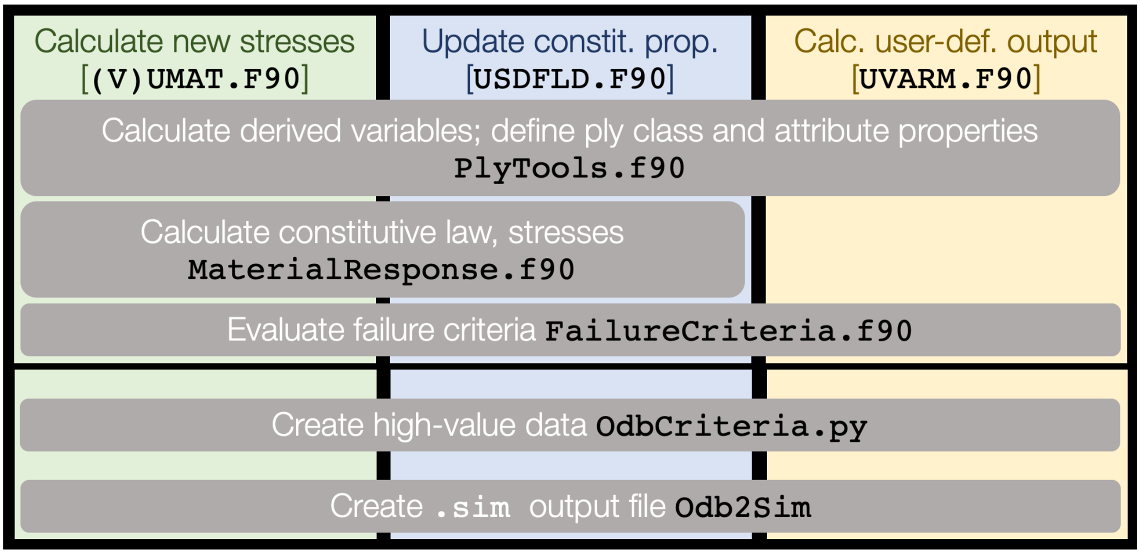

Figure 4: While different interfaces are differently suited for different scales of analysis and for different idealisations of the material, the modelling framework is designed to always use the same underlying code, hence ensuring a harmonised modelling approach across the various scales [4].

3. Application: wingbox

We created a detailed CAD model of an aircraft wingbox based on the Airbus A350 and using only data that is publicly available (**Error! Reference source not found.**). The model contains 81 full-sized components. These include CFRP parts (upper and lower covers, front and rear spars, 22 upper and 22 lower stringers) and aluminum parts (33 ribs).

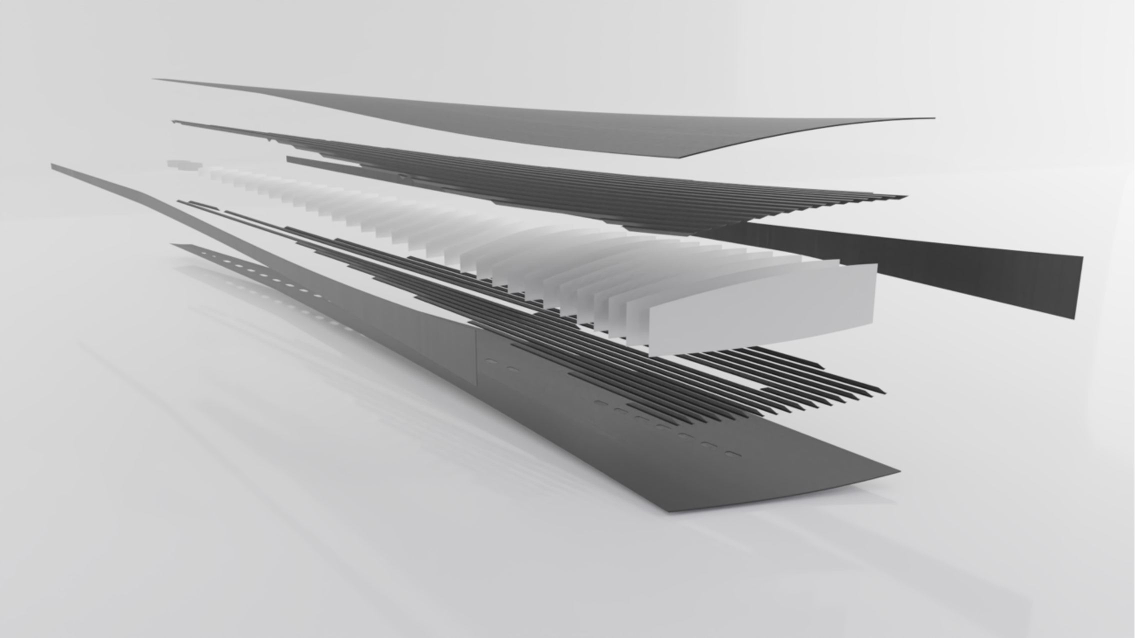

Figure 5: CAD model of a realistic aircraft wing [4].

