EXPERIMENTAL AND MICROMECHANICS-BASED NUMERICAL ANALYSIS OF HIGH-VELOCITY IMPACT ON LAMINATED COMPOSITE PLATES

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Abstract
A computationally efficient model for the simulation of high-velocity impact events on composite laminated plate structures is developed, which utilizes a micromechanics-based model for the prediction of material properties and intraply failure. GENOA multi-scale progressive analysis is exploited, using calibrated micromechanical constituent properties in explicit FEA, to simulate impact event and determine the structural integrity of composite structures in terms of damage footprint and penetration energy. Impact experiments are also conducted on a high-velocity impact test bench, on woven IM-7/RTM-6 epoxy plates impacted by steel ball impactors (D=30 mm) with high velocities and energies reaching and exceeding the ballistic limit (v=60-100 m/s, E=200-500 J). Finally, the impact simulation results are successfully correlated with experimental results, and important conclusions are provided regarding the validity of the proposed modeling assumptions.

1 Introduction

The usage of fiber reinforced composites materials in aeronautical and aerospace applications has dramatically increased due to their excellent mechanical properties, like high specific stiffness and strength, resistance to corrosion and increased fatigue life to mention some. A major concern is, however, their poor performance under impact loading, such as hail stones, tool drops, runway debris, and so forth [1]. The impact behavior of composite structures is even more complicated at high velocity impacts, where the velocity and kinetic energy of the impactor approaches the penetration limit, thus setting new challenges for constituent models, computational structural dynamic models and experimental studies. One case of high-velocity impacts, which is the driver for the presented research, encompasses fractured blades from counter rotating open rotor (CROR) turboprop engines colliding on the fuselage structure, which mandates the development of reliable blade impact containment structures.

Limited experimental, analytical and meso-scale numerical studies [2]–[6] have been reported on this topic. Moreover, the available impact modelling methods for carbon fiber composites appear to be currently hindered by the lack of validated and robust material models for analysis. The current work aims to develop and validate a multi-scale finite element model, which involves a micromechanics-based composite material model using MCQ and GENOA software [7]. The inclusion of micromechanics enables the synthesis of composite properties using the constituent properties (fiber/matrix) as input. Conversely, it enables calculation of microstresses and failure prediction at the fiber/matrix scale. The incorporation of the micromechanics model reduces the amount of testing and material characterization campaigns required to model plies and laminates of various fiber architectures and/or fiber volume ratios. But most importantly, it provides the capability to include strain-rate effects into the analysis, at the matrix constitutive models, thus reducing the number of required characterization tests and enhancing the robustness of the constituent model.

Basic UD specimens of identical fiber/matrix system have been fabricated and tested to extract lamina properties and to back-calculate the fiber matrix properties, which provide the input of the multi-scale model. The capability of the multi-scale model is evaluated on woven laminated IM-7 Carbon/RTM-6 strip specimens and plates. The woven specimens are tested in three-point bending and the woven plates are impacted with 30mm steel balls at high velocities below and above the ballistic limit. Finally, multi-scale progressive failure explicit dynamic FEA analyses are performed to assess impact response and predict progressive intraply damage and interlaminar fracture evolution. Correlations with high-velocity impact tests and post-impact NDE validate the capability of the multi-scale FEA model to determine the structural integrity of the impacted composite structures in terms of (1) type of failure (delamination, matrix cracking, etc.), (2) damage footprint (pattern and size), (3) penetration energy (ballistic limit).

2 Multi-scale Numerical Model

The composite micro-mechanics model is provided by MCQ and GENOA software. In the bottom down analysis cycle the micromechanical stresses of a representative volume element (unit cell) yield the damage initiation and damage progression in the micromechanical constituents (fiber/matrix). In the bottom-up synthesis cycle, the degradation of the micromechanical constituent properties due to damage propagation is then translated back to degraded macro-mechanical properties. Strain-rate effects on the matrix properties are incorporated in both the failure analysis and synthesis cycles. The aforementioned process is rigorously demonstrated in Figure 1.

