Low-Velocity Impact Analysis of Composite Plates using the Hashin 3D Criterion and Layer-Wise Models

Materials Research Proceedings 69 (2026) 1171-1175 https://doi.org/10.21741/9781644904251-201

Low-Velocity Impact Analysis of Composite Plates using the Hashin 3D Criterion and Layer-Wise Models

Marco PETROLO[1,a *], Matteo FILIPPI[1,b], Erasmo CARRERA[1,c], Chiara FRANCESCHINI[1,d] and Elisa TORTORELLI[1,e]

[1]MUL2 Lab, Department of Mechanical and Aerospace Engineering, Corso Duca degli Abruzzi 24, 10129, Torino, Italy

[a]marco.petrolo@polito.it, [b]matteo.filippi@polito.it, [c]erasmo.carrera@polito.it, [d]chiara.franceschini@polito.it, [e]elisa.tortorelli@polito.it

Keywords: Carrera Unified Formulation (CUF), Low-Velocity Impact, Higher-Order Structural Modeling, Continuum Damage Mechanics, Delamination

Abstract. Numerical simulations are an essential tool for predicting structural response under low-velocity impact and for damage evolution. The present work investigates the low-velocity impact (LVI) response of composite laminate plates by applying the Carrera Unified Formulation (CUF) for structural modelling combined with a fully three-dimensional (3D) Hashin failure criterion for damage evaluation. Previous studies have employed two-dimensional (2D) Hashin criteria, combined with cohesive zone models, to detect intralaminar and interlaminar damage. However, such approaches neglect out-of-plane stress components, which are critical in impact scenarios. The methodology discussed overcomes this limitation by adopting the 3D Hashin criterion within each ply, thereby allowing all six stress components to be included and providing a more accurate prediction of intralaminar damage and interlaminar delamination activation. The numerical model is developed within the CUF framework, using higher-order structural theories based on Lagrange polynomial expansions and a layer-wise representation through the laminate thickness. The results highlight the accuracy of the proposed approach and its computational cost advantages.

Introduction

Impact response is one of the most critical loading cases for the lightweight, layered structures widely used in aerospace. LVI, in particular, are localized events that can introduce intralaminar and interlaminar damage that is difficult to detect visually. As a consequence, the residual strength of the structure is reduced. Numerical simulation helps reduce costly testing and enables rapid sensitivity studies to optimize the design. This, in turn, allows prediction of damage scenarios and stiffness degradation over time. Computational approaches for damage simulation are generally divided into two main categories. Discrete damage models, such as those based on cohesive zone methods (CZM) [1], provide detailed damage representation but are often computationally demanding. As an alternative, the continuum framework employed in [2] facilitates efficient damage simulation with reduced numerical overhead. This study is motivated by the need for a fast, computationally efficient tool to analyze impacts on composite structures. The advantages of using the Carrera Unified Formulation (CUF) in this context lie in achieving 3D fidelity at reduced computational cost. By coupling CUF with explicit dynamics and progressive damage models, it is possible to obtain a rapid, robust, and accurate simulation tool for impact problems.

Structural theories and damage model

The structural theories adopted in this paper are based on the Carrera Unified Formulation (CUF) [3], which employs higher-order Lagrange polynomial expansions and yields a layer-wise representation through the laminate thickness. CUF enables the derivation of 1D and 2D theories thanks to a compact notation by representing the displacement fields, over the cross-section for beams and through the thickness for plates and shells, as basic functions whose type and order are arbitrary. The three-dimensional displacements in the layer-wise 2D model adopted in this work can be expressed as:

$$u(x,y,z) = F_\tau(z) N_i(x,y) u_{\tau i}, \qquad \tau = 1, \ldots, M, \qquad i = 1, \ldots, N \tag{1}$$

That is, as the product of nodal displacements $u_{\tau i}$ for the expansion function $F_\tau(z)$ of M terms, which approximates the kinematics through the thickness of the plate, and for the 2D shape function $N_i(x,y)$.

