SIMULATION AND TESTING OF A POLYPROPYLENE-GLASS FIBRE REINFORCED WOVEN COMPOSITE UNDER HIGH STRAIN RATE COMPRESSION LOADING

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Abstract

Medium costs composites materials are good candidates to develop lightweight and economical shock absorber for the next generation of cars. In this context we are interested in simulating the behaviour under compression loading of Twintex a long glass fiber reinforced polypropylene. Simulation will be using ABAQUS Environment, its explicit solver and a custom written material behaviour law. Material testing will be carried with a standard tensile rig and an original layout using a crossbow/Hopkinson rig. A special attention is made to compression behaviour, often neglected but critical for crash absorber behaviour. The model will be checked on the testing specimen and its validity will be discussed.

1 Introduction

To develop a modern automotive crash absorber having the ability to simulate the compressive behaviour of a material is essential. We propose a numerical model and an experimental characterisation for the Twintex, a glass fiber-polypropylene woven composite showing good mechanical characteristics, availability and provided in a reasonable price range. Previous work on this material was done for the development of automotive absorber [1 2] and showed the potential of this composite. A constitutive law is introduced based on a mesoscopic model [3 4 5]. We will study the case for an equilibrated woven. Testing and simulations will be carried on block specimen (figure 1) for compression following works [6 7 8] on microbuckling in compressed carbon epoxy materials and on classical tensile specimen (figure 2).

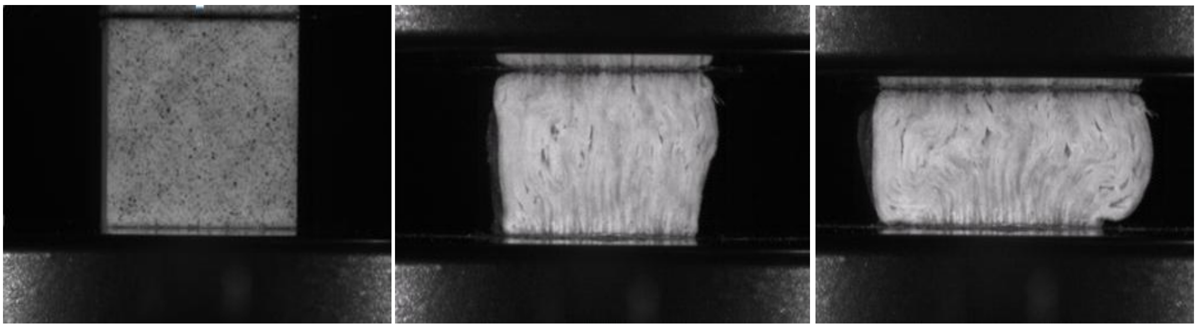

Figure 1. Compression specimen. Left intact with paint for correlation. Center and right crush with ply buckling.

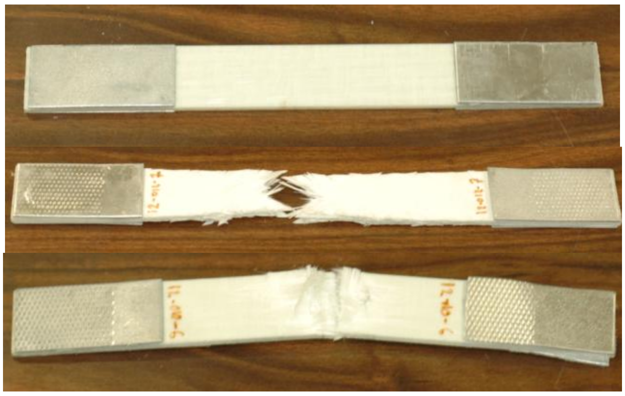

Figure 2. Tensile specimen. Upper: Intact. Center: 45° Broken. Lower 0° Broken.

These layout where introduced to prove that compressive failure in AS4 epoxy composite is triggered by elastic buckling of fibers in the matrix. The sensitivity of material stiffness and plasticity to strain rate will be investigated following works on AS4 epoxy from Marguet [5] and works on thermoplastic by Schoßig [9] finally a comparison between tests and simulations is exposed.