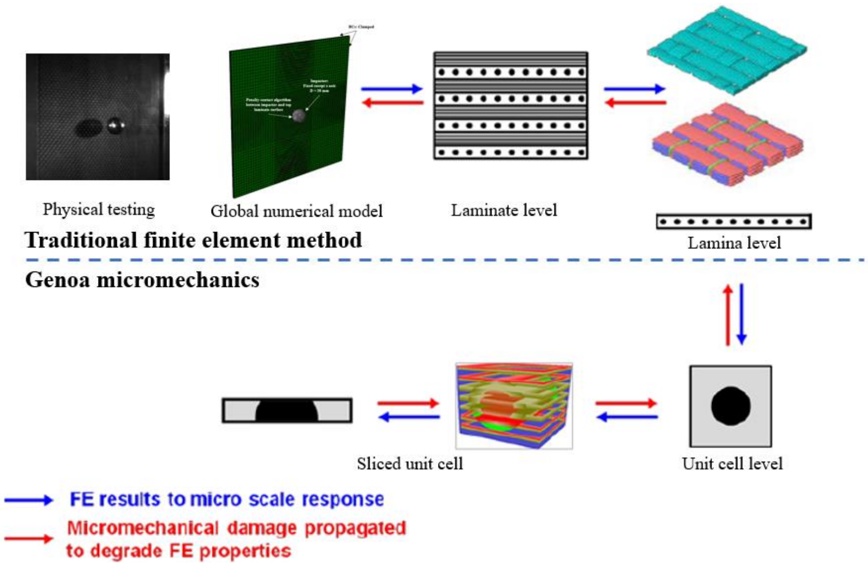


Figure 1. Graphical presentation of the multi-scale progressive failure analysis.

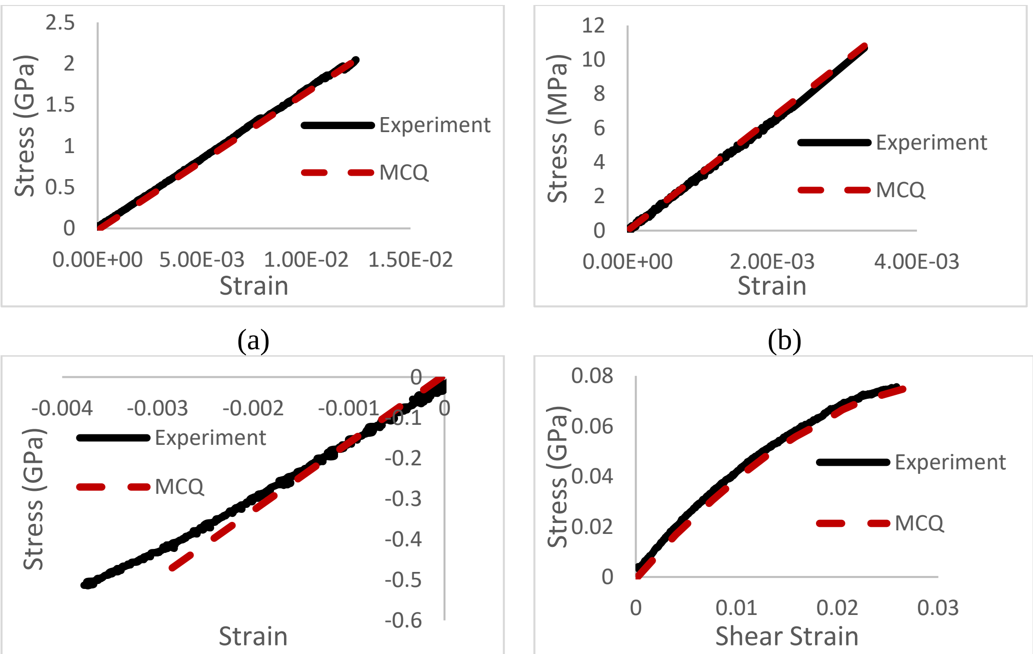
2.1 Calibration of Constituent Material Properties

In composites, damage initiates at the fiber/matrix or constituent level. However, it is very difficult to obtain the transversely anisotropic material properties of the fibers and the isotropic material matrix properties by testing procedures. As a result, MCQ-Composites is used to reverse engineers in-situ constituent mechanical properties for both the fibers and the matrix (isotropic/anisotropic) by utilizing a micromechanics-based optimization approach. Matrix nonlinearity can also be reverse engineered using in-plane shear stress–strain data obtained from the test (ASTM D3518). Rule-of-mixtures-based micromechanical formulation is used by MCQ Composites to calculate mechanical properties of lamina from constituent fiber and matrix properties. In addition, manufacturing defects, such as void, are considered when computing fiber and matrix contribution to the mechanical properties.

Stiffness and strength properties of the constituents materials were calculated according to [7] and are illustrated in Table 1. Micro-mechanics material calibration was verified by performing MCQ analytically on four different classical loading conditions: longitudinal tension and compression, transverse tension and in-plane shear. Good agreement between analytical solution and test is achieved as shown in Figure 2. Moreover, a virtual three-point bending test was performed on woven specimen and the results (Figure 3) are almost identical confirming and validating the developed multi-scale finite element model.