The damage model [4,5] is divided into a criterion for which the damage is activated and a model for the evolution of this damage. The 3D Hashin criterion, which accounts for failure in both fibers and matrix, predicts damage initiation under compression and tension. Here, the 3D Hashin model is adopted for fiber tension and matrix and fiber compression. Only for matrix compression, the Puck criterion [6] is considered. Once the criterion for initiating failure is triggered, the subsequent progression of the damage follows a linear pattern, with the material stiffness decreasing until final failure. Using a unified subscript $P \in \{ft, fc, mt, mc\}$ to represent the four modes of damage, d_P is a parameter governing the evolution of damage in each mode. The constitutive elastic stress-strain relation during the damage evolution can be written as:

$$\sigma = C_{dam} \epsilon \tag{2}$$

where C_{dam} is the stiffness matrix in the damage state, function of damage parameters d_P.

Numerical examples

The first numerical example presents a multibody analysis of a spherical impactor (diameter 16 mm) striking a square, linearly elastic composite plate with a side length of 100 mm. The composite is modeled as a quasi-isotropic laminate with a stacking sequence $[90/45/0/-45]_{2s}$ and a total thickness of 2 mm. The material system is IM7/8552 CFRP; see Ref. [7], Table 1, for material properties. The plate is fully clamped along its edges, and the impactor hits the center with an initial velocity of 5 m/s.

Different CUF models are employed, characterized by increasing orders of Lagrange expansion through the thickness, denoted CUF-LE*x*, where *x* is the expansion order. In addition, a CUF model with multiple linear expansions per ply (CUF-3LE1/ply) is examined. Model details are provided in Model 1 (Table 1).

Figures 1 and 2 show the stress distributions from the CUF models near the center of the plate, benchmarked against a standard ABAQUS 3D FEA [7]. The numerical results indicate that in-plane stresses predicted by CUF are in excellent agreement with the ABAQUS solution (Fig. 1). By contrast, the interlaminar shear stresses (Fig. 2) are more challenging and require either higher-order through-thickness expansions or multiple linear expansions per ply to be captured accurately.

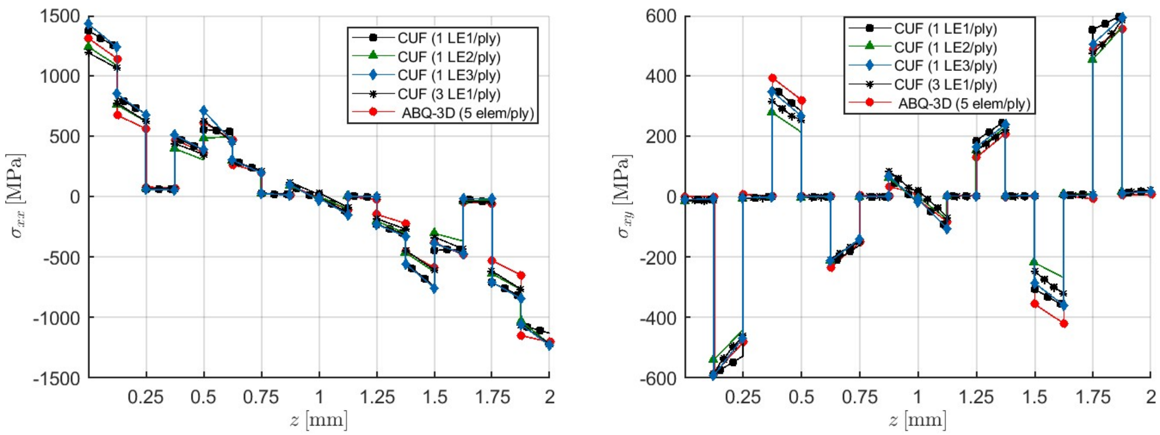

Figure 1: In-plane stress components through the thickness of the composite plate at the point (x,y)=(48 mm,48 mm).

