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# CRASH OF 3D-BRAIDED THERMOPLASTIC TUBES: NUMERICAL AND ANALYTICAL TOOLS FOR BEHAVIOUR PREDICTION

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**Abstract.** *This article deals with the experiment and numerical simulation of the crash of composite tubes made of 2,5D-braided composite. First we present the material characterization at different strain rates as well as the results of tubes which have been tested in a drop-weight tower. In a second part, simple analytical tools results are described and their results are compared with experimental ones. In a third part, we describe the bi-phase material model which has been developed. It is based on Drozdov's modelling for thermoplastic matrix and on the kinking modelling for fibers. Finally we present the experiment and numerical simulations correlations and we will conclude more particularly about the good predicting the value of energy absorption.*

## 1. INTRODUCTION

A major issue for car manufacturers is to decrease the fuel consumption of vehicles and the CO2 emissions. Among all the prospected solutions, one consists in the reduction of the vehicle weight. Due to their properties, composite materials appear to be good candidates for structural parts such as energy absorbers. Indeed, replacing these pieces, usually made of metallic, could lead to gain around 3 times the weight of these structural parts. However, the complexity of the composite behavior (heterogeneity from quasi-static to dynamic) poses the problem of possessing reliable numerical tools in order to well predict their capacity to absorb energy during the crash. This paper presents some work done in this direction.

For many years, the mechanical behavior of metallic tubes during a crash is well understood. Alghamdi et al. [1] has done an overview on the behavior of metallic energy absorbers. They have described several modes of energy dissipation and have also suggested some analytical models which have been validated. El-Hage et al. [2] have studied the crash of rectangular aluminum tubes in the numerical point of view using LS-DYNA software. This model has also been used by Yamazaki et al. [3] to optimize the structural parameters of square and circular metallic tubes. A literature overview of crash simulations of metallic tubes by Jones et al.[4] pointed also the problem of elastic and plastic stress waves propagation and their huge influence on the structural response of en energy absorber. They insisted on needed further studies to predict accurately the dynamic inelastic failure of metallic materials. In order to decrease weight of crushing tubes, different attempts have also been made to combine metallic and composite materials, such as filling metallic tubes with foams [5] or by wrapping them with fibers [6].

The crashing of tubes made of only composite materials has also been studied. Due to their lower viscosity, thermosetting matrix are more often studied and used for energy absorbers. One of the most studied composite materials is made of carbon fibers and epoxy resin. Obradovic et al. [7] used LS-DYNA Material models 54 and 55 to simulate the brittle behavior of this material. They obtained a 10% close prediction of the energy dissipated by a circular tube. The same material model has been used by Deleo et al. [8] to obtain a close match with a parameter study on square carbon/epoxy composite tubes. Greve at al. [9] uses the enhanced Ladevèze–Puck model (LP) for global ply fracture and the energy absorbing contact (EAC) implemented in PAM-CRASH. This model works only for a fragmentation mode of dissipating energy, which doesn't occur with thermoplastic composite. Zarei et al. [10] used material model 54 of LS-DYNA to simulate the crash of woven glass fibers/polyamide composite crash boxes. They get a precise prediction of the energy absorbed but not of the mode of energy dissipation. A problem with these materials is the laminate fracturation which is a low energy dissipation phenomenon. Composites with 3D fibers structures and thermosetting matrix have been introduced to solve this issue and models have been developed to simulate their behavior during lateral impact [11, 12] but not the crash of tubes.

The purpose of this paper is dedicated to experimental and numerical studies of the crash of circular 2,5D-braided thermoplastic composite tubes. We can notice that this is an innovative concept in regard of the current literature and particularly due to the fact that thermoplastic resin with 2.5D fiber structure is investigated and modeled. In a first part, the experiments about the material characterization and the crash behavior of tube are presented. In a second part, the model based on bi-phase material as well as its implementation within a VUMAT, are explained. We will conclude by the comparisons between experimental and numerical results.

