Low-Velocity Transverse Impact Investigations of CFRP Composite Laminated Plates - Simplified Static Simulations Versus Dynamic Experimental Tests

Marius Nicolae Baba[1](✉) and Florin Dogaru[2]

[1] Transilvania University of Brașov, Eroilor Blvd no. 29, 500036 Brașov, Romania
mariusbaba@unitbv.ro

[2] Consaro Engineering SRL, Mihail Kogalniceanu Blvd no. 23, 500090 Brașov, Romania

Abstract. Nonlinear contact and large displacements static simulations were conducted using Ansys FE software to assess the response of CFRP composite laminated plates tested to low-velocity impact. The scope is to present a solution of enough accuracy and a method of analysis equivalent to a transient dynamic model but more straightforward. The experimental tests were performed upon plate specimens with rectangular geometry dimensions of $150 \times 100 \times 2.5$ mm^3, made of 8 unidirectional laminae (carbon fiber/epoxy vinyl ester resin), stacked in a [0/-45/45/90]s layup configuration. Results are presented in terms of contact force versus central plate deflections, covering a range of impactor velocities between 0.25 m/s to 3 m/s. Within this interval, the predicted numerical response agrees well with the experimental data.

Keywords: Low-Velocity Transverse Impact (LVTI) · Carbon Fiber Reinforced Plastics (CFRP) · Finite Element Analysis (FEA) · Laminated composite

1 Introduction

Although considerable efforts have been made over the years to improve the design, analysis, and prevention of CFRP laminated composites against damages due to low-velocity impact, their use in large-scale industrial applications, however, remains quite limited. The polymeric composite materials reinforced with carbon fibers are already used conventionally in aerospace and automotive industries and soon appear to become more involved in a broader range of engineering applications requiring enhanced mechanical properties for reduced overall weight [1–3]. Indeed, the potential of these materials to sustain the barely visible impact damages (i.e., BVID) is still a particular topic of concern for many researchers in the field of design for manufacturing laminated composite structures. At its core, the low-velocity impact damage might affect the composite material's outer layers, the inner layers, or both the outer and inner layers [4–7].

A large amount of computational and experimental work has been carried out over the years toward developing an accurate prediction of the low-velocity transverse impact

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of CFRP laminated plates. Comprehensive reviews are available in the literature [8–12] and will not be treated here. We note, however, that in pre-sizing design phases, the use of complex finite element models, intended to accurately represent the heterogeneous nature of these materials as well as their complex intra- and inter-ply damage mechanisms, is often limited due to extremely low computational efficiency and numerical integration issues [13]. Moreover, during the design workflow of CFRP laminated composites prone to low-velocity impact damages, experimental testing is often unlikely to provide all the design information over the material, loading and geometric parameters adopted in current structural engineering practices. Therefore, simplified and well-documented finite element models must be available to verify and supplement the existing input data.

Based on the results obtained through the use of a simplified nonlinear finite element model, the purpose of this paper is to determine the level of accuracy between the impact response acquired through experimental tests at different thresholds of impactor velocity and the predicted responses obtained through static FE numerical simulations. In addition, the results of a quasi-static analytical assessment based on the impact energy conservation proposed by the authors in a previously published paper [14] are considered.

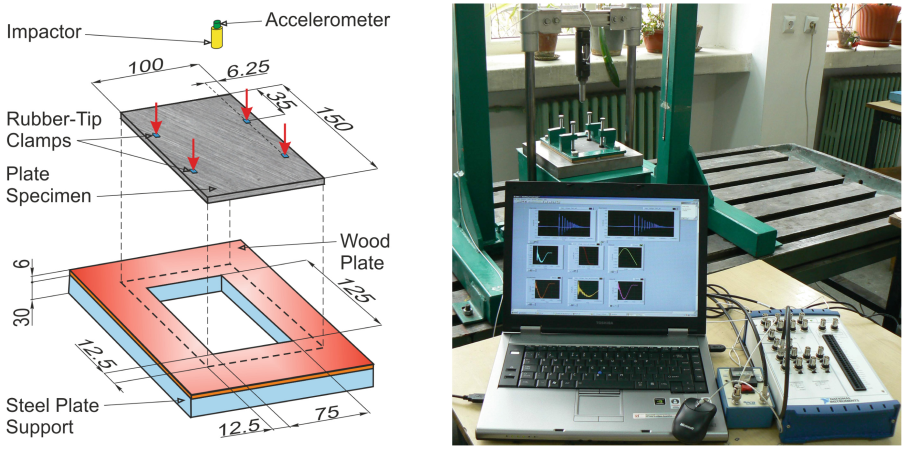
2 Materials and Methods

2.1 Experimental Set-up

Experimental investigations were done on plate specimens of rectangular geometry, made of epoxy vinyl ester matrix (Derakane 470–30), reinforced with carbon fibers.

