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Low-Velocity Impact on Composite Stiffened Panels Using a Component-Wise Approach

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

[1]MUL2 lab, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Italy

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

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Abstract. Composite stiffened panels, widely used in the aerospace sector, are exposed to low-velocity impacts (LVI) during operation, maintenance, and transport. Computational methods help predict deformation and the extent of damage under dynamic loading, reducing the need for an extensive testing campaign. In this work, structural theories based on the Carrera Unified Formulation (CUF) are proposed for the analysis of low-velocity impacts on stiffened composite panels. The dynamic response of both the skin and the stiffeners is described through refined 1D elements with higher-order kinematic expansions, enabling an accurate evaluation of local deformation effects and stress concentrations, especially at the skin-stiffener interface. A progressive intralaminar damage model is adopted to account for material nonlinearities. The proposed approach is assessed on representative composite stiffened panels subjected to LVI. The results are compared with those obtained from commercial finite element models based on full 3D discretization. The comparison shows that the CUF-based models provide accurate predictions of the structural response while reducing the computational cost in terms of Degrees of Freedom (DOFs). These features make the proposed methodology an efficient alternative to conventional 3D modelling strategies for the design and analysis of lightweight composite stiffened structures.

Introduction

Composite stiffened panels are extensively employed in aerospace structures because they combine low structural weight with high bending stiffness, buckling resistance, and load-carrying capability. Nevertheless, their damage tolerance under low-velocity impact remains a major design concern. Impact events may produce barely visible impact damage, involving matrix cracking, fibre failure, and delamination, with a potentially significant reduction in residual structural performance [1]. The continuing interest in this problem is demonstrated by recent experimental and numerical studies addressing multiple impacts and compression-after-impact behaviour of thin CFRP laminates [2], the influence of impact energy, laminate thickness, and stacking sequence [3], and the response of hybrid carbon-fibre/metal laminates [4]. In stiffened panels, stiffeners introduce discontinuities in stiffness and stress concentration points because the load is redistributed over the complex geometry of the structure. Impact damage on reinforced composite plates has been studied by Li et al. [5] and by Rahman et al. [6]. Generally, the analyses are computationally demanding because these detailed models usually require fine 3D discretization and dedicated material subroutines. An alternative modelling strategy is offered by the Carrera Unified Formulation (CUF), which enables the systematic derivation of refined one- and two-dimensional structural theories using arbitrary-order kinematic expansions [7]. Within this framework, higher-order layer-wise models have been developed for the progressive damage and low-velocity impact analysis of composite laminates [8,9]. The accurate three-dimensional stress fields provided by these models have also been combined with failure criteria and continuum damage formulations for the analysis of tensile and compressive failure [10,11]. More recently,

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Materials Research Proceedings 73 (2026) 109-113 https://doi.org/10.21741/9781644904459-22

the framework has been applied to LVI on unstiffened composite plates using 2D layer-wise theories, the 3D Hashin criterion, and cohesive interfaces [12]. These studies demonstrated the capability of refined structural theories to predict local stress and damage fields without requiring conventional solid-element discretization. The present work extends the CUF-based impact framework to 1D component-wise models of composite stiffened panels. Higher-order expansions describe the displacement field over complex skin–stiffener cross-section. The implementation is first verified on an unstiffened composite plate and is subsequently applied to the impact and intralaminar damage analysis of a stiffened panel.

Methodology

The structural theories adopted in this work are developed within the Carrera Unified Formulation (CUF), which enables the systematic derivation of refined one- and two-dimensional models through compact notation. For the one-dimensional formulation, the three-dimensional displacement field is expressed as

$$\mathrm{u}(\mathrm{x},\mathrm{y},\mathrm{z}) = \mathrm{F}_{\tau}(\mathrm{x},\mathrm{z})\mathrm{N}_{\mathrm{i}}(\mathrm{y})\mathrm{u}_{\tau\mathrm{i}} \quad \tau = 1,\dots,\mathrm{M}; \quad \mathrm{i} = 1,\dots,\mathrm{N}. \tag{1}$$

where $N_i(y)$are the finite element shape functions along the beam axis, $F_\tau(x,z)$ are arbitrary expansion functions defined over the cross-section, and $u_{\tau i}$contains the generalized displacement variables. The type and order of the expansion can be selected without modifying the general formulation. Higher-order Lagrange polynomial expansions are employed to discretize the cross-section. In the adopted layer-wise approach, each composite layer is represented as an independent subdomain and different expansions can be assigned to different regions of the cross-section, providing an accurate evaluation of the three-dimensional stress state even for complex stacking sequences. This feature is particularly advantageous for stiffened panels. In 1D CUF models, the skin and the stiffener can be represented directly within the cross-sectional discretization, allowing complex shape stiffener to be modelled while retaining a 1D finite element mesh along the longitudinal direction. An accurate stress prediction is essential because it may affect both damage initiation and propagation. An explicit time-integration procedure based on the Central Difference Scheme is used as solver. Node-to-surface contact, previously only available for 2D elements, has been extended to 1D elements by creating an artificial contact surface. The reliability of the new implementation was verified by comparing the results of 1D and 2D models on an unstiffened plate.