2 Models and Numeric methods: Behaviour law

We are using an evolution of a mesoscopic model [3 4] with explicit formulation developed previously inside our laboratory [5]. This model is based on a work on dynamic damage evolution in carbon epoxy composite. Damage quantify material stiffness reduction. With E actual Young modulus, Eo initial Young modulus, damage *d* is defined as:

$$E=E_0(1-d) \tag{1}$$

For a mesoscopic model two laws are defined, one for the ply and one for the interface. Directions reinforced by fiber are elastic with a damage factor. K11 and K22 are stiffness matrix factor for direction 1 and 2:

$$K11=\frac{E1\times(1-d1)}{1-v12^2} \quad K22=\frac{E2\times(1-d2)}{1-v12^2} \tag{2}$$

with Ei young modulus, *di* damage factor for direction i. v12 is the Poisson's coefficient. Damage evolution energy Yi is computed for direction 1 and 2 with respective strain εii:

$$Y1 = \frac{1}{2}K11 \times E11^2 \quad Y2 = \frac{1}{2}K22 \times E22^2 \tag{3}$$

A function defining damage evolution is defined:

$$f(Y1) = \frac{\sqrt{Y1}-\sqrt{Yo1}}{\sqrt{Yc1}-\sqrt{Yo1}} = d1 \tag{4}$$

Yoi represent a minimum energy for initiating damage for direction i. Yci is the energy corresponding to full damage (1.0) for direction i.
This kind of model does not converge with mesh refining so we are using a model regularization by controlling damage evolution rate:

$$\dot{di} = \frac{1}{\tau}\left(1-e^{-\alpha\langle f(Yi)-di\rangle}\right) \tag{5}$$

A Newton method is used to guarantee convergence between stress and damage at each time point. A comparable law is used for interface behavior to describe delaminating but damage is shared with a common damage factor for opening and shear delaminating. A maximum damage is defined to delete the element past a specified damage.
For shear behavior plasticity is taken into account with classical plasticity hardening and is time regularized too. Damage evolution is using a modified evolution formula:

$$f(Y12) = \frac{\log(Y12)-\log(Yo12)}{\log(Yc12)-\log(Yo12)} \tag{6}$$

A set of variables has to be determined at each time step comprising stress, plastic strain, a plastic parameter and finally damage. A Newton method for multiple variables, return mapping algorithm [10], is used to find a valid set of variables within acceptable error.
Figure 3 show typical reaction of model at integration point:

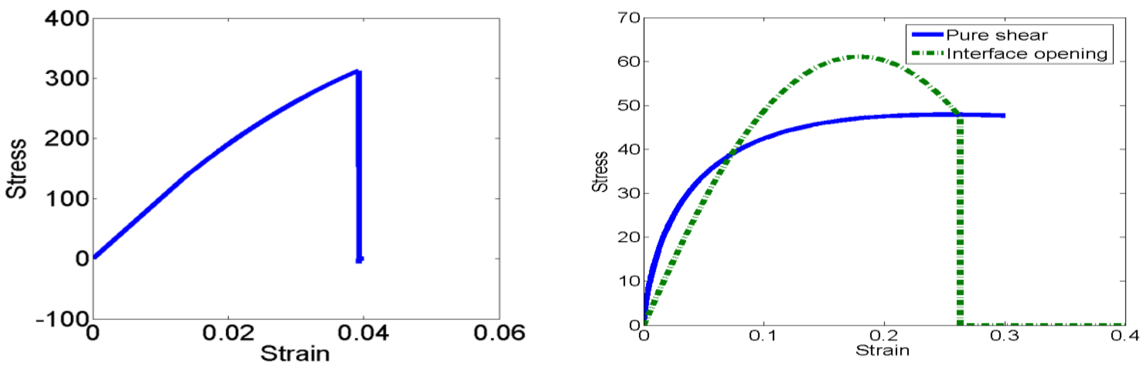

Figure 3. Model output for typical loadings: Left 0° orientation Right 45° and interface.

Modulus, Yo, Yc and maximum damage can all be affected by strain rate with Johnson Cook type of formulation if needed following work from Johnson [4].
Ply elements material properties are identified with tensile tests results. Interface elements are identified with an invert method on compression testing simulation. A possible alternative would be to use a Double Cantilever Beam rig to identify interface coefficients.
The objective is to present a model describing observed physics correctly but keeping a reasonable computational time cost. Material law is coded in FORTRAN and implemented in ABAQUS Explicit solver via VUMAT interface.