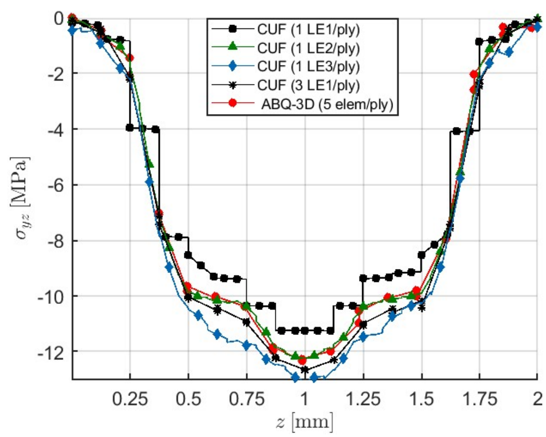

Figure 2: Interlaminar shear stress through the thickness of the square plate at the point (x,y)=(40 mm,40 mm).

Model 1	Discretisation of the laminate	DOF
CUF-LE1	400 Q9 (1 LE1/ply)	85,731
CUF-LE2	400 Q9 (1 LE2/ply)	166,419
CUF-LE3	400 Q9 (1 LE3/ply)	247,107
CUF-3LE1	400 Q9 (3 LE1/ply)	247,107
ABQ	512000 C3D8R (5 el./ply)	1,594,323
Model 2	Discretisation of the laminate	DOF
CUF-132Q9/LE2	132 Q9 (1 LE2/ply)	39,816
CUF-192Q9/LE1	192 Q9 (1 LE1/ply)	38,448
CUF-192Q9/LE2	192 Q9 (1 LE2/ply)	57,672
CUF-192Q9/LE3	192 Q9 (1 LE3/ply)	76,896
CUF- 260Q9/LE2	260 Q9 (1 LE2/ply)	77,832

Table 1: Model information

The second numerical study considers the impact of a rigid sphere on a circular composite plate with a stacking sequence of $[0/90]_{2s}$ and ply thickness 0.25 mm. The plate radius is 37.5 mm, thickness 2 mm, and is clamped at its boundary. The material is HTS40/9772 unidirectional CFRP. The impactor has a diameter of 15 mm, initial velocity 3.83 m/s, and kinetic energy 7.35 J. Delamination is modeled with cohesive elements inserted between adjacent plies. Material properties and cohesive parameters are taken from [7].

A mesh-convergence study on the peak impact force (Fig. 3) was performed using the same CUF LE2 expansion and varying in-plane discretizations of 132, 192, and 260 Q9 elements; see Model 2 in Table 1 for model and DOF details. The 192 Q9 mesh was chosen for subsequent analyses with different expansions. Force–time curves were denoised with MATLAB’s smooth (centered moving average) using spans of 10–15%. Damage-variable contour maps for the 192 Q9–LE3 model are shown in Fig. 4, and the predicted inter-ply delamination is reported in Fig. 5 for each of the seven cohesive interfaces. The cohesive law triggers delamination once a relative displacement threshold is exceeded [8,9]. Experimental [10] and numerical results are compared.

