MECHANICAL CHARACTERISATION OF 3D WOVEN MATERIALS AGAINST IMPACT LOADS

R. Muñoz[1*], R. Seltzer[1], F. Sket[1], C. González[1, 2], J. Llorca[1, 2]

[1]Imdea Materials Institute, c/Profesor Aranguren, s/n, 28040, Madrid, Spain
[2]Department of Materials Science, Polytechnic University of Madrid, E.T.S. de Ingenieros de Caminos, 28040, Madrid, Spain
**raul.munoz@imdea.org*

Keywords: 3D woven composites, impact, X-Ray Tomography, finite element

Abstract

Damage caused on a 3D woven hybrid composite by low-velocity impacts was studied from both experimental and numerical point of view. Samples were made of a composite material with several layers of Carbon and S2/glass fiber bundles impregnated with an epoxy-vinylester resin. In addition, preforms included a through-thickness reinforcement. After impact, materials were inspected by means of C-Scan and X-Ray tomography techniques, showing the influence of z-yarn reinforcement on damage patterns. A set of simulations was generated to better understand the mechanical response of 3D woven hybrid composites. A simplified version of the LarcO4 damage criteria was used to account for intralaminar damage. Furthermore, z-yarns were inserted via Binary Modeling technique. A good agreement was found between experiments and simulations in terms of force-displacement curves.

1. Introduction

Unidirectional fibre reinforced polymer matrix composites are widely used in aerospace industry, mainly due to their adaptability, excellent fatigue and corrosion performance, and high specific mechanical properties. The main drawback of such materials is their low interlaminar fracture toughness, which usually causes delamination when subjected to impact loads, dramatically reducing their stiffness and strength. This problem can be overcome by using FRP composites reinforced with a three-dimensional fibre structure in which the damage tolerance is enhanced by weaving z-yarns through-thickness. In spite of the advantages of 3D composites, the use of these materials is still limited. An important reason for this limited use is the lack of knowledge of their mechanical response under both static and impact loads, so a deeper understanding of the mechanical behaviour of such materials is required [1,2]. We present here a detailed analysis of 3D composite materials behaviour against low-velocity impact from both experimental and numerical viewpoint. Several impact tests at different energy levels were performed on fibre reinforced polymers. After impact tests, specimens were inspected by both C-Scan ultrasound and X-Ray Tomography techniques to analyze failure mechanisms. A set of FEM simulations trying to replicate results from the aforementioned tests were also carried out.

2. Materials and methods

2.1 Experimental tests

Materials tested were 3D composites manufactured by vacuum infusion of an epoxy vinylester resin in a 3D orthogonal woven perform. More details of the constituents, thickness, processing and areal density can be found in Table 2.1.

Matrix	**Fiber type**	**Processing**	**Thickness**	**Areal density**
Epoxy/Vinylester	S2-glass T700 Carbon Dyneema	Vacuum infusion	4.1 mm	6.3 (kg/m^2)

Table 2.1. Main characteristics of the 3D woven hybrid composite

The 3D composite was made up by alternating layers formed by fiber bundles oriented in the warp and weft directions, in a similar way as a non-crimp fabric. Layers were clustered into two groups: the impacted side, which contained 2.5 consecutive warp and weft layers made from T700 carbon fiber, and the back side of the specimen, that included a second group of 4.5 consecutive warp and weft layers made of S2 glass fiber. It led to a not symmetric laminate of 7 layers and 4.1mm thick with the following stacking sequence. The z-yarn binder, aimed to enhanced delamination resistance, was made up of ultra-high molecular weight polyethylene fiber (Dyneema).

Specimens were subjected to low-velocity impact tests at two energy levels (94J and 162J) to obtain partially and fully penetrated results, respectively. Tests were carried out using a DynaTup 8250 drop weight testing machine with a Ø 1/2 *in* steel tup. Square specimens of 145x145 mm^2 were cut from the composite panels. The composite plates were simply supported to the fixture at the edges with special clamping tweezers and free impact area of 127x127 mm^2. The indentor was instrumented with an accelerometer to continuously measure and record the applied force P, velocity v and displacement δ of the point where the load was applied.

2.2 Inspection

After impact, damage on specimens was evaluated by using advanced inspection techniques. Ultrasonic C-Scan technique was used to visualize a 2D projection of damage from the back face, whereas X-Ray tomography provided a three dimensional inspection of the damage patterns, including matrix cracking, fiber breakage and intertow debonding.