3 Testing Method

Two kinds of samples are tested. A flat coupon with aluminium wedges is used for static tensile tests presented figure 2. A thick cube containing many layers is used for compression tests (figure 1). For 0° traction specimens several geometry were tried but the flat coupon with aluminium wedges showed best strength and was the only one to break in gauge part far from grips. Flat coupons and cubes are large enough to contain a full representative element of the woven fabric. Flat coupons are $200 \times 25 \times 3mm^3$ with a 100mm long useful zone. They contains 6 ply and orientations are [0°] or [±45]. Cubes dimensions are 20mm by side and contain 40 ply. A 100kN INSTRON test rig is used to process static experiments for both compression and tensile. It is equipped with auto-tightening grips for traction and two plates for compression. Dynamic crushing of cubes is carried out with a crossbow system depicted in figure 4. The crossbow test rig is using an impactor mass (24kg or 260kg) propelled by big elastics and a receiver Hopkinson bar. Both are guided to move only longitudinally. Impactor speed is measured by lasers and Hopkinson bar use standard strain gauges. The experimental set-up is equipped with a high speed video camera: PHOTRON APX It allows us to following qualitatively the absorption mechanism for compression testing and data will be available for future work using correlation.

The quasi-static tensile and compression experiments are carried out at a strain rate equal to 0.001/s. On the crossbow system two impact speeds are investigated: 4m/s and 8m/s yielding strain rates of 200/s and 400/s respectively. At quasi-static strain rates, some specimens are loaded by cycle of solicitation-relaxation. This allows measuring plastic strain at zero stress and isolate damage *d* on the next loading.

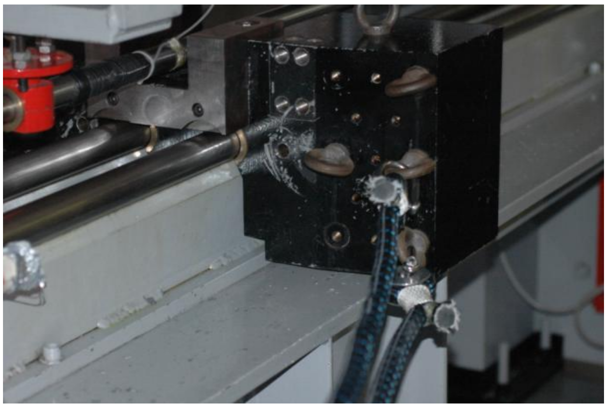

Figure 4. Crossbow/Hopkinson impactor.

3 Test Results

3.1 Traction 0°

Behaviour is almost elastic with brittle rupture (figure 5). We can observe a loss of modulus "damage" with cycles (figure 5). From an initial 15GPa modulus goes to 13GPa before a fragile breaking at 3.2%. A specimen broken in the useful region is pictured figure 2.

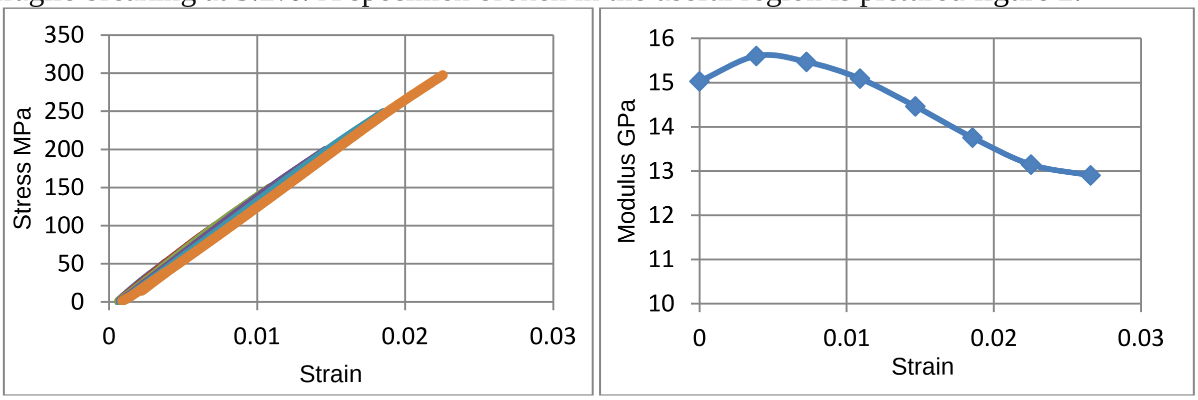

Figure 5. Left: cycled quasi static tensile test. Right: modulus evolution between cycle

3.2 Traction 45°

±45° specimens show permanent plastic deformation after unloading, a sensible loss in modulus and an important hysteresis (figure 6). On the ±45 degree specimens non-linear effects are much more important. The modulus goes from 3.4GPa initially to 0.75GPa for 17% strain. Breaking occurs in a smooth sliding around 22% strain, figure 2.