The composite base plates utilized to cut off the rectangular specimens were manufactured manually at laboratory scale by brushing on the resin (a fraction of 30% volumetric ratio of carbon fiber was estimated). The composite plate thickness of 2.5 mm was obtained by stacking eight unidirectional laminae and following a symmetrical layup configuration with [0/-45/45/90]s. The tests were carried out using a tower test device (see Fig. 1), designed to adjust the impact velocity to any particular value ranging from 0.25 m/s to 3 m/s by changing the height of a projectile of 1,9 kg weight.

The impacted specimens were leaned against a perforated steel plate support with a rectangular cut-out of 125×75 mm^2. An intermediate wood plate of 6 mm thickness was attached upon, as schematically represented in Fig. 1(a), to avoid the damages of specimens at the contact with the edges of the support. The specimen was clamped to the supporting steel plate for each test through four tighten screws placed laterally, close to the specimen edges. Rubber-tip clamps were used to avoid local damages due to excessive tightening and to reduce the vibration effects. At the beginning of each test, a hemispherically nosed projectile of 16 mm diameter, made of high hardness alloy steel and vertically aligned on two guiding bars, is raised to the required drop height and then released to fall onto the specimen at its center. A rigidly connected accelerometer to the rear side of the projectile is placed to measure the acceleration and the resulting contact force during the impact. Besides this accelerometer, the involved hardware acquisition system also includes a signal amplifier, a data acquisition board, and a PC station. For each test, after the first impact event, the projectile was manually caught to avoid multiple impacts.



a) Specimen fixtures b) Lab testing assembly

Fig. 1. The tower test device and specimen fixtures for low-velocity impact tests

2.2 FE Simulation

The commercial FE software Ansys was employed to simulate the three-dimensional low-velocity impact tests of CFRP laminated composite plates. Since the inertia effects are pretty minor, they were disregarded so that a straightforward static nonlinear analysis was performed implicitly, which provides a more detailed stress distribution [15]. The primary source of nonlinear behavior is assumed to occur due to the contact area change with the magnitude of the applied load by using SOLID187 tetrahedron elements to model the projectile impactor. The effects of large displacements were also considered with the aid of higher-order 3D elements composed of 20 nodes named SOLID186 in Ansys FE software, used hereafter to model the laminated composite plate. Each node has three degrees of freedom: i.e., translations along the nodal x, y, and z directions. This kind of solid element exhibits a quadratic displacement response, and thus, it appears to be more accurate in estimating the deflections than any other three-dimensional element with linear shape functions.

On the other hand, since the underlying plate elements have mid-side nodes at the contact interface due to quadratic shape function, specific elements satisfying this condition have had to be used to represent and compute both the contact and sliding between 3-D surfaces, including the projectile and the laminated composite plate under investigation. Here, it is worth mentioning that in Ansys FE software, these kinds of elements are CONTA174 and TARGE170. The pair of potential contact surfaces are usually referred to as either contact surface or target surface. The CONTA174 elements model the contact and sliding response between the target surface and the deformable plate surface, defined by these particular elements. Moreover, the Coulomb friction, as well as shear stress friction, are allowed for CONTA174 elements.

The augmented Lagrangian method was utilized as a contact algorithm in the simulation. In such a way, the contact stresses are enlarged during equilibrium iterations leading to a value of final penetration lower than the allowable tolerance. Typically, the augmented Lagrangian method generates better conditioning relative to the penalty method, while it is less sensitive to the contact stiffness magnitude [16].

The laminated plate was simply supported upon the edges, and the load was applied through the projectile impactor with the maximum value acquired throughout the experimental investigations. Due to the symmetry, only a quarter of the model was considered to minimize the size of the FE model and hence, the computational time. The edges and symmetry restraints, both for the plate and the projectile, are schematically represented in Fig. 2.

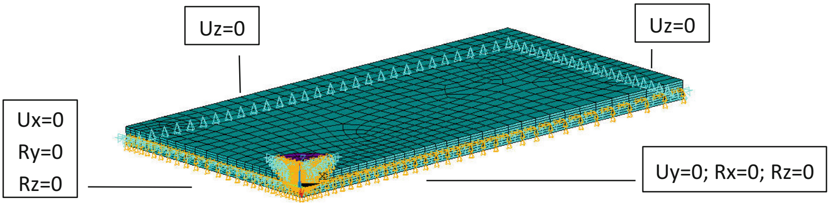


Fig. 2. The quarter FE-model of projectile and plate in contact

Plane orthotropic and linear elastic material properties (see Table 1) were assigned to each unidirectional composite layer with reference to a global predefined coordinate system. The fiber direction of 0° layer is directed along the higher side of the specimen.