2.3 Simulations

The modeling strategy followed is characterised by the use of two separated parts: plies and z-yarns. Plies are modelled with solid elements, whereas z-yarns are assumed to behave as truss elements. Both meshes are superposed via Binary Modeling technique (see Figure 2.1). Early work demonstrated that the Binary Model gives an accurate account of the global stiffness of textiles with complex 3D reinforcement architecture [3]. The main advantage of this technique is that nodes from effective medium mesh (plies) are not necessarily coincident with those from 1D elements, which makes the meshing an easy straightforward process.

The behaviour of each layer is considered linear orthotropic and elastic up to the onset of the intralaminar damage by matrix or fiber failure. A continuum damage model based on the Larc04 failure criteria [4,5], where the components of the stress tensor follow a softening law dominated by the material fracture energy has been used. This model was implemented as a user subroutine VUMAT within Abaqus Explicit. A brittle behaviour was assigned to z-yarns.

Elastic properties of each lamina were calculated from the Chamis [6] micromechanics equations (1), (2), (3), (4), (5) and (6) in two steps. Firstly, starting from the properties of individual fibers and matrix, properties of the tows were estimated. After that, based on the yarn volume fraction calculated by means of digital analysis of tomographies, the same formulae were again applied to estimate properties of each lamina. The same procedure was applied to calculate strengths and fracture energies of each lamina.

$$E_l = E_f V_t + E_m (1 - V_f) \tag{1}$$

$$E_t = \frac{E_m}{1 - \sqrt{V_f \left(1 - \frac{E_m}{E_f}\right)}} \tag{2}$$

$$G_{lt} = \frac{G_m}{1 - \sqrt{V_f \left(1 - \frac{G_m}{G_{flt}}\right)}} \tag{3}$$

$$G_{tt} = \frac{G_m}{1 - \sqrt{V_f \left(1 - \frac{G_m}{G_{ftt}}\right)}} \tag{4}$$

$$\nu_{lt} = V_f \nu_{flt} + (1 - V_f)\nu_m \tag{5}$$

$$\nu_{tt} = \frac{E_t}{2G_{tt}} - 1 \tag{6}$$

where E_i and G_i are the elastic and shear moduli, respectively, ν_i the Poisson's ratio and V_f the global volumetric fraction of fibers. Subscripts *lt*, *tt* refer to the longitudinal and transverse values under tension, whereas *m* corresponds to matrix values.

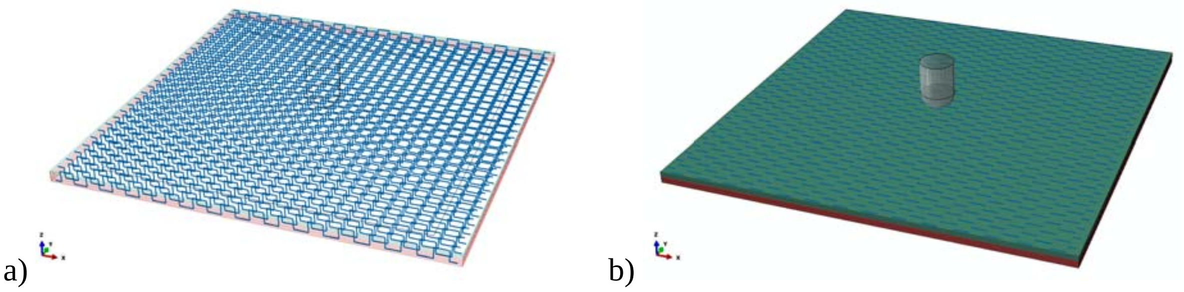

Figure 2.1. Isometric views of the FEM model. a) Z-yarn visualization and b) Solid geometry

3. Results

C-Scan Ultrasound inspection of the back face of the specimens revealed that damage is not concentrated in the impacted region, but spread across the whole specimen, following an X shape (see Figure 3.1).

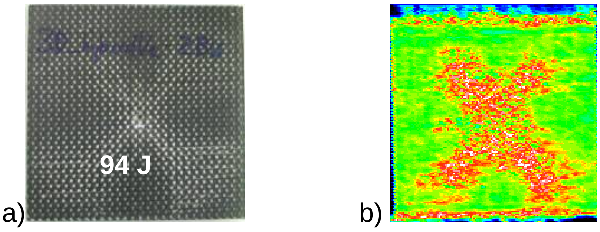

Figure 3.1. Photograph (a) and C-Scan (b) of the 3D woven hybrid composite after a 94J dropweight impact.

More detailed information can be obtained from X-Ray tomography. This technique allowed us to identifiy the location and type of damage mechanisms, like matrix cracking, z-yarn debonding, tow splitting, fiber breakage, fiber kinking and intertow debonding (see Figure 3.2).