Intralaminar damage initiation is evaluated using the Hashin 3D criterion, which distinguishes fibre and matrix failure under tensile and compressive loading. When one of the four failure indices reaches unity, the corresponding damage evolution is described through a linear law that reduces the material stiffness up to final failure. Interlaminar damage can be represented within the proposed framework through cohesive interface elements. However, cohesive delamination is not activated in the numerical results presented in this work, which focus on the validation of the one-dimensional contact formulation and on the prediction of intralaminar damage in stiffened composite panels.

Numerical Results

The first case reproduces the benchmark presented in [12] to validate the node-to-surface formulation developed for CUF-1D models. A 16 mm spherical impactor strikes at 5 m/s a fully clamped 100×100 mm composite plate. The 2 mm thick quasi-isotropic laminate has stacking sequence $[90/45/0/-45]_{2s}$. The CUF-1D results are compared with CUF-2D and three-dimensional ABAQUS solutions, see Table 1 for models' details. Different cross-sectional refinements provide converged displacement and force histories, confirming the robustness of the contact formulation, see Fig. 1. The 1D models used 320 L9 elements across the cross-section but with different refinements in the contact zone (CZ). The in-plane stress components at (x,y) = (48

Materials Research Proceedings 73 (2026) 109-113 https://doi.org/10.21741/9781644904459-22

mm, 48 mm) and interlaminar shear stresses at (x,y) = (40 mm, 40 mm) show good agreement with the Abaqus solution, see Fig. 2.

Table 1: Model discretization and numbers of degrees of freedom of the unstiffened plate.

Model	Discretisation	DOF
CUF-2D (1 LE1/ply)	400 Q9 (1 LE1/ply)	85'731
CUF-2D (1 LE2/ply)	400 Q9 (1 LE2/ply)	166'419
CUF-2D (1 LE3/ply)	400 Q9 (1 LE3/ply)	247'107
CUF-1D	320 L9 – 20 B4	247'599
ABQ-3D (5 elem/ply)	512000 C3D83 (5 el/ply)	1'594'323

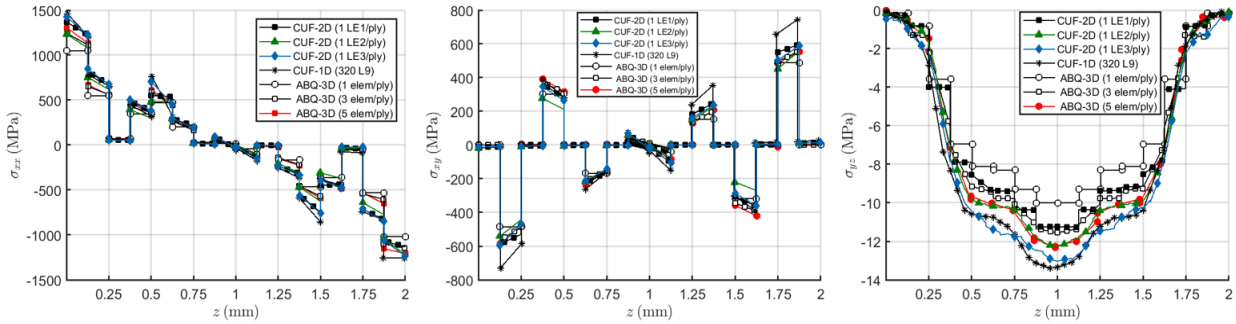


Figure 1: Through-thickness stress distribution of the unstiffened plate. CUF-1D (320 L9) refers to the 8L9 in the contact zone CZ.

The second case considers a fully clamped 200 × 200 mm composite plate reinforced by two I-shaped parallel stiffeners, subjected to central impacts at 20, 30, and 40 m/s. The skin laminate has stacking sequence [0/90/0/90/0]and a total thickness of 2.69mm. The unidirectional [0] stiffeners have a reference height of 7 mm. The structure is made of T300/934 graphite/epoxy taken from [5] and is impacted by a rigid spherical impactor with a radius of 6 mm. Both the skin and stiffeners are represented using CUF-1D elements, with a total of 77 L9 and 12 B4 and 39'183 DOFs. Good agreement with the reference solution [5] is obtained during the initial loading stage and for the first contact-force peak, see Fig. 3. The late-stage differences may be attributed to the different contact formulations: the reference model uses Hertzian indentation, whereas the present model evaluates contact reactions through Lagrange multipliers. The 3D Hashin criterion reproduces the initiation and early evolution of matrix damage near the impact region, see Fig. 4. Larger differences are observed at later stages. Since delamination is not included, the present results should be regarded as a preliminary assessment of intralaminar damage.