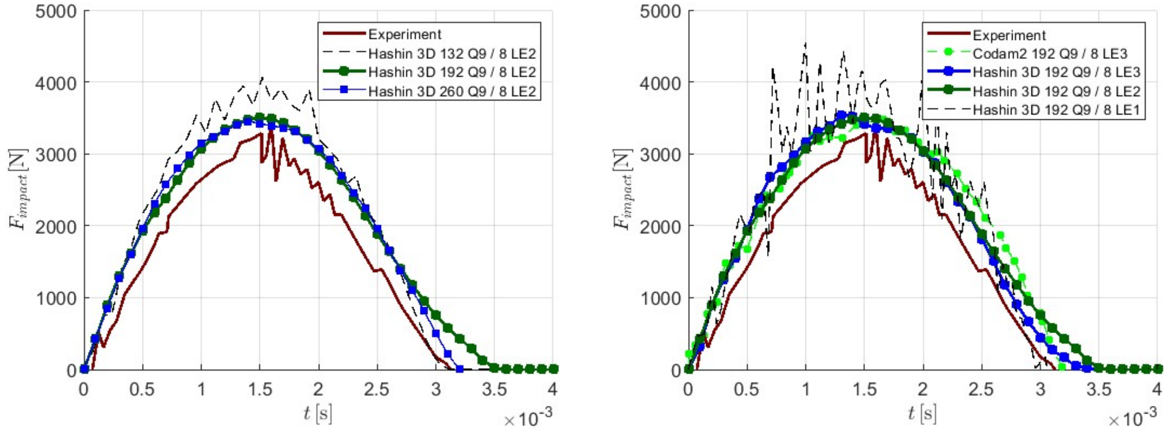

Figure 3: Impact force–time response; From left: (a) effect of in-plane mesh refinement; (b) effect of through-thickness expansion order. Reference experimental and numerical curves from [11].

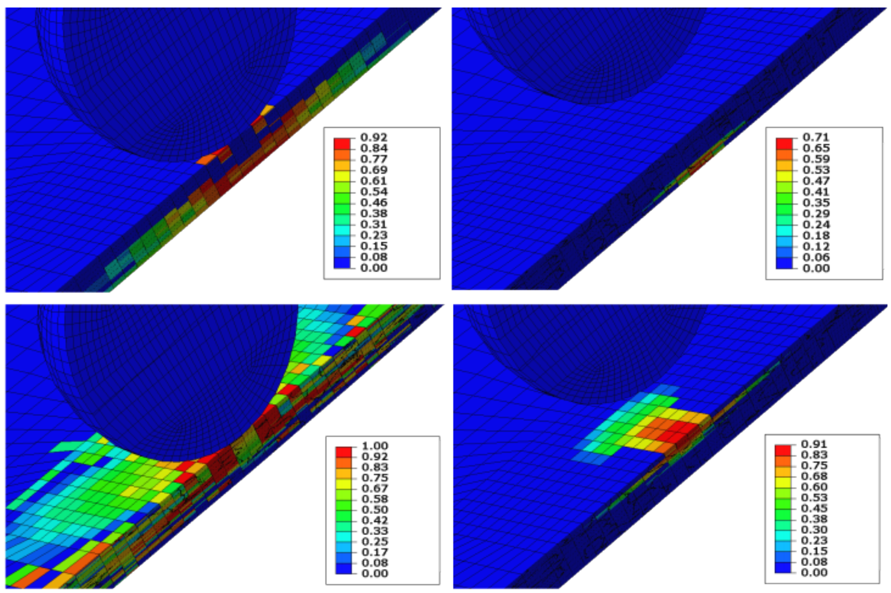

Figure 4: Damage in the impact region. Clockwise from the top-left: (a) Matrix tensile damage; (b) Fibre tensile damage; (c) Matrix compressive damage; (d) Fibre compressive damage.

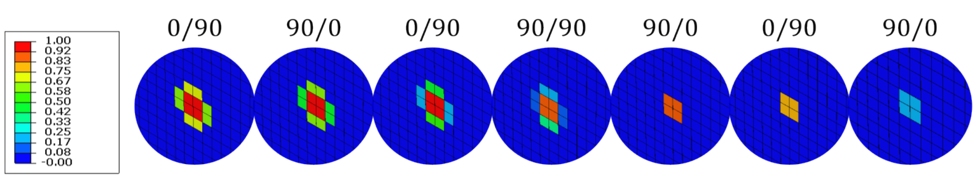

Figure 5: Predicted delamination at the ply interfaces ordered through-thickness from impacted surface (left) to back face (right).