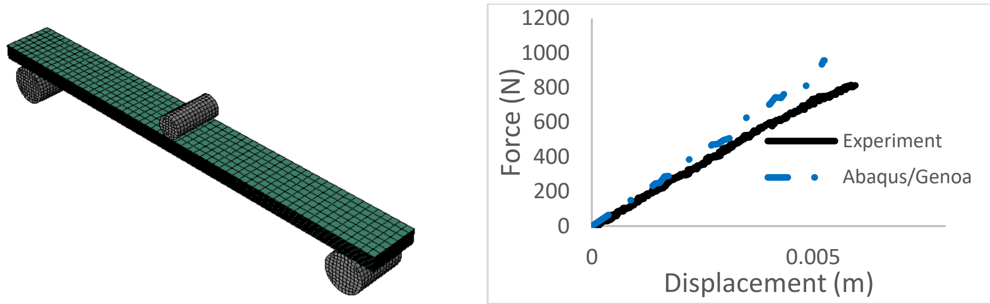
Table 1. Reverse engineered (In-Situ) fiber matrix properties. (a) IM-7. (b) RTM-6.

	IM-7	RTM-6
E_{11} (GPa)	288.73	3.32
E_{22}=E_{33} (GPa)	3.29	3.32
G_{12}=G_{13} (GPa)	93.32	1.12
G_{23} (GPa)	0.92	1.12
v_{12}=v_{13}	0.48	0.48
v_{23}	0.48	0.48
S_T (GPa)	3.61	0.09
S_C (GPa)	1.40	0.17
S_S (GPa)	-	0.45



(c) (d)

Figure 2. Material modeling verification through static tests on UD specimens. (a) Longitudinal Tension. (b) Transverse Tension. (c) Longitudinal Compression. (d) Shear Tension.



(a) (b)

Figure 3. Multi-scale progressive failure simulation of three-point bending on woven specimen. (a) 3-D continuum explicit FEA model. (b) Force-Displacement curve.

2.2 Dynamic Finite Element Model

A series of virtual impacts tests has been conducted with GENOA multi-scale progressive failure analysis software, by using the calibrated micromechanical constituent properties. Moreover, analyses were performed by coupling the ABAQUS EXPLICIT solver with the GENOA VUMAT in order to (1) predict ballistic limit and residual velocity; and (2) perform damage assessment (damage type and footprint).

The projectile was modeled using rigid shell elements (R3D4) with a diameter of 30 mm, while the 300x300x5 mm plate was modeled using continuum solid elements with reduced integration (C3D8R) and appropriate boundary conditions were defined as shown in Figure 4. Global and local coordinates were defined to account for ply orientations and correctly describe the laminate and material behavior. All the nodes of the plate edge were fixed in all directions (x, y, z) to simulate the experimental clamped conditions. The 5 mm thick laminate was consisted of 10 plies and was modeled in Genoa using micromechanics formulation and the appropriate unit cell for woven. To ensure an adequate element size and number in the vicinity of contact region, an edge-biased technique was applied.

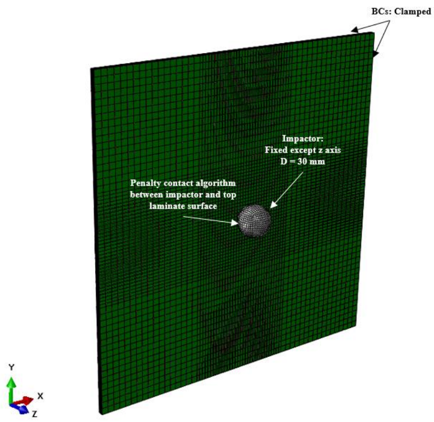


Figure 4. 3D continuum FE model used for the numerical validation of impact event.

Strain-rate effects of RTM-6 were taken into account for tension and compression according to [8]. The simulation of ballistic impacts, which commonly involves the perforation of the target, requires the use of a finite element erosion criterion. An element was deleted when fiber microstress exceeded fiber strength and when transverse macrostrain exceeded 0.2 for elements with excessive distortion. Delamination is modeled using cohesive interaction with properties calibrated from fracture tests and listed in Table 2.

Table 2. Material parameters used in the cohesive interaction.

