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# Finite element simulation of 0°/90° CFRP laminated plates subjected to crushing using a free-face-crushing concept

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ABSTRACT

This paper describes the development of a numerical model of (0°/90°) CFRP plates subjected to low velocity crushing, based on physical observations. The developed model is represented at the meso-scale and is based on five main ideas: 1 – meshing of each ply of the laminate; 2 – use of cohesive elements to represent delamination and plies splaying; 3 – simulation of macro-scale fragments; 4 – representation of the localized crushing of plies at their extremities with the introduction of a free-face-crushing concept; 5 – representation of contacts between plies, plies and impacted base, plies and debris. The results of the Abaqus/Explicit simulations show a good agreement with the experimental results, which demonstrates that the proposed methodology is able to predict the force, the main failure mechanisms and the phenomenology observed during experiments. Furthermore, an analysis of the repartition of absorbed energies is done, which shows that the most efficient mechanism is the localized crushing in the 0° plies.


## 1. Introduction

The use of composite materials in vehicles structural design is increasing significantly which requires a comprehensive understanding of their behavior when subjected to crash loads. The aim is to demonstrate their ability to maintain the same level of safety and crashworthiness as compared to conventional materials. Therefore many studies on composite crashworthiness have been done for the last 30 years with a wide range of knowledge and information gained concerning their crushing behavior.

However, in recent years [1–6], the interest in crashworthiness studies focus more on the development of numerical modeling resulting from the availability of better computational resources and new explicit finite element codes in order to replace the high cost experimental works. The numerical modeling of composite crashworthiness was initiated in 1989 [7]. Starting from that point, many efforts have been made by many researchers to improve the numerical modeling of composite crashworthiness in various aspects such as the choice of constitutive models [3,4], delamination techniques [4] and triggering mechanisms [5] in order to predict with accuracy the crushing morphology, specific energy absorption (SEA) and force–displacement curve, as observed experimentally. However, the complex nature of fracture behaviors in crushing makes them difficult to be predicted numerically. These behaviors are highly dependent on many parameters such as geometry, laminate sequences, mechanical properties, contact and friction [7,8]. Thus, the capability of existing numerical models to describe the initiation and progression of a crushing mode right up to the point of final failure is still limited.

Crush phenomenon in composites generally involves failure modes different from those observed in conventional metallic materials which take place at different length scales [8]. Hence, limitations in numerical models can also result from the choice of modeling scales to predict the crushing mechanisms. Some of the models developed in the past [2–5,9,10] are based on global test characterizations (macro-scale) making the model strongly dependent on the laminate behavior. Even though this methodology makes modeling simpler and decreases computational time, but it cannot represent the damage mechanisms that takes place at sub-ply scale.

Concerning models using micro-scale approach, physical representation of such a complex phenomenon is difficult, and even if it is possible, detailed physical parameters and internal variables concerning each kind of damage involved [11] are needed which are very difficult to obtain. Furthermore, it requires high computational time that would restrain study cases only to small structures.

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Between these two scales, the meso-scale approach, commonly used in composite modeling [12], seems to be the appropriate one. Although it requires more detailed laws as compared to macro-scale models, it nonetheless has the potential to capture most of the physical phenomena occurring at the crushing front [1].

A challenge in composite crashworthiness modeling is to be able to predict crushing damage modes, their evolution during crushing, and the energy absorption. This paper describes the development of a numerical modeling for carbon fiber reinforced plastic (CFRP) laminated plates subjected to crushing. The modeling methodology presented is based on numerous physical observations made during experimental crushing tests of composite plates [13–15]. Results of these observations enabled to determine the appropriate scale (ply scale or meso-scale), to numerically represent the mechanical phenomena involved in the progressive crushing of composite plates.

To adequately describe the crushing morphology in the numerical modeling which involves large deformation, the use of non-linear analyses via an explicit code is recommended along with suitable damage models [6]. Most of the damage models used in crushing modeling are based on conventional failure criterions with varying degrees of success in simulating crushing behaviors in composite structures. However, in this work an unconventional damage model is used to develop a meso-scale numerical model in order to represent the mixed-mode crushing (fragmentation and splaying) including the modeling of localized crushing at the extremity of the plies in fragmentation mode and at the same time other failures that might occur away from the plate extremity during progressive crushing. Details of the failure modes, constitutive laws and the numerical modeling strategy are explained in this paper. All parameters required in this model are elementary material characteristics, identified at the ply scale.