## 2. MATERIALS AND EXPERIMENTS

### 2.1. Materials

The material of interest is called Twintex®. It is made of a comingled glass fibers and polypropylene matrix. The 2,5D-braided reinforcements were realized by DJP with ply by ply interlocked bias fibers. The produced fiber configurations was 320 doubled axial fibers and 320 simple fibers oriented at ±45°. All tubes were braided on a 120 mm-mandrel and consolidated under an air-empty bag in an oven at a temperature of 210°C. A thermal duct was used to avoid folds of the braided composite. The cylindrical composite tubes are either 100 (V-45-1 and V-45-2) or 200 mm long (V2-45-1 and V2-45-2). The inner and outer diameters are 116.5 and 123.5 mm respectively.

Concerning the material characterization, one braided tube has been cut and unfolded before the curing. The plate was then consolidated at 210°C. Test samples have been cut out with a 3 mm-reamer: 40*20*3.5 mm for quasi-static traction and 25*20*3.5 mm for dynamic trials. Three standard directions for the testing samples have been chosen: 0°, 45°, 90°.

### 2.2. Experimental setup

Crushing tests were carried out by using a drop-weight tower. A 319 kg mass can fall from a height of 1.3 (V tubes) and 3.4 m (V2 tubes) for an energy of 4070 and 10650 J respectively. The tubes are fixed with rivets and instrumented with a force transducer. The crash is filmed by a synchronized Photron SA1 high speed video camera. Images are stored at a frequency rate of 4000 pictures per second and combined with an accelerometer give us the displacement of the falling mass.

A 100kN INSTRON test rig is used to process static experiment. The strain rate during traction tests was 10-3 s-1. Medium strain rates tests (0.1 and 1 s-1) are conducted on MTS test rig. Dynamic tests (100 and 300s-1) are carried out by using a crossbow system. The same high speed video system is used and image correlation software gives us the deformation field of the test coupon. The local stress is given by the division of the force given by the test rigs transducer by the coupons section.

## 3. EXPERIMENTAL RESULTS

### 3.1. Traction

Tensile test gives the strain-stress curve of the material:

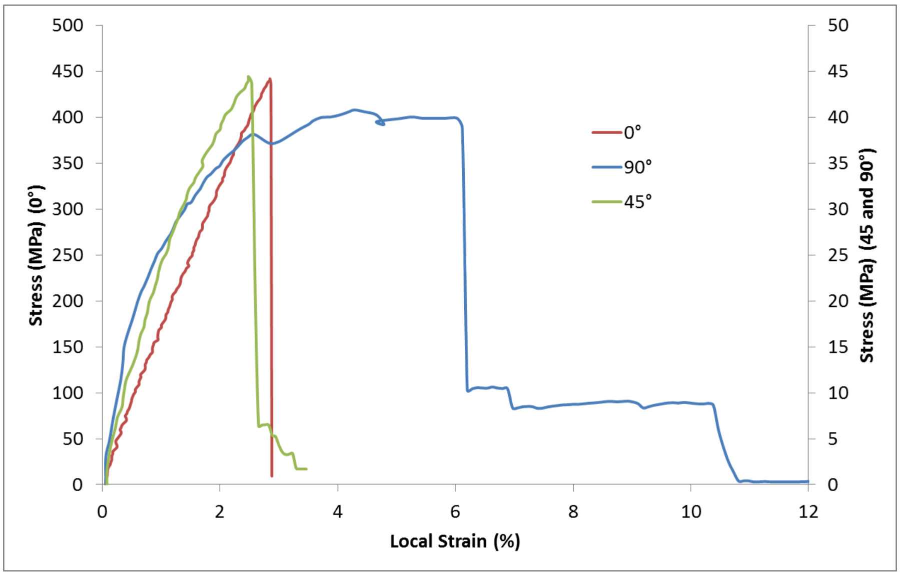


**Figure 1:** Quasi-static traction curves

Several behaviors can be noticed: at 0°, the material behavior is almost elastic brittle. For the two others directions, the behavior is non-linear, with an important plastic part of the strain. At 0°, increasing the strain rate doesn't influence the value of Young modulus (16GPa) but increases the ultimate tensile stress and the ultimate tensile strain.