We fixed the wing at the root and applied a uniform distributed normal pressure to the covers. We ran the FE analysis using Abaqus Implicit with non-linear geometric behaviour on an HPC cluster.

4. Results for full wingbox model

The full wingbox model ran successfully up to complete structural collapse. We found that the wing collapsed due to unstable compressive failure of the upper cover near the root of the wing (**Error! Reference source not found.**), and that this failure started due to local buckling near the rear spar.

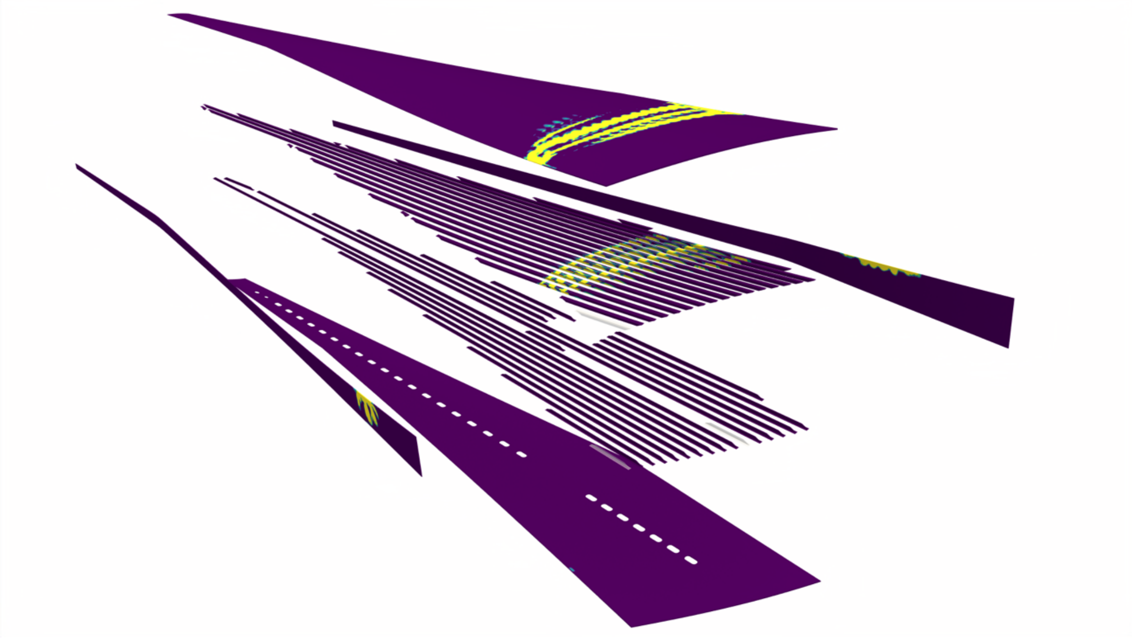

Figure 6: Fibre kinking damage variable (maximum cross section) at end of analysis for the full wingbox model [4].

5. Multiscale analysis: setup

Based on the hotspot identified by the full wingbox model (**Error! Reference source not found.**), we created models at two further scales (**Error! Reference source not found.**). We ran all models using sub-modelling so that the boundary conditions came from a suitable larger-scale model.