	Mode I	Mode II
Interlaminar Strength (MPa)	35	40
Interlaminar Fracture Toughness (KJ/m^2)	0.604	3.333

3 Experimental Facility

The laboratory is equipped with a functional Impact Test Bench (ITB), which mainly consists of three main parts: **i)** A pre-charged nitrogen gas gun. A sturdy gas gun (Figure 5) with a 10lit pressure vessel, 3m barrel and 60mm diameter bore is capable of launching any spherical projectile up to 50mm diameter and up to 972km/h (velocity was tested & verified for a 25mm diameter ice ball). The repeatability of impactor velocity and trajectory was thoroughly tested and calibrated for each impactor case (for different masses and velocities), in order to achieve accurate results which are further investigated by efficient micromechanical numerical models.

Figure 5. Impact Gas Gun

ii) Measurement devices and supporting apparatus. A high precision digital pressure gauge (Omega DPG1000DAR) for accurate measurements and repeatable impact velocities is located on the vessel. The entire impact event is captured by a high speed camera (Photron SA4) with typical 50k-100k fps capacity (Figure 6a) and two chronographs (Chrony M-1) measure both the launching and the penetration velocity at each impact case (Figure 6b). The impacted structure is monitored using SoA equipment. Strain gauge rosettes (LDT1-028K Piezosensors; high voltage capacity and high strain rate) are used for monitoring target's post-impact response. Sensor signals are captured using NI PXI 6070E at 10k samples/sec. A custom-made LabVIEW VI has also been developed to eliminate human error and ensure that all the apparatus is properly triggered at each impact experiment.

(a) (b)

Figure 6. Measurement devices and supporting apparatus. (a) High-speed camera. (b) Chronographs for measuring launching and penetration velocity.

iii) Non destructive testing apparatus. The lab has access to the Ultrapac II by Mistras Group (Figure 7a), which provides reliable C scans and is used for assesing pre- and post-impact condition of the impacted structures. The post-impact condition (i.e the size of the delaminated area) is schematically validated by micromechanical models. For complex composite structures such as sandwich panels and leading edges, an ultrasonic set-up of pitch-catch is conducted using the Olympus BondMaster 1000e+(Figure 7b). The bond condition beneath the two probe tips (elements) will affect the characteristics of the acoustic energy that is transmitted between the two tips, hence the device is used for the investigation of delaminations and debondings.

(a)

(b)

Figure 7. Non destructive testing apparatus. (a) Ultrapac II by Mistras Group. (b) Olympus Bondmaster.

The ITB was already employed by two Cleansky projects which were efficiently closed. The gas gun has been already employed to perform an adequate number of experiments, using both hailstone and steel projectiles of various diameters, per project requirements. As for the impacted targets, flat plates, thick sandwich plates and leading edges were mounted and successfully tested.

4 High-velocity Impact Results

A series of woven IM-7/RTM-6 plates with volume fraction 46% were fabricated using resin transfer molding (RTM) and tested under the below conditions:

1. Two impact tests with a 30 mm steel ball at 56 m/s (below ballistic limit).
2. Two impact tests with a 30 mm steel ball at 80 m/s (ballistic limit).
3. Two impact tests with a 30 mm steel ball at 96 m/s (above ballistic limit).

Damage footprint and penetration energy were compared to assess the accuracy of the proposed multi-scale finite element model, that attempts to estimate the impact resistance of the woven composite laminate. As shown in Figure 8-Figure 10, the numerical impact damage has the same shape and size with the non-destructive evaluation even in case of barely visible damage (case 1). Post-processing of matrix damage visualization was performed in GENOA GUI. Figure 11 shows representative snapshots from the test and the analysis, which are almost identical, ensuring the validity of the proposed model. Residual velocity (case 3) and ballistic limit were captured precisely as illustrated in Table 2. Thus, the consideration of strain-rate effects of RTM-6 proved to be crucial for the accurate modeling of high-velocity impact on composite structures, as illustrated by the exact predictions of damaged area and residual velocity.

Table 3. Prediction of ballistic limit and residual velocity.