Table 1. The elastic properties of unidirectional composite lamina

E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	υ_{12} [-]	G_{12} [GPa]	G_{23} [GPa]
55	4	4	0.3	1.35	1.35

The mesh density in the contact region was found to influence the solution accuracy directly. Thus, a comparative study was performed by employing different element sizes (1, 1.5 and 3 mm) in the contact area. The results obtained for an element size of 1.5 mm provided satisfactory convergence both in stresses and strains.

3 Results and discussion

In the current study, FEA-based predictions and experimental tests, under the aforementioned conditions and assumptions, were made for nine particular values of the projectile's initial velocities (i.e., 0.25 m/s, 0.35 m/s, 0.5 m/s, 0.75 m/s, 1 m/s, 1.5 m/s, 2 m/s, 2.5 m/s and 3 m/s). Figure 3 shows the deflection fringe plot of the laminated plate under question, acquired by FEA at step number 17, corresponding to an impact velocity of 1 m/s (i.e., an applied force of 760 N). It can be observed that a maximum displacement of 2.78 mm is reached at the contact area. For the sake of illustrating its level, the central plate deflection obtained for the maximum applied contact force of

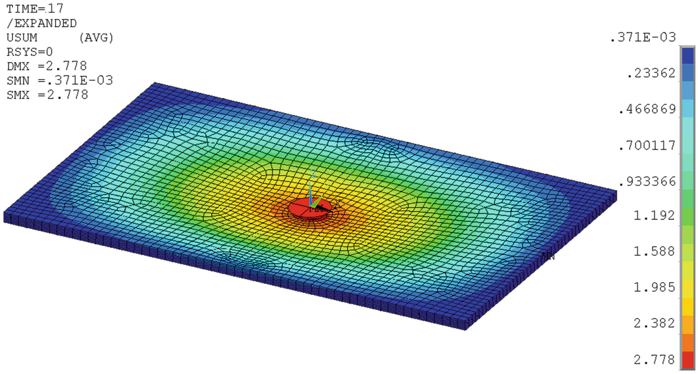
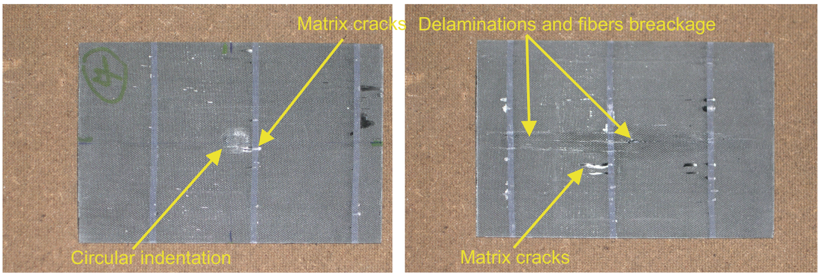


Fig. 3. The plate deflection acquired by FEA at time step no. 17, corresponding to a force of 760 N (i.e., an impact velocity of 1 m/s)

3750 N (experimentally averaged at a projectile's velocity of 3 m/s) was found equal to 7.35 mm (not represented graphically here, but referenced later, in Fig. 6).

Photographs of damages that occurred upon the plate specimens impacted at a projectile's velocity of 3 m/s are portrayed in Fig. 4. A slight indentation is visible on the impacted side, while upon the non-impacted side, complex interactions of matrix cracks, delaminations, and fibers breakage can be observed, although they are not much apparent. No damages were visible for the projectile's velocities with initial values lower than 3 m/s (corresponding to an average indentation in the contact area equal to 0.4 mm). A specific threshold value of 0.3 mm to 0.5 mm, pointing out the permanent indentation for BVID (i.e., substantial damages/failures that occur in the underlying layers with only a minor surface indent detectable by visual inspection on their external surfaces) is outlined by Bouvet and Rivallant [2]. Thus, for the laminate under investigation, the projectile's velocity of 3 m/s establishes the impact energy corresponding to the level of BVID (i.e., 8.6 J).



a) Face side (Impacted) b) Back side (Non-impacted)

Fig. 4. The damages occurred upon the plate specimen impacted at a projectile's velocity of 3 m/s (corresponding to BVID level)

Figure 5 depicts a time-varying deflection event obtained by both FEA, experimental test and analytical, corresponding to a projectile's velocity of 1 m/s. For this velocity, the prediction of maximum displacement based on FE-model and analytical are about the same and consistent with the experimental result. However, the estimated deflection is 8% higher than the empirically determined level of 2.5 mm. This difference might be the result of the peculiar failure behavior of CFRP laminates under low-velocity impact.