Conclusions

In this study, the layer-wise 2D-CUF framework for impact analysis was extended from 2D damage criteria [11] to the 3D Hashin criterion, while retaining mixed-mode cohesive elements to model delamination. The proposed approach matches numerical and experimental results. The simulations indicate widespread, saturated matrix damage, while fiber damage remains partially unsaturated (see Fig. 4).

The 3D interlaminar stresses help calculate the extent and morphology of delamination, which more closely aligns with reference results [10]. In fact, slight back-face delamination is also captured. Overall, the methodology resolves both intralaminar and interlaminar damage while preserving computational efficiency, as the present approach requires a fraction of 3D FEM DOF.

Acknowledgements
This study was carried out within the Space It Up!, funded by the Italian Space Agency, ASI, and the Ministry of University and Research, MUR, under contract n. 2024 - 5 -E.0 - CUP n. I53D24000060005.

References

[1] D. Xie, A. G. Salvi, A. M. Waas, and A. Caliskan, "Discrete cohesive zone model to simulate static fracture in carbon fiber textile composites", in Proc. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conf., Austin, Apr. 2005, AIAA Paper 2005-2320. https://doi.org/10.2514/6.2005-2320

[2] C. Zhao, B. N. Fedulov, C. Liu, K. Zhang, and H. Liu, "Establishment and development of an incremental constitutive model for CFRP considering the impact adiabatic effect", Aerotecnica Missili & Spazio, 2025. https://doi.org/10.1007/s42496-025-00261-9

[3] E. Carrera, M. Cinefra, M. Petrolo, and E. Zappino, "Finite Element Analysis of Structures through Unified Formulation", Hoboken, NJ, USA: Wiley, 2014. https://doi.org/10.1002/9781118536643

[4] M. Petrolo, E. Tortorelli, S. Saputo, and E. Carrera, "Tensile damage analysis of composite structures based on 3D Hashin failure criteria and 2D higher-order structural theories", Int. J. Non-Linear Mech., vol. 127, Art. no. 103591, 2020.

[5] M. Petrolo, E. Tortorelli, S. Saputo, "Compressive damage analysis of composite structures using 3D failure criteria and 2D higher-order structural theories", Mechanics of Advanced Materials and Structures, 2025. https://doi.org/10.1080/15376494.2025.2489138

[6] Y. Zhang, W. Van Paepegem, and W. De Corte, "An enhanced progressive damage model for laminated fiber-reinforced composites using the 3D Hashin failure criterion: A multi-level analysis and validation", Materials, vol. 17, no. 21, Art. no. 7681, 2024. https://doi.org/10.3390/ma17215176

[7] M. H. Nagaraj, E. Carrera, and M. Petrolo, "Progressive damage analysis of composite laminates subjected to low-velocity impact using 2D layer-wise structural models", Int. J. Non-Linear Mech., vol. 127, Art. no. 103591, 2020. https://doi.org/10.1016/j.ijnonlinmec.2020.103591

[8] I. Kaleel, E. Carrera, and M. Petrolo, "Progressive delamination of laminated composites via 1D models", Composite Structures, 235:111799, 2020. https://doi.org/10.1016/j.compstruct.2019.111799

[9] P.P. Camanho, C.G. Davila, and M.F. De Moura, "Numerical simulation of mixed-mode progressive delamination in composite materials", Journal of composite materials, 2003. https://doi.org/10.1177/0021998303034505

[10] Y. Shi, T. Swait, C. Soutis, "Modelling damage evolution in composite laminates subjected to low velocity impact", Composite Structures, Volume 94, Issue 9, 2012. https://doi.org/10.1016/j.compstruct.2012.03.039

[11] M. H. Nagaraj, J. Reiner, R. Vaziri, E. Carrera, and M. Petrolo, "Progressive damage analysis of composite structures using higher-order layer-wise elements", Compos. Part B Eng., vol. 200, Art. no. 107921, 2020. https://doi.org/10.1016/j.compositesb.2020.107921