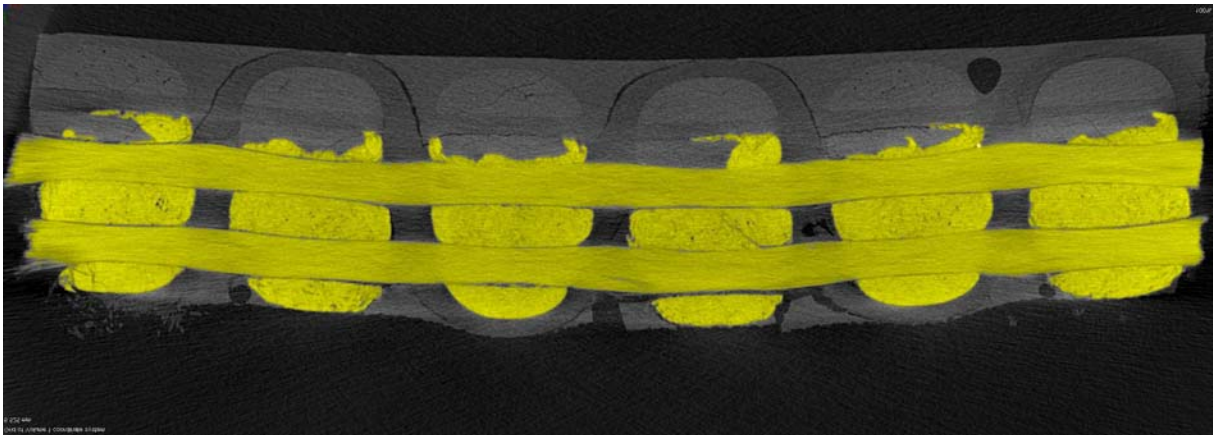

Figure 3.2. Cross section of the reconstructed volume measured by X-Ray tomography near the impacted area. S2 glass fibers are plotted in yellow.

Simulations showed that extensive matrix cracking takes place below the tup, due to a combination of plate bending and indentation (see Figure 3.3).

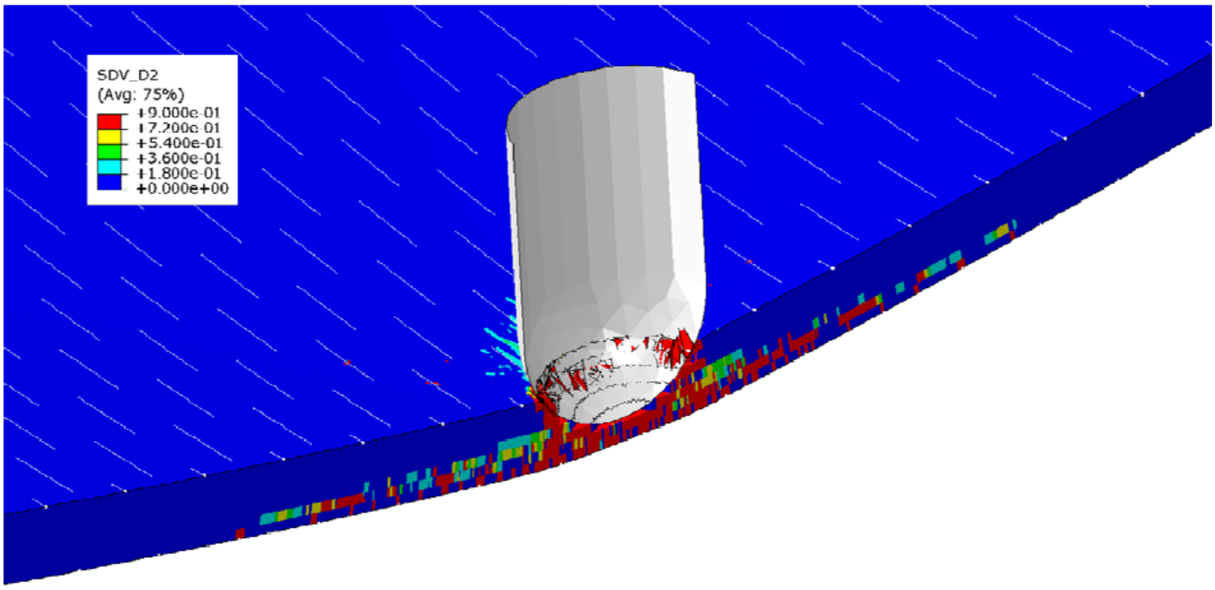

Figure 3.3. Cut of the FEM model showing matrix cracking at t=3.5ms.

Excellent correlation was found between experimental and numerical force-displacement curves for the two energy levels studied in terms of both stiffness and strength (Figure 3.4).