**Table 1:** Young modulus values at different strain rates at 0°

| | | | |
|---|---|---|---|
| **Strain rate ($s^{-1}$)** | 0,00016 | 134 | 278 |
| **Young modulus (MPa)** | 16321 | 16772 | 16703 |
| **Ultimate tensile strain (%)** | 2.82 | 2.94 | 6.91 |

At 45° and 90°, shear and Young modulus as ultimate strain and stress are increasing while the strain rate is increasing. This is due to the influence of strain rate on the behavior of thermoplastic resins.

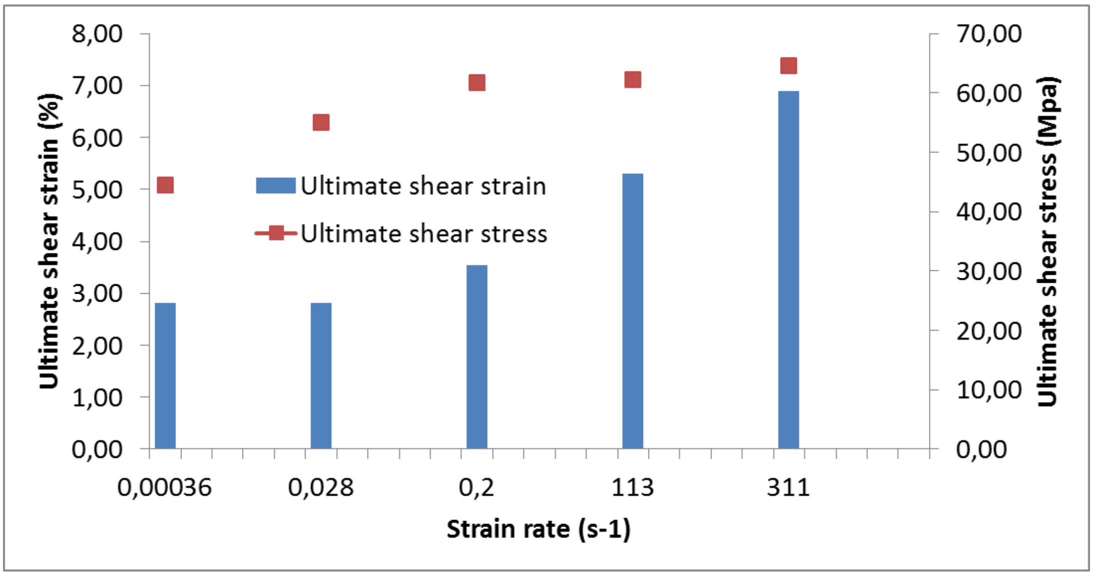


**Figure 2:** Ultimate shear strain and stress at several strain rates

### 3.2. Crash test

Several crash tests have been performed:

**Table 2:** Crushing tests of tubes made on the drop-weight tower

| Trial | Orientation (°) | Impact angle (°) | $F_{max}$ (N) | $F_{ave}$ (N) | SEA (J/kg) |
|---|---|---|---|---|---|
| V2-45-1 | 45 | 0 | 96527 | 49452 | 23097 |
| V2-45-2 | 45 | 0 | 106762 | 46873 | 22408 |
| V-45-1 | 45 | 0 | 87376 | 71351 | 34331 |
| V-45-2 | 45 | 0 | 143432 | 73377 | 34546 |

The energy was dissipated according to a mode called “splaying mode” (Figure 3). The tube is forced by the impacting mass to increase its diameter leading to a circumferential deformation and to the propagation of vertical cracks.

