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A reduced model to simulate the damage in composite laminates under low velocity impact

S. Metoui [a,b,*], E. Pruliere [a], A. Ammar [b], F. Dau [b]

[a] Ecole Nationale Supérieure d'Arts et Métiers, Campus de Bordeaux, I2M-DuMAS, Esplanade des Arts et Métiers, Talence 33405, France
[b] Ecole Nationale Supérieure d'Arts et Métiers, Campus d'Angers, LAMPA, 2 Boulevard de Ronceray, 49035 Angers Cedex 01, France

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ABSTRACT

This article presents an efficient numerical strategy to simulate the damage in composite laminates under low velocity impact. The proposed method is based on a separated representation of the solution in the context of the Proper Generalized Decomposition (PGD). This representation leads to an important reduction of the number of degrees of freedom. In addition to the PGD, the main ingredients of the model are the following: (a) cohesive zone models (CZM) to represent the delamination and the matrix cracking, (b) a modified nonlinear Hertzian contact law to calculate the impact force, (c) the implicit Newmark integration scheme to compute the evolution of the solution during the impact. The method is applied to simulate an impact on a laminated plate. The results are similar to the solution obtained with a classical finite element simulation. The shape of the delaminated area is found to be coherent with some experimental results from the literature.

1. Introduction

The ever growing demand for lighter structures results in the increasing replacement of metallic materials by composite materials. While composite materials offer a number of superior design characteristics, composite structures are much more sensitive to impact damage than similar metallic structures. Impact can result in numerous damage mechanisms, ranging from barely visible impact damage (BVID) to complete penetration, which nevertheless severely reduces the stiffness and the residual strength of the composite structures. Impacts caused by foreign objects may arise during the life span of a structure including manufacturing, service, and maintenance operations. In the present work only low velocity impact events will be considered although the proposed numerical strategy may be applied to other kind of dynamic loads.

The development of efficient dynamic simulations for composite structures under low velocity impact is a very challenging issue. There are many scientific locks, in particular:

- Composite structures have often a small dimension (thickness) compared to the others (shell or plate structures). When using 3D elements, a fine mesh is required to keep a good precision in the thickness which results in a very high number of elements to cover the entire volume.
- The modeling of damages can also lead to numerical difficulties. For example, the use of cohesive elements is an appealing choice. This kind of elements is particularly well adapted to treat delamination and fibers/matrix decohesion. However, cohesive elements need very fine meshes to ensure the numerical stability.
- Explicit dynamic calculations lead to restrictive time steps to satisfy the stability condition. In the other hand, the use of implicit scheme causes solving some non linear problems many times which is numerically costly. The strong non-linearities related to the damage model are generally difficult to solve and require high computational resources.

The main objective of this work is to propose an efficient numerical solver able to simulate the complex behavior of composite laminates with reasonable computational time and accuracy. To reach this objective, an approach based on model reduction is chosen.

* Corresponding author at: Ecole Nationale Supérieure d'Arts et Métiers, Campus de Bordeaux, I2M-DuMAS, Esplanade des Arts et Métiers, Talence 33405, France.

E-mail addresses: sondes.metoui@ensam.eu (S. Metoui), Etienne.Pruliere@ensam.eu (E. Pruliere), amine.ammar@ensam.eu (A. Ammar), frederic.dau@ensam.eu (F. Dau).

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1.1. Model reduction

The idea is to approximate the solution under a separated form. If we consider a plate structure where z is the coordinate in the direction normal to the plate, an unknown field (the displacement in general) can be expressed with the following separated representation:

$$u(x,y,z) = \sum_{i=1}^{n} F_i(x,y) \times G_i(z) \quad (1)$$

where the functions F_i and G_i for $i = 1,\ldots,n$ need to be determined. A few solvers exist to compute this kind of solution. Here, the Proper Generalized Decomposition (PGD) will be considered.

This numerical method consists in building the separated representation of the solution using a greedy algorithm with no a priori knowledge of any reduced basis. If n is small enough, the total number of degrees of freedom is significantly reduced. Only a 2D mesh is required and the problem is greatly simplified in comparison to the full 3D approach.

The PGD with a space-time separated representation was originally proposed by Ladeveze under the name "radial loading decomposition" in the context of the LATIN method. The idea was to develop a non-incremental solver [1,2]. Ammar et al. [3,4] devised the first version of the PGD strategy for multi-dimensional problems. It was originally applied to the high-dimensional kinetic models of complex fluids. After that, the PGD was successfully applied to a wide variety of problems. For instance, the PGD procedure was applied by Ammar et al. [5] to model the degradation of a plastic material which is a complex transient problem. A separated representation was also used by Chinesta et al. for solving the chemical master equation [6] and stochastic equations within the Brownian configuration field framework [7]. The PGD was applied in other studies for thermal problems in composite materials [8]. Nouy used the PGD to study stochastic problems [9,10]. This approach also allows for the fast computation of problems defined in plate or shell domains. The advantage is that 3D solutions can be obtained with a computational cost characteristic of standard 2D solutions [11]. This approach has been applied to composites shell structures [12] and have been improved using high order interpolation in the thickness [13,14]. In this work the PGD will be adapted to simulate a low velocity impact on a composite laminate involving damages.