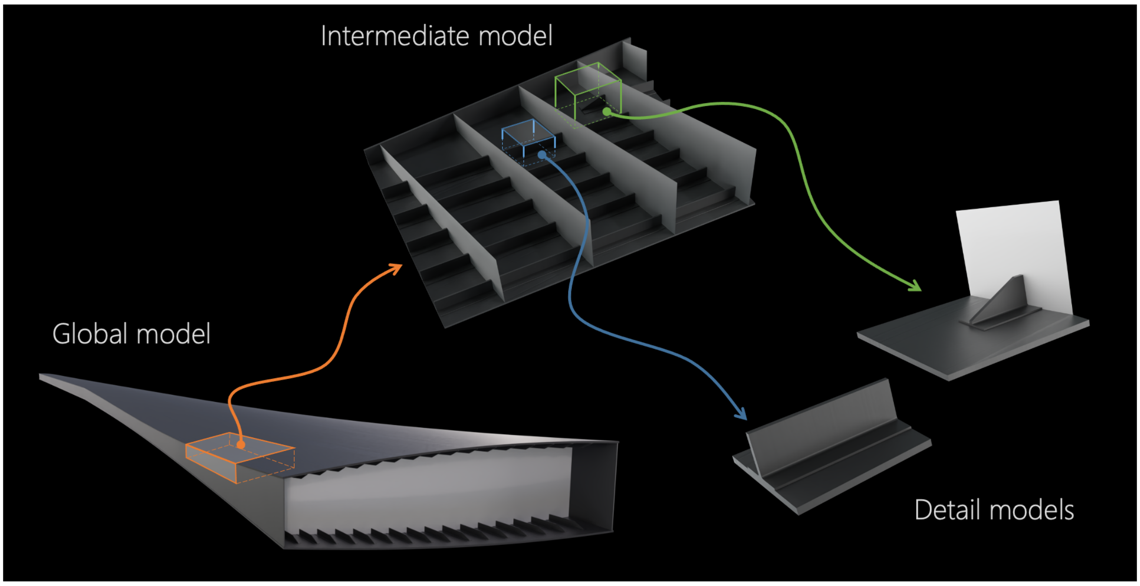

Figure 7: Multiscale analysis with 3 scales [4].

6. Multiscale analysis: results

The intermediate-scale model with surface *tied* contact interactions (between stringers and cover) exhibited a structural failure mode very similar to that of the full-scale

We ran each detail-scale model three separate times using suitable boundary conditions coming from all larger-scale models (**Error! Reference source not found.**).

To compare quantitatively the results all multiscale simulation settings, we plotted in **Error! Reference source not found.** the load experienced by the wing, as a function of the displacement of a suitable point in the cover chosen for experiencing large deflections due to the local buckling which initiated the failure process.

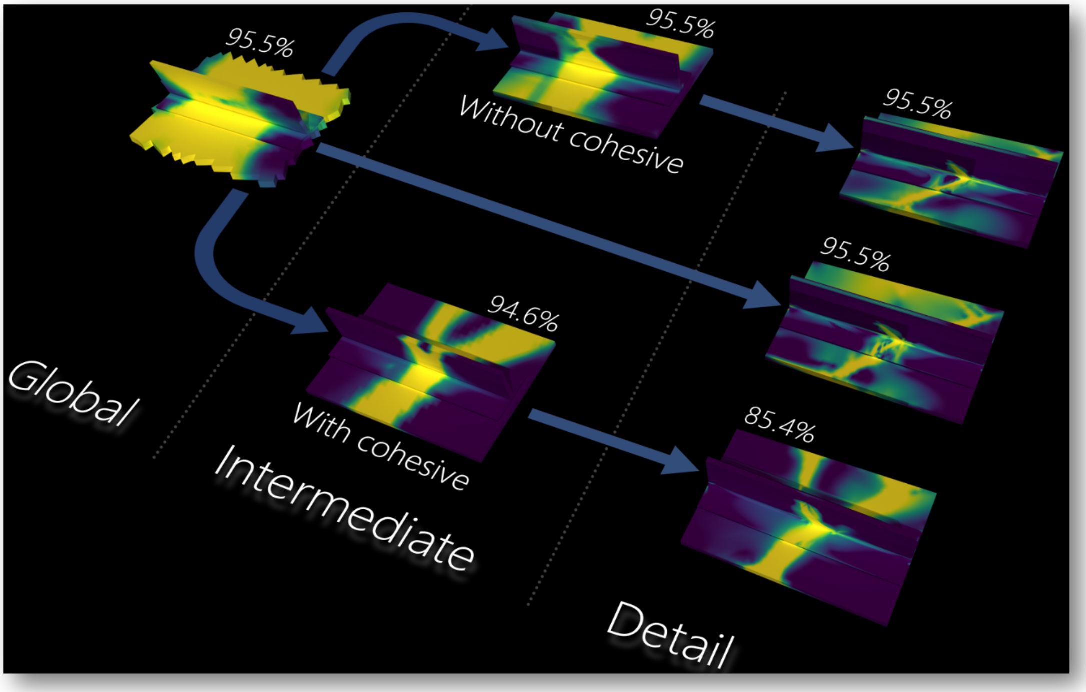

Figure 8: All multiscale simulation settings considered (the field shown is kink-band damage (maximum across section)) [4].