**Figure 3:** Picture of the splaying mode of energy dissipation

The specific energy absorbed (SEA) was calculated:

$$SEA = \frac{W}{\rho A(\delta_2 - \delta_1)} = \frac{\int_{\delta_1}^{\delta_2} F d\delta}{\rho A(\delta_2 - \delta_1)} \tag{1}$$

where $W$, $\rho$, $\delta_1$, $\delta_2$ and $A$ hold for the absorbed energy, composite material density, boundaries of the interval of stable crushing and cross-sectional area of the tube, respectively. The SEA value is around 30 kJ/kg which is the same performance as metallic tubes.

From crash $test the force-displacement curve can be drawn as Figure 4:

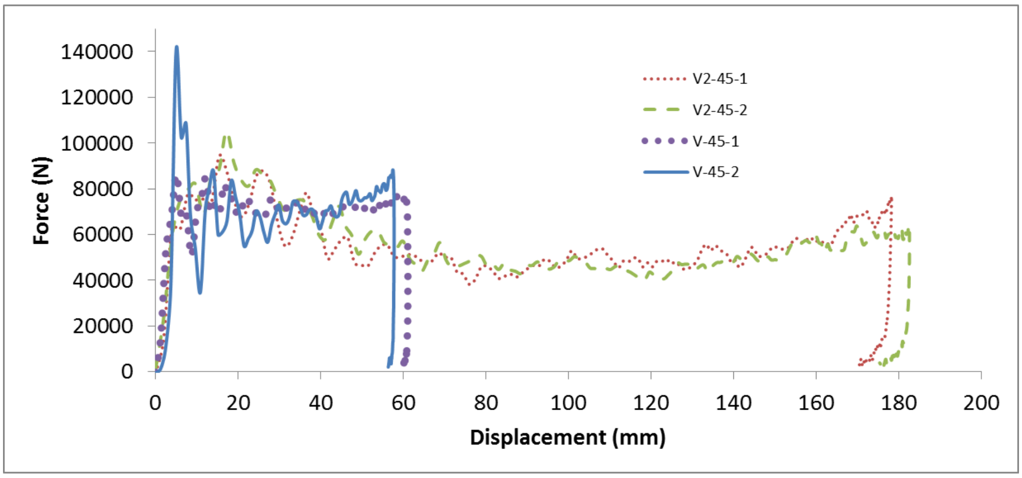


**Figure 4:** Force-displacement curve of the crash of composite tubes

## 4. ANALYTICAL MODEL

In the previous part, a crash test campaign on composite tubes allows us to see a steady dissipation of the kinetic energy of the impactor by progressive damaging the tube. Two important aspects of the crash have been identified:

- The first is the failure mode which drives the energy dissipation.
- The average strength during the stable part of the crash of the tube.

The splaying failure mode has been observed during the tests. The performances of tube during a crash such as the average effort are dependent of this mode. To enable a quick and easy performance prediction of a tube knowing his failure mode, an analytical model was developed. Using a simple chart paper, it would be possible to obtain an interesting approximation to the average effort, allowing a first choice of material for the part of the manufacturer.

Jones [14] created an analytical model to represent the crash of a metallic tube with the local bending mode. The material is perfectly plastic and the sum of the energy of different phenomena is minimized to get the value of the average strength during the crash. This result is obtained by solving the derivation of these energies by an internal parameter (characteristic length) equals to zero. More phenomena have been added to represent other materials suachas composite materials [15-17].

A model has been developed for the splaying failure mode:

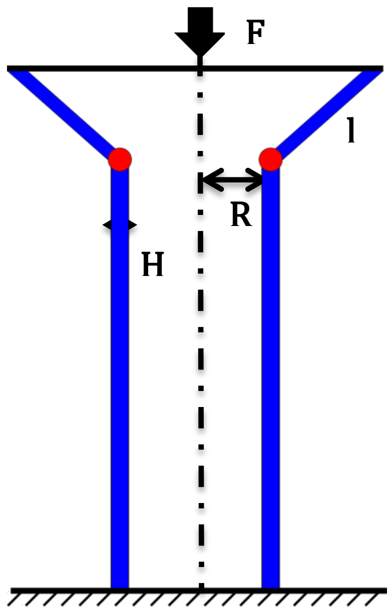


**Figure 5:** Picture of the splaying mode

The material is orthotropic. The problem is resumed to a wall element of length l which rotates outwardly. Energy is dissipated between a plastic hinge, the circumferential extension, shear deformation and friction. We get the dissipation by the plastic hinge:

