Progressive failure:
dynamic analysis for composite structures

A new computational methodology for progressive failure analysis of composite structures has been developed. The analysis utilises both implicit and explicit computational approaches. The transient dynamic algorithm is based on an explicit time marching technique. At each time step, a micromechanics-based computational module is used to examine micro-level damage in composite laminates. Accordingly, the mechanical properties of the composite constituents are updated based on the damage state at each finite element. This methodology can be successfully used to simulate a complete crash event including damage initiation, damage propagation and final failure of a composite structure subject to low or high velocity impacts.


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Finite element analysis of composites for crashworthiness is increasingly gaining attention in the automotive and aerospace industries. However, conventional industrial finite element codes have been challenged by the complex behaviour and variety of failure mechanisms in composite structures.

In a typical finite element analysis, failure is assessed at the macro-scale (lamina and/or laminate level). On the other hand, it is well known that the initiation of damage in composite materials occurs at the micro-scale (fibre/matrix level). Progressive Failure Dynamic Analysis (GENOA-PFDA) is an enhancement of commercial finite element codes based on computational composite engineering micromechanics [1]. It provides a reliable and accurate industrial software tool that can simulate progressive failure in composite components and structures subject to a wide range of static and dynamic loading conditions.

Methodology

GENOA-PFDA is based on the three main functional components:
1) Computational composite engineering micromechanics,
2) Com-mercial FEA software, and
3) Hierarchical damage tracking [1, 2].

In addition, the user can perform uncertainty analysis using a probabilistic module or optimise the design with respect to a given target function with the aid of an optimisation module.

Displacement, stress and strain fields in a structure are obtained from the finite element solution. The corresponding response fields at the laminate and lamina (macro) scales are calculated using enhanced classical lamination theory. Most of the commercial finite element programs operate strictly at this level. Because the initiation of damage in composite materials occurs at the micro-scale (fibre/matrix level), GENOA-PFDA utilizes the hierarchical approach illustrated in Figure 1. The hierarchical modelling reaches down to the micro-scale level through the subdivision of unit cells composed of the fibre bundles and

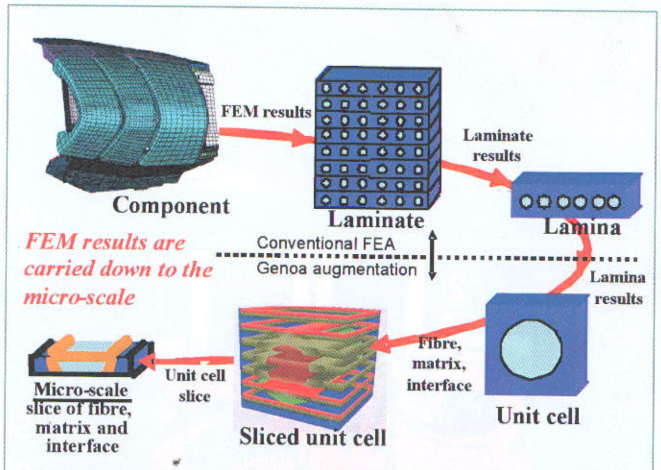

Fig. 1: Hierarchical modelling from the structural scale to the micro-scale - transmission of the FEA results at the structural scale down to the micro-scale

surrounding matrix material.
Stress-strain fields at the micro-scale are calculated based on the macro-scale results using the computational composite engineering micromechanics. The volume elements of the unit cell are interrogated for possible damage using a set of failure criteria, which is presented in Figure 2.

Micro-Mechanics Failure Criteria

1. Longitudinal tension
2. Longitudinal compression
3. Transverse tension
4. Transverse compression
5. In-plane shear (+)
6. In-plane shear (-)
7. Fibre strain limit
8. Modified distortion energy
9. Strain invariant failure theory
10. Normal compression
11. Custom criteria
12. Normal tension
13. Transverse normal shear (+)
14. Transverse normal shear (-)
15. Longitudinal normal shear (+)
16. Longitudinal normal shear (-)
17. Relative rotaria criteria

Delamination criteria
Unit cell damage criteria

Fig. 2: Fibre and matrix failure criteria applied at the micro-scale of a composite

Once damage at the unit cell level has been detected, GENOA-PFDA degrades the relevant fibre/matrix mechanical properties based on the rules of material behaviour and experience. The accumulation of damage at the micro-level eventually leads to the fracture at the lamina (macro) level. Because damage is tracked at the micro-scale, it is possible to have several types of damage in a particular ply. This detailed analysis distinguishes GENOA-PFDA from other commercial finite element codes and enables a high-fidelity simulation of the complicated composite failure phenomena.