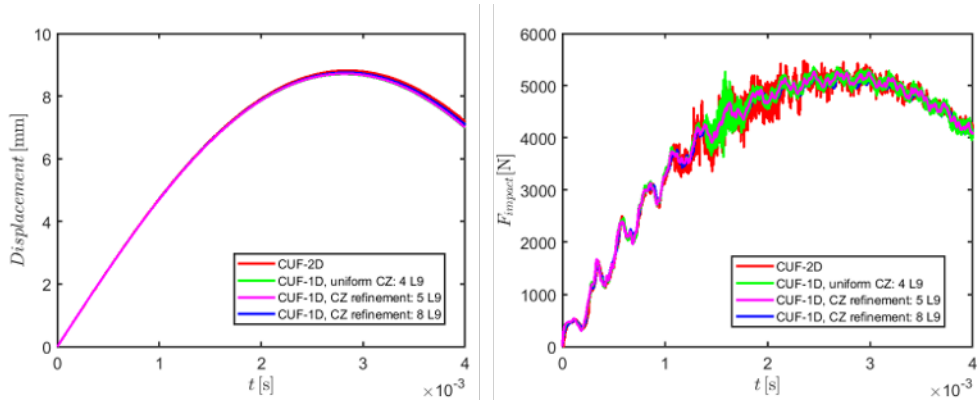


Figure 2: Mid-point displacement and impact force histories of the stiffened plate.

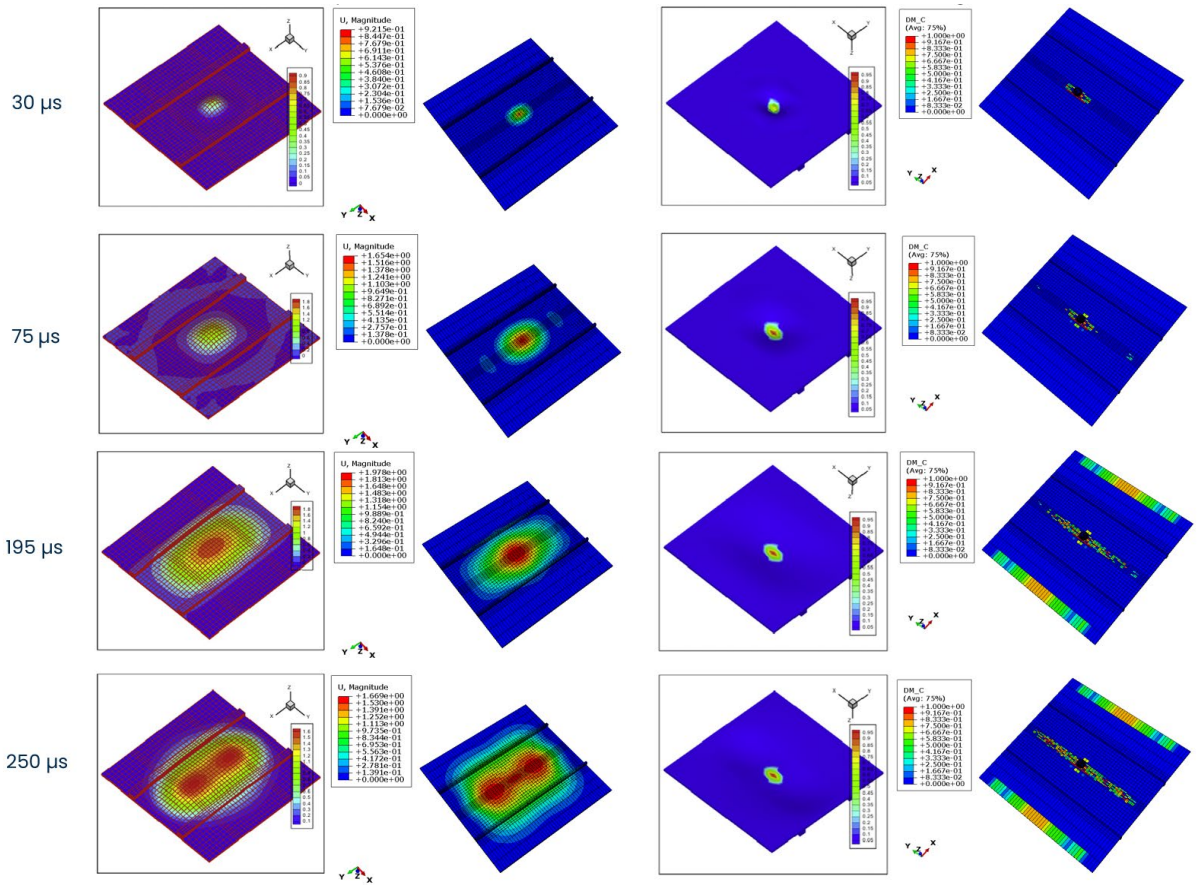


Figure 3: Displacement and matrix-damage contours at selected times for an initial velocity of $V_0 = 20\ m/s$ of the stiffened plate. Boxed panels show the reference solution from [5].

Conclusions

A node-to-surface contact formulation was successfully extended to CUF-1D models through the reconstruction of an artificial contact surface. The unstiffened plate benchmark shows good agreement with CUF-2D and full 3D solutions while using only about 15% of the DOFs of the three-dimensional model. The formulation was then applied to a stiffened composite plate, accurately capturing the initial impact response and the onset of intralaminar damage. Future developments will include cohesive delamination modelling and element deletion beyond a critical damage threshold.

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