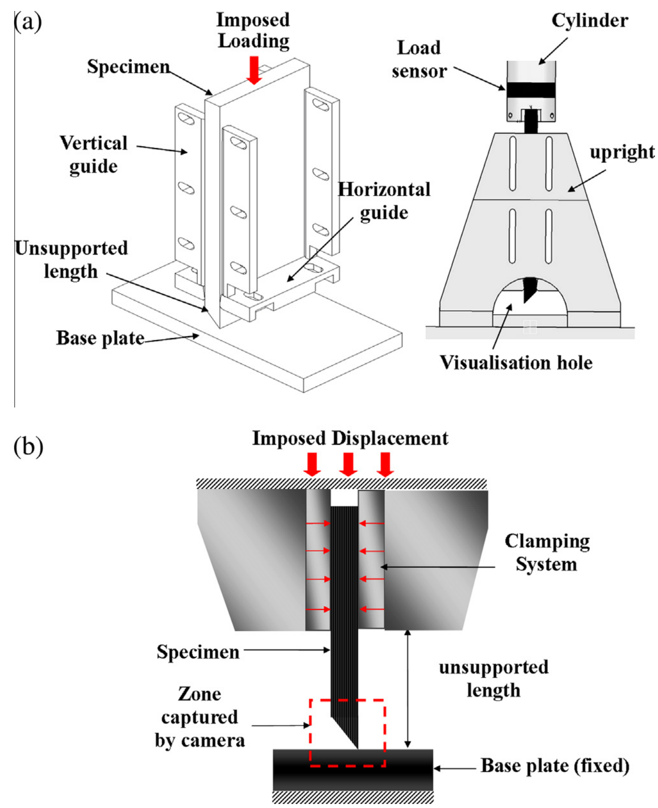


**Fig. 1.** Test fixture: (a) dynamic plate test (b) medium-scale quasi-static test. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

## 2. Experiments

### 2.1. Specimen and test set-up

Two types of experimental tests taken from previous studies [13–15] are used to observe damage mechanisms involved in low velocity crushing of plates for the development of the numerical model and also for validation purpose. For each configuration, the experimental tests are carried out twice. The same type of specimen but with different dimensions is used in both tests. These specimens are 16 ply laminates $[(0°/90°)_4]_s$ made of T700/M21 carbon epoxy UD prepregs and the ply thickness is 0.26 mm. One end of each specimen is cut to form a 45° chamfer trigger (Fig. 1).

The first kind of test is a dynamic plate crushing test performed using a drop tower with a 9 m/s initial speed and a 36 kg falling weight. The specimens are 160 mm × 60 mm flat plates. The test fixture of this test is shown in Fig. 1a [13,14]. The unsupported length was fixed to 20 mm and is constant throughout the crushing test. The design of this test fixture enables introducing constant boundary conditions across the whole width of the crushing front. As a result, the visible edges of the plate are representative of the crushing phenomenon in the whole width. The use of high speed cameras allows a real-time visualization of the crushing front during the initiation and propagation of damage and allows correlations with the force–displacement curve. The image acquisition speed is 20,000 frames per second, with a 40 pixels per mm resolution. Detailed explanations of this test can be found in [13,14].

The second test is a medium-scale quasi-static crushing test on smaller specimens: 60 mm length and 10 mm width. This test is performed using a hydraulic testing machine in compression, at a 6 mm/min constant speed. The unsupported length is set to 30 mm and decreases as the imposed displacement increases. Cameras are also used to observe precisely the crushing mechanisms (1 Hz acquisition, 100 pixels per mm). Fig. 1b shows this test set-up, and test details are available in [15].

Apart from that, additional observations are also made from micro-scale quasi-static crushing tests performed inside a scanning electron microscope (SEM), on the same laminates (but smaller specimens), to investigate details of the micro-mechanisms. High quality images of the front geometry are obtained during all tests to support a physical observation work in order to develop a phenomenological model.

### 2.2. Damage mechanisms

Due to the chamfer trigger at one end of the plate, most of the specimens experienced crushing under a combination of fragmentation and splaying. Generally, during crushing one can observe three main kinds of damage in both tests (dynamic or static) as shown in Fig. 2 and described in the following sections.

#### 2.2.1. Splaying

Early in the crushing process, ply interfaces at the tip of the specimens are subjected to high stresses. This leads to delamination and then splaying of plies. The proportion of plies that bend on each side is variable. Initiation and propagation of delamination can occur either in pure opening (mode I), shear (mode II) or more often in a combination of these two modes.

#### 2.2.2. Fragmentation

Plies that do not turn to the splaying mode undergo fragmentation which occurs at two different scales.

The first scale is a fragmentation localized at the tip of the plies. In 0° plies, localized fragmentation is due to micro-buckling of