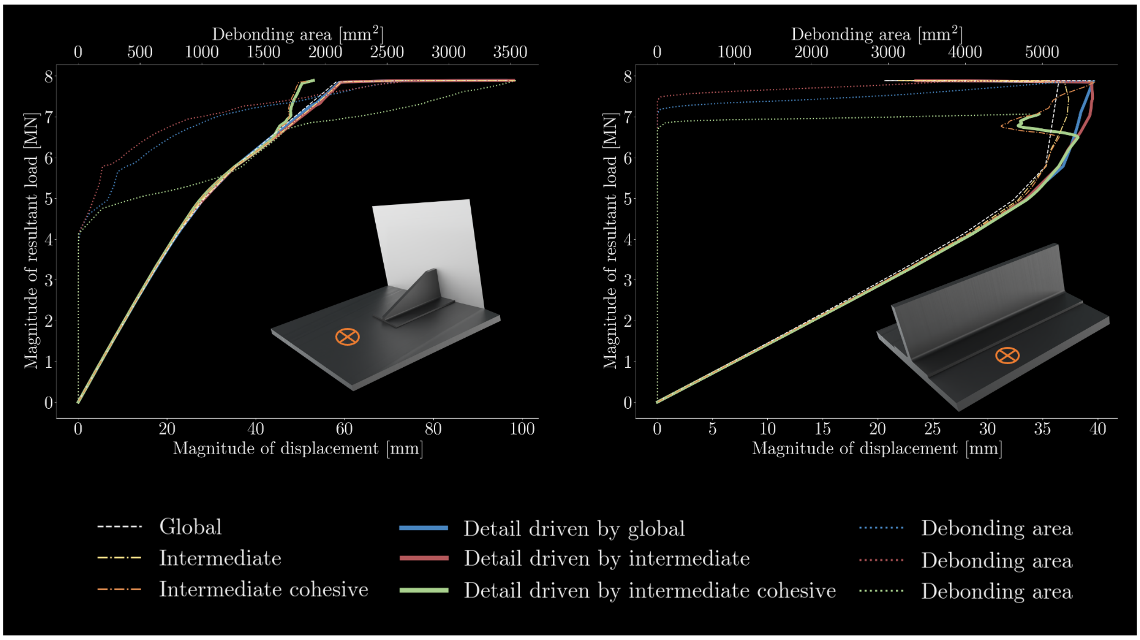

Figure 9: The various simulation settings lead to similar mechanical responses, even in the regions most affected by non-linear deformations. However, modelling debonding at the intermediate scale is needed to fully capture the deformation state in the cover during the later stages of the analysis [4].

7. Conclusions

In this work, we implemented a modelling framework for analysis of very large composite structures. Its key characteristics are:

- the numerical implementation works across various user interfaces;
- it employs back-end high-value data calculation (e.g. proportion of failed plies; coded output).
- it leads to manageable output files + data for decision making; and
- it is agnostic to actual failure model used.

We can conclude that this framework can be successfully used in models with 15M DOF for:

- extending predictions of full-wing models into the non-linear region, including full collapse of the wing;
- identifying hot-spots in the wing; i.e. regions which merit more detailed attention; and
- driving meaningful multiscale analyses for the hot-spots.

This work provides a foundation for (and constitutes a significant step towards) achieving virtual twins of very large composite structures. The interface for high-value data can be extended to include a plethora of specific types of high-value data suitable for the most varied situations. The multiscale analysis, sequential in this work, can be extended to be made concurrent or even adaptive [7].

8. References

1. Airbus, https://www.airbus.com/, last accessed 06-November-2023
2. Pinho ST, Darvizeh R, Robinson P, Schuecker C, Camanho PP, 2012, Material and structural response of polymer-matrix fibre-reinforced composites, *Journal of Composite Materials*, Vol: 46, Pages: 2313-2341, ISSN: 0021-9983
3. S. T. Pinho, S. Kocaman, R. Costa. Emerging numerical approaches for numerical design and optimisation of composite structures. *MECHCOMP7*,1-3 September , Porto, Portugal, 202
4. S. T. Pinho, M. Matos, R.O.S.S. Costa, A. Ibbotson, M. Ostergaard. Enabling multiscale analysis of very large composite structures. *COMPOSITES 2021*, 22-24 September 2021, Göteborg, Sweden
5. S. T. Pinho, R.O.S.S. Costa, M. Matos, A. Ibbotson, M. Ostergaard. Multiscale analysis of an aircraft wingbox . *ECCM-20*. 26-30 June, 2022, Lausanne, Switzerland
6. R.O.S.S. da Costa. Finite element methodologies for structural design and optimisation. *PhD Thesis*, Imperial College London, 2023
7. E.S. Kocaman, B.Y. Chen, S.T. Pinho, 2019, A polymorphic element formulation towards multiscale modelling of composite structures, *Computer Methods in Applied Mechanics and Engineering*, Vol: 346, Pages 359-387, ISSN 0045-7825