$$D_1 = 2\pi R M_0 \frac{\pi}{2} \tag{2}$$

where $M_0 = \frac{2\sigma_0}{\sqrt{3}}\frac{H^2}{4}$ the moment of plastic bending, $R$ the radius of the tube, $\sigma_0$ the elastic yield stress and the thickness $H$ of the tube.

The calculation of the dissipated energy by the circumferential deformation is based on the integration of the stress-strain curve in the circumferential direction. It is assumed that the height tube rotates to form a high angle which exceeds the limit rupture strength defined by a length $l_1$ of approximately $R\varepsilon_{max} = 2.6\ mm$. We get:

$$D_2 = 2\pi H\left[\int_{R}^{R+l_1} \sigma : \varepsilon\ dV + \int_{R+l_1}^{R+l} e_{max} dV\right] \quad (3)$$

Energy dissipation is added by shear in the thickness of the wall thanks to the stress-strain curves at 45° at high speed of deformation. So we assume that the shear curves 12 and 13 are identical, given the lack of experimental data on the mechanical properties in the thickness:

$$D_3 = \pi H e_{cmax}(l^2 + 2Rl) \quad (4)$$

Where $e_{cmax}$ is the maximum energy density dissipated by high-rate shear deformation. Finally, in case of splaying mode, the friction energy between the composite and the plane is calculated:

$$D_4 = \mu P_m l \quad (5)$$

In the case of splaying, we obtain an average force of 47923N which is in the interval of variation of the experimental values (49452 and 46873 N).

## 5. COMPOSITE BEHAVIOR LAW AND ITS IMPLEMENTATION

To be more adaptive and to adapt to the law for thermoplastic behavior, the model developed is biphasic: the calculation of fibers and matrix strain and strength are separated. The fibers have an elastic brittle behavior and only the strain in fibers direction is considered. The different orientations of the strands of fibers are considered and uncoupled. A damage model is used to obtain a progressive breaking of the fibers between two user-defined values of strain. For oriented strands of fibers, global strains are projected in the fibers coordinate system. Fibers stress and damage is calculated and projected in the global coordinates.

To better simulate the behavior of fibers under compression a kinking model is used. The angular acceleration of fibers is determined by application of the principle of virtual work on a basic element. Strains induced by this phenomenon are introduced in the strain matrix calculations. Its calculations are based on the model of Drozdov for the behavior of thermoplastic [13]. This model uses a quasi-incompressible formulation. Stresses and strains have to be split in deviatoric and hydrostatic part. An elastic plastic separation is done for the deviator part while the hydrostatic part is considered as fully elastic. The elastic strain represents a polymer strand stretch and plastic strain describes polymer strand slippage. Two cases are defined: active loading if the deformation reached the highest value which has ever occurred and loading-reloading if not. The plastic deformation is calculated using the function $\phi$ according to these equations:

$$\frac{d\varepsilon_{max\ p}}{dt} = \phi(t)\frac{d\varepsilon_{mat}}{dt} \quad (6)$$

where $\varepsilon_{mat}$is the deviatoric part of the matrix strain. The function $\phi$ is defined using:

$$\frac{d\phi}{dt} = \bar{A}\big(1-\phi(t)\big)^{\bar{B}}\ with\ \phi(0) = 0 \quad (7)$$

$$\bar{A} = A\left|\frac{d\varepsilon}{dt}\right| \; with \; A \geq 0 \tag{8}$$

$$\bar{B} = B_0\left(1 + B_m \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \tag{9}$$