	Experiment	Simulation
Ballistic Limit (m/s)	80	75
Residual Velocity (m/s)	59.64	60.07

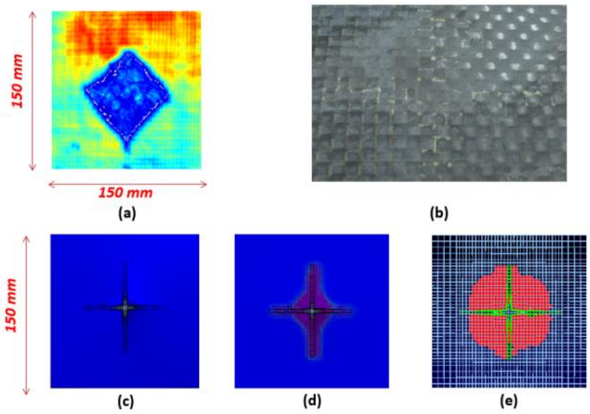


Figure 8. Correlation of damage footprint of impacted plate at 56 m/s (case 1). (a) Post-Impact C-scan. (b) Front side of the impacted plate. (c) Fiber damage (Deleted Elements). (d) Delamination (Cohesive). (e) Matrix damage.

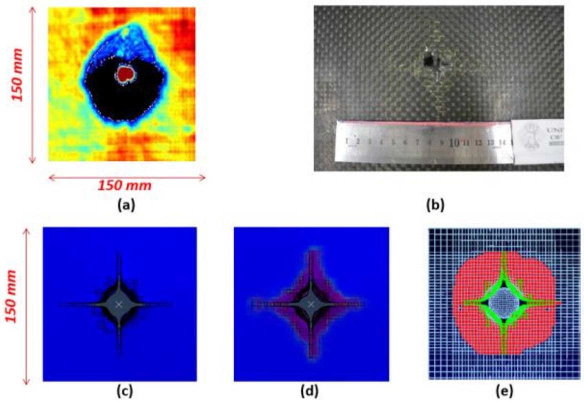


Figure 9. Correlation of damage footprint of impacted plate at 80 m/s (case 2). (a) Post-Impact C-scan. (b) Front side of the impacted plate. (c) Fiber damage (Deleted Elements). (d) Delamination (Cohesive). (e) Matrix damage.

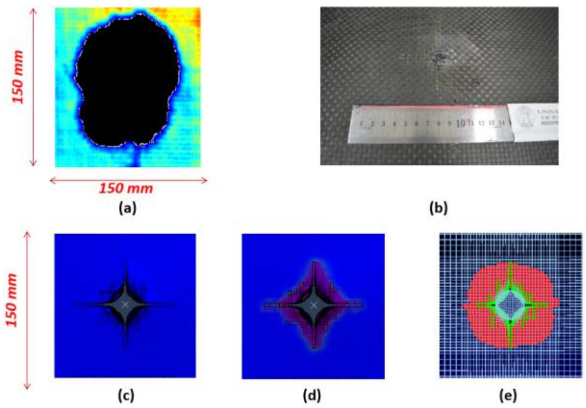


Figure 10. Correlation of damage footprint of impacted plate at 96 m/s (case 3). (a) Post-Impact C-scan. (b) Front side of the impacted plate. (c) Fiber damage (Deleted Elements). (d) Delamination (Cohesive). (e) Matrix damage.

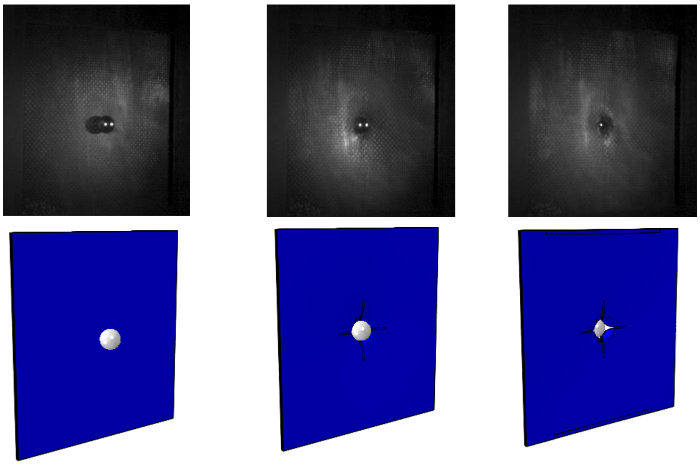


Figure 11. Screenshots of impact test and numerical impact simulation on the woven carbon/epoxy plate 300x300x5mm with 30mm steel ball at 96 m/s.

5 Conclusions

A number of impact tests were simulated with a multi-scale finite element model in high velocities and energies reaching and exceeding the ballistic limit. The IM-7/RTM-6 woven laminate was modelled using micromechanics formulation with the inclusion of strain-rate effects of RTM-6 and the finite element model was validated with experimental results considering both residual velocity and damage extent with excellent results. It was considered that these experimental results were adequate to calibrate the numerical model.

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