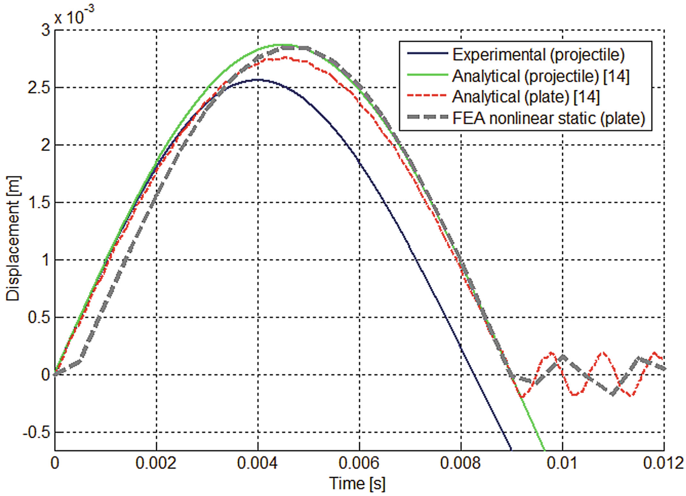


Fig. 5. The time-varying deflection event corresponding to a projectile's velocity of 1 m/s (experimental, FEA and analytical [14])

An envelope plot of contact force versus central plate deflections obtained for all the particular values of the projectile's initial velocities, as underlined at the beginning of this section, is represented in Fig. 6. It can be seen that the analytical solution developed in reference [14] is accurate only for small displacements, generally speaking, for a maximum transversal displacement lower than the thickness of the plate. Nevertheless, the mean value of empirically recorded contact force falls somewhere between the linear analytical solution and the nonlinear numerical solution. It is also worth noting that the results are pretty scattered for projectile's velocities higher than 1 m/s. Such a response behavior may be expected for this loading level since the intra- and interlaminar damages are introduced in the laminated plate, thus determining a considerable reduction of stiffness as well as the resultant contact force. Moreover, as already mentioned in reference [14], for values of the initial projectile's velocity up to about 3 m/s, the maximum values of contact force and deflection are reached at the same time, which means that within this velocity range, the impact response may be assumed as quasi-static.

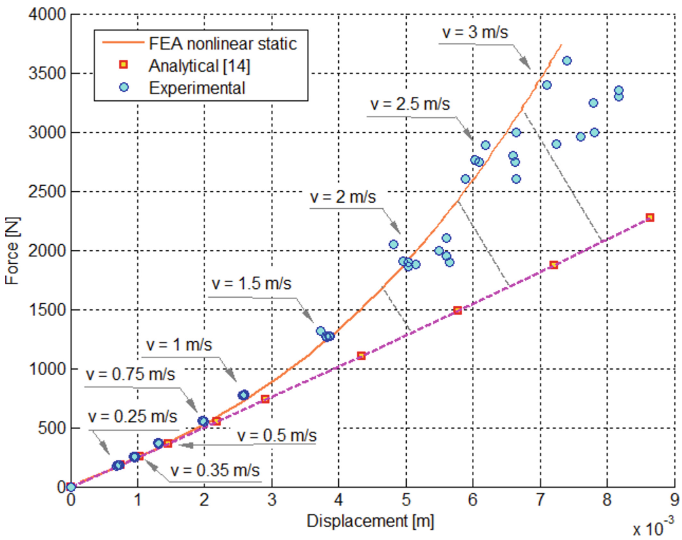


Fig. 6. Force - displacement envelope plot for different projectile's velocities between 0.25 m/s and 3 m/s

4 Conclusions

Employing the current low-velocity impact testing methodologies, the energy that induced the level of BVID equal to 8.6 J was found for a CFRP laminated composite plate made of 8 unidirectional laminae (carbon fiber/epoxy vinyl ester resin), stacked in a [0/-45/45/90]s layup configuration of 2.5 mm thickness.

Although the testing results are pretty scattered for the projectile's velocities higher than 1 m/s, the mean value of empirically recorded contact force falls somewhere between the linear analytical solution and the nonlinear static FEA solution. Such a response behavior may be expected since, beyond this loading level, matrix cracks, fibers breakage and interlaminar damages are introduced in the laminated plate, thus determining a considerable reduction in stiffness and resultant contact force. However, the analytical solution based on classical plate theory (see reference [14]) gives accurate results only for the initial projectile's velocities lower than 1 m/s (corresponding to a maximum displacement that is smaller relative to the thickness of the laminate plate under analysis).

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