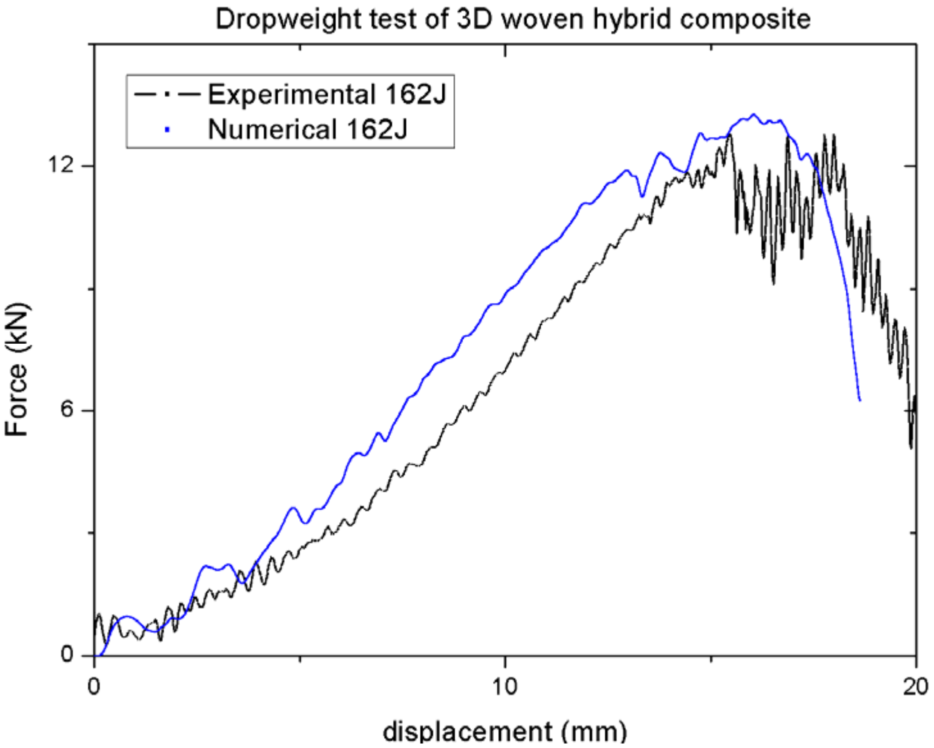

Figure 3.4. Comparison of force-displacement curves of experiments and simulations

4. Conclusions

Experimental tests can be assessed with advanced inspection techniques, like C-Scan ultrasound and X-Ray tomography, and numerical simulations to better understand the mechanical response of composites against low-velocity impact loads.

In this investigation, 3D woven hybrid composites were subjected to two levels of impact energy, showing a good performance due to the confining effect of z-yarns, which spread damage across the whole specimen.

Several damage mechanisms were found from X-Ray inspection, all of them contributing to energy dissipation.

Modelling strategy followed, which accounts for intralaminar damage and z-yarn reinforcement by means of the binary modelling technique, seems to capture well the mechanical response of 3D woven materials against impact. Excellent correlation was found between experimental and numerical load-displacement curves.

5. References

[1] A. P Mouritz, C Baini, I Herszberg. Mode I interlaminar fracture toughness properties of advanced fibreglass composites. *Composites Part A: Applied Science and Manufacturing*, **Volume 30**, pp. 859-870 (1999).

[2] Stepan V. Lomov, Alexander E. Bogdanovich, Dmitry S. Ivanov, Dmitri Mungalov, Mehmet Karahan, Ignaas Verpoest. A comparative study of tensile properties of non-crimp 3D orthogonal weave and multi-layer plain weave E-Glass composites. Part 1: Materials, methods and principal results. *Composites Part A*, **Volume 40**, pp. 1134-1143 (2009).

[3] B.N. Cox, W. C Carter, N.A. Fleck. A binary model of textile composites-I. Formulation. *Acta Metallurgica et Materialia*, **Volume 42**, pp. 3463-3479 (1994).

[4] C. Dávila, P. Camanho. Failure criteria for FRP laminates in plane stress. *Tech. Rep. NASA/TM-2003-212663. USA: National Aeronautics and Space Administration* (2009).

[5] Maimí, P, Camanho, P.P., Mayugo, J.A., Dávila, C.G. A continuum damage model for composite laminates. Part I: Constitutive model. *Mechanics of Materials,* **Volume 39**, pp. 897-908

[6] C.C. Chamis. Simplified composite micromechanics equations for strength, fracture toughness, impact resistance and environmental effects. *NASA Technical Memorandum 83696* (1984).