Making the hypothesis that internal energy is the sum of elastic energy for each polymer strand averaged on the medium plus an hydrostatic term and using the inequality of Clausius-Duhem:

$$\sigma_{mat} = 2\mu_m(1-\phi(t))\varepsilon'_{mat\,e} + K\,tr(\varepsilon)I \tag{10}$$

where $\mu_m$is the modulus of the matrix for the deviatoric part and $K$ the modulus for the hydrostatic pressure. $\mu_m$depends of the strain rate as the $\bar{B}$ parameter. The calculation of the homogenized stress is done using a Reuss model and the volumic ration of matrix in the composite $V_m$:

$$\sigma_{hom} = \frac{\sigma_{fibre}(1-V_m) + \sigma_{matrix}V_m}{(1+\varepsilon_{transverse_1})(1+\varepsilon_{transverse_2})} \tag{11}$$

The material has been implemented in Abaqus using a VUMAT. An explicit method of integration has been chosen with a Newmark scheme. The programming language is Fortran90 and the compiler is Intel Fortran Compiler.

## 6. VALIDATION

### 6.1. Tensile tests

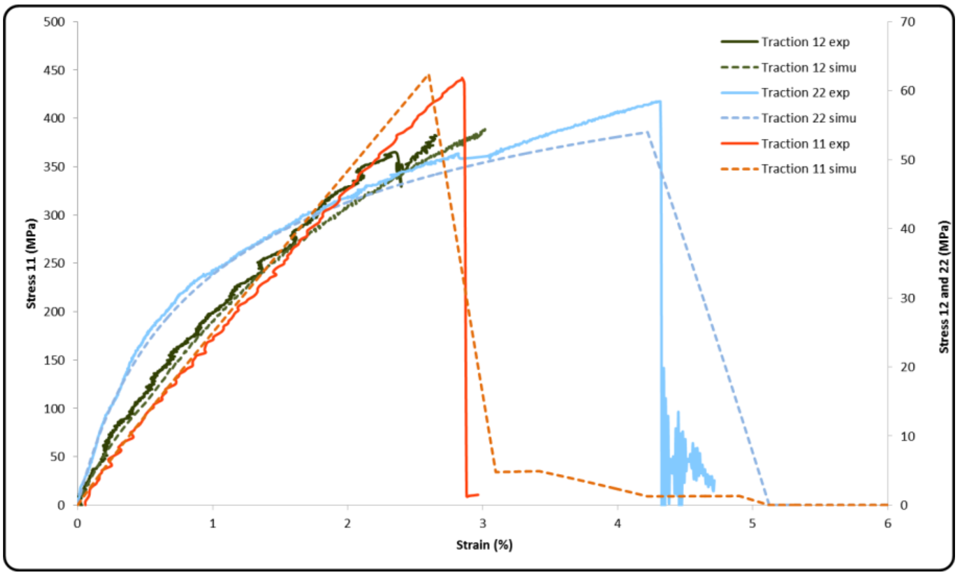


**Figure 6:** Experimental and simulation curves for traction curve in different directions

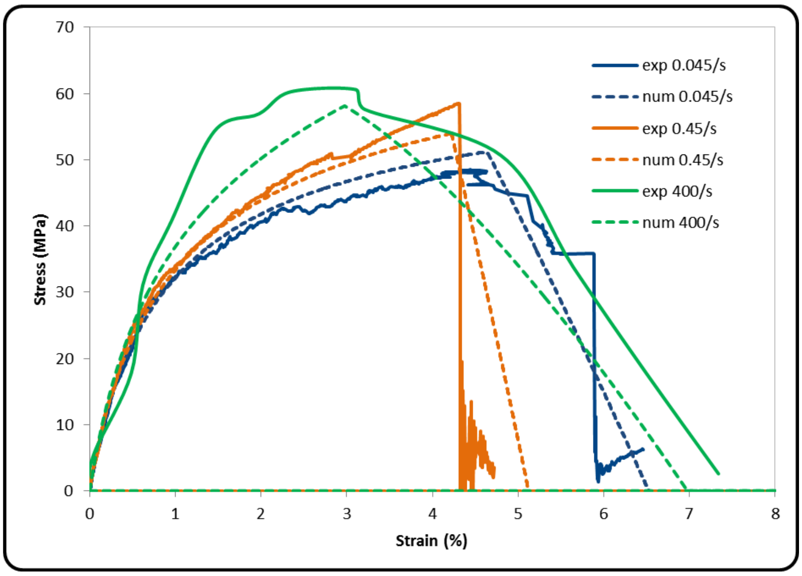


**Figure 7:** Experimental and simulation curves for traction curve at different strain rates

To verify the validity of our model, simulations of tensile tests have been realized. Using the software Abaqus, first tests were made on a unique 3D element with a linear interpolation. One face was blocked for the direction of traction. On the opposite face was imposed a constant velocity. Several material orientations and deformation rates have been tested. A good coherence with the experimental results has been found.

To validate our model, the tensile tests have been fully represented. The same elements have been used. Using different orientations and deformations rates, the material model have been validated.

## 6.2. Drop-weight tower tests

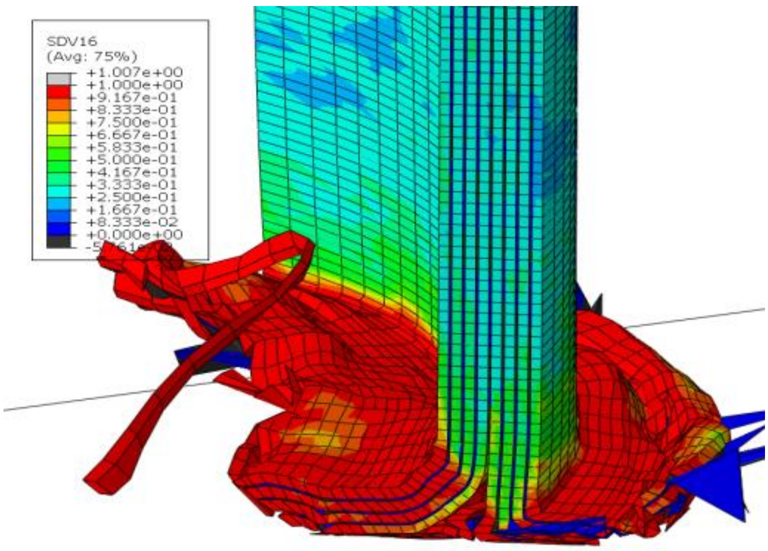