Results and discussion

In this section, the low-speed impact of a 13 by 13 cm G30-500/R6376 woven composite panel is analysed using GENOA-PFDA and compared with experimental results [3] (Figure 3). The layers were arranged in the [45/-45/[0/90]2]S lay-up with a total thickness of 0.213 cm. The panel was clamped around the perimeter.

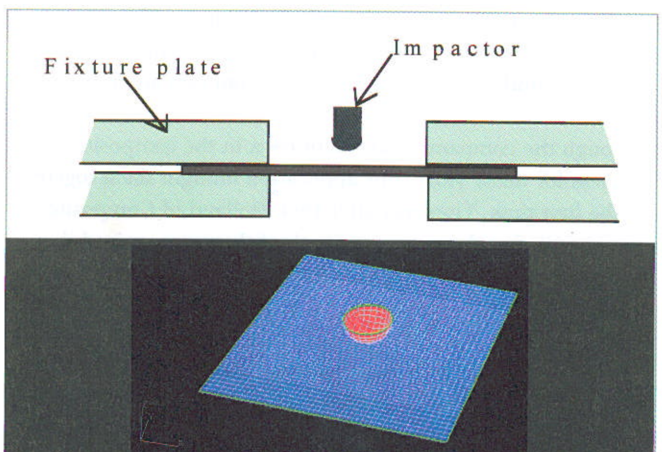

Fig. 3: Low-speed impact of the woven G30-500/R6376 composite panel: a) Experimental set-up, b) Finite element model.

The spherical impactor had a diameter of 2.54 cm and weighed 24.38 kg. The panel was impacted at a speed of 0.92 m/sec that resulted in the impact energy value of 10.28 J. The duration of the impact event was approximately 19.75 msec.

The GENOA-PFDA analysis predicts the initiation of damage at 1.6 msec (Figure 4). As can be observed in Figure 5, the contact force peaks at approximately 7 msec, before reducing to zero after approximately 20 msec. According to both the experiment and simulation, the maximum value of the contact force reaches approximately 408 kg. The simulated maximum deflection at the centre of the panel is 0.46 cm, which underestimates the experimental value of 0.51 cm by only 10% [3].

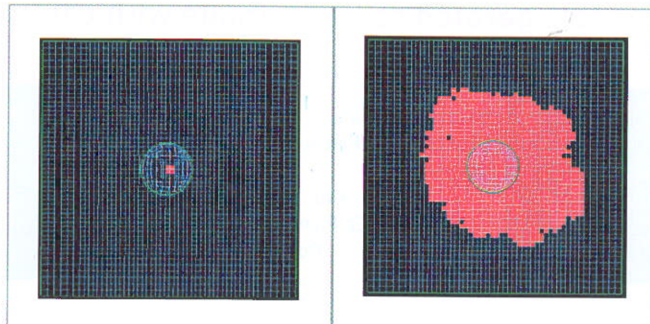

Fig. 4: Damage distribution throughout the woven panel:
a) Initiation at 1.6 msec, b) Propagation at 14.1 msec.

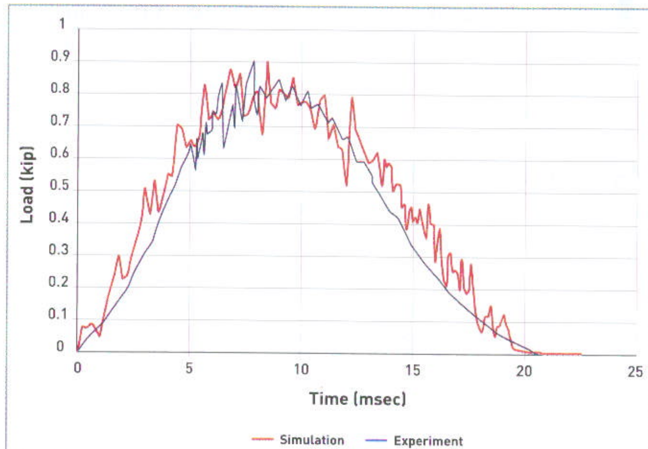

Fig. 5: Comparison between the experimental and simulated change of the contact force versus time

Conclusions

The new methodology is based on a step-by-step verification approach that ensures an accurate simulation of the composite behaviour at the micro- and macro-scale. The new approach was applied to the simulation of the low-velocity impact of a woven laminated composite plate. An excellent comparison between the measured and simulated contact force versus time histories was demonstrated, including the accurate prediction of the maximum value of the contact force and the qualitative picture of the damage state at various time intervals during the impact event. ■