1.2. Failure mechanisms in low velocity impact

Low velocity impact damage in composites is insidious due to the invisible damages they can cause. These damages can drastically decrease the residual strength of composite structure, for instance in compression after impact. For unidirectional (UD) laminates under low velocity impact, significant amount of permanent damage in the form of matrix cracking, delaminations and fiber breakage may be present without being detectable by visual inspection. The failure mechanisms usually occur in the listed order with increasing impact energy. Matrix cracking has been widely reported as the first type of failure induced by transverse low velocity impact [15–17]. It acts as a starting point for the propagation of delamination. Fig. 1 shows the typical matrix cracking and delamination damage found in an impacted composite specimen. Matrix cracks appear parallel to the fibers due to tension or shear.

The initiation and propagation of matrix cracks are strongly dependent on the stacking sequence [18–20]. Two types of matrix cracking can be observed: tensile matrix cracks and shear matrix cracks. Tensile matrix cracks are formed by the flexural deformations due to the tensile bending stresses. These cracks are generally located at the lower plies. Shear matrix cracks form in the upper plies directly under the impact zone and are induced by the high transverse shear stress through the material, and are inclined at approximately 45°. The matrix cracks first appear in the lowest ply [21]. Due to the coupling between delamination and matrix cracking, the initiation of delamination is located on the matrix cracks.

Delamination is often considered to be the most energy consuming damage mechanism during a low velocity impact. The majority of the energy absorbed in the laminate during impact dissipates into delamination propagation. Delaminations occur at the interfaces between plies with different fiber orientations and tend to initiate at the bottom interface and progressively becomes smaller towards the impact face. The shape of the delaminated area changes with the orientation of plies and is usually a peanut with its major axis oriented in the fiber direction of the lowermost layer at the interface, as depicted in Fig. 2. The peanut shape is a result of the shear stress distribution around the impactor, the interlaminar shear strength in the fiber direction and the matrix cracking. Fiber failure mostly appears after matrix cracking and delamination. This failure mode may occur under the impactor due to locally high stresses and indentation effects.

2. Problem statement

2.1. Governing equation

The weak form of the equilibrium equation in a domain Ω without body force and neglecting the damping effects reads:

$$\iint_{\Omega} \rho \mathbf{u}^* \cdot \ddot{\mathbf{u}} d\Omega + \iint_{\Omega} \varepsilon(\mathbf{u}^*) \cdot (\boldsymbol{A}\varepsilon(\mathbf{u}))d\Omega = \int_{\Gamma} \mathbf{T}_{ext}\mathbf{u}^* d\Gamma \quad (2)$$

where $\mathbf{u} = (u, v, w)^T$ is the displacement field, $\ddot{\mathbf{u}} = (\ddot{u}, \ddot{v}, \ddot{w})^T$ is the acceleration field, $\mathbf{u}^*$ is the virtual displacement and $\boldsymbol{\varepsilon}$ is the strain tensor using the vectorial form:

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ 2\varepsilon_{yz} \\ 2\varepsilon_{xz} \\ 2\varepsilon_{xy} \end{pmatrix} \quad (3)$$

$\mathbf{T}_{ext}$ is the external force on the boundary Γ. $\mathbf{A}$ is a matrix related to the material law in each layer. For a linear orthotropic material, $\mathbf{A}$ is defined by Eq. (4).

$$\boldsymbol{A}^{-1} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_x} & -\frac{\nu_{xz}}{E_x} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{yz}}{E_y} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} \end{bmatrix} \quad (4)$$

$E_x,\ E_y,\ E_z$ are the elastic modulus, $\nu_{xy},\ \nu_{xz},\ \nu_{yz}$ are the Poission's ratio and $G_{xy},\ G_{xz},\ G_{yz}$ are the shear modulus expressed in the orthotropic basis (x, y, z).

After assembling all mass and stiffness matrices with a finite element approximation, the discretized motion equations of the laminate take the following form:

$$[\mathbf{M}]\{\ddot{\mathbf{u}}\} + [\mathbf{K}]\{\mathbf{u}\} = \{F\} \quad (5)$$

where $[\mathbf{M}]$ and $[\mathbf{K}]$ are the coherent mass and stiffness matrices of the composite laminate, $\{\mathbf{u}\}$ and $\{\ddot{\mathbf{u}}\}$ are respectively the nodal