**Figure 8:** Simulation of drop-weight tower test

Using the same software, we simulate the crash of circular tubes. To reduce CPU time cost, only an eighth of the tube is represented and bigger elements are used far from the impact area. An eighth is enough considering that the splaying mode presents a cylindrical symmetry. Symmetry boundary conditions are used. The support and the impacting weight are represented by two rigid plans. The first one is embedded. The impacting weight have been imposed a vertical speed and a mass corresponding of an eighth of the real one.

The simulation of a crash of a composite tube is still in development. More work are needed to get a satisfying prediction of the crushing and of the performances of the tube.

## 7. CONCLUSIONS

A material model has been developed to simulate the behavior of 2.5D braided composite with glass fibers and a polypropylene matrix. The material has been characterized using tensile tests at different deformation rates. An analytical model has been created to model of the splaying based on the calculation of the energy dissipated by several phenomena. The value obtained for the average force is in the range of the experimental ones. A VUMAT model of material has been developed for Abaqus simulations. As a biphasic model, fibers and matrix calculations are separated then combined using a Reuss model. The kinking of the fibers is implemented. A visco-elastoplastic model is used for the matrix. Simulations of the tensile tests have been realized and the material model has been validated. Used to simulate the crash of the tubes, the material model will give a good prediction of the mode of energy simulation and of the performances of the energy absorber. To go further, simulations with other materials can be done to evaluate the potential of the model and its domain of validity. Another perspective is the development of an analytical model to get the mean crush force of a tube.

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