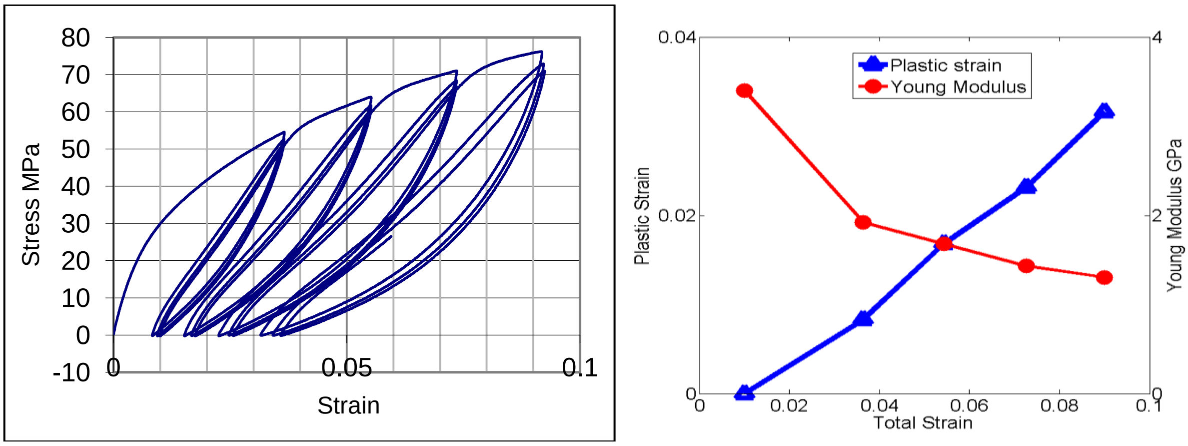

Figure 6. Left: Cycled quasi-static tensile test ±45°. Right: modulus and plastic evolution with cycles.

3.3 Compression 0°

Quasi static cycled tests were conducted but showed no reduction in modulus between cycles. A kind of adaptation of specimen to metal plates pushing them occurred but the strain measure is in the 0.001 range and so will be neglected. Two kind of dynamic tests are presented. A first set of 3 specimens where impacted at 4m/s and failure did not occur. In a second time those where impacted and destroyed at 8m/s. A second set was tested directly at 8m/s. Those results are compared to a static test (figure 7). A low pass filter with a 35 kHz cut is used to remove parasites.

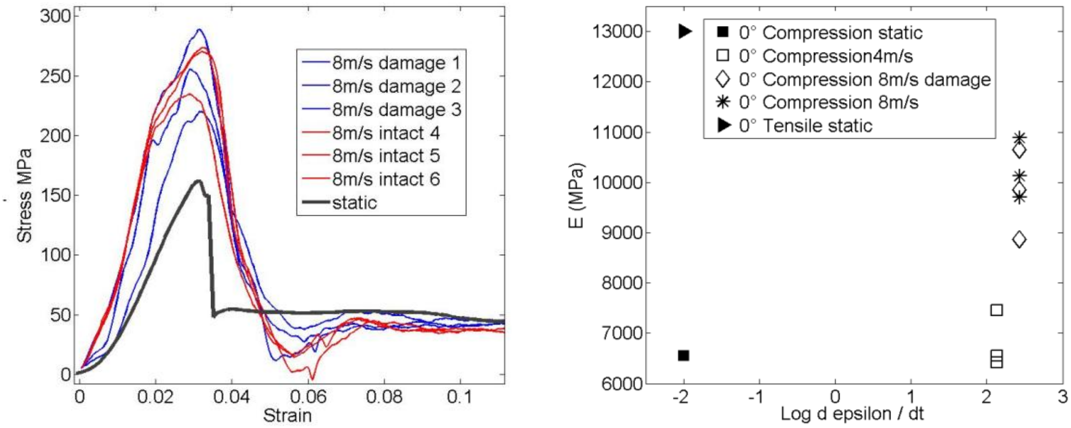

Figure 7. Compression 0° specimens results. Right modulus evolution with strain rate.

Modulus in static compression is 50% lower than in traction and maximum stress see the same reduction (figure 7). Rising impact speed increase Young modulus but it does not reach static traction stiffness.

Two out of three specimens being damaged before their 8m/s crush show no particular difference with intact specimen but one is softer. A pack of fibers may have been deteriorated by the first test.

3.4 Compression 45°

For 45° specimen behavior is comparable with traction tests but static stress levels are 20% lower for a given strain (figure 8 right). Maximum stress is obtained at a smaller 13% strain (figure 8). Static modulus is 45% lower in compression compared to traction with 1.4GPa compared to 2.5GPa.

Young modulus for ±45° specimen is increasing with speed but the difference is much more important than 0° specimen with a 2.7 factor. It can be noted too that 4m/s and 8m/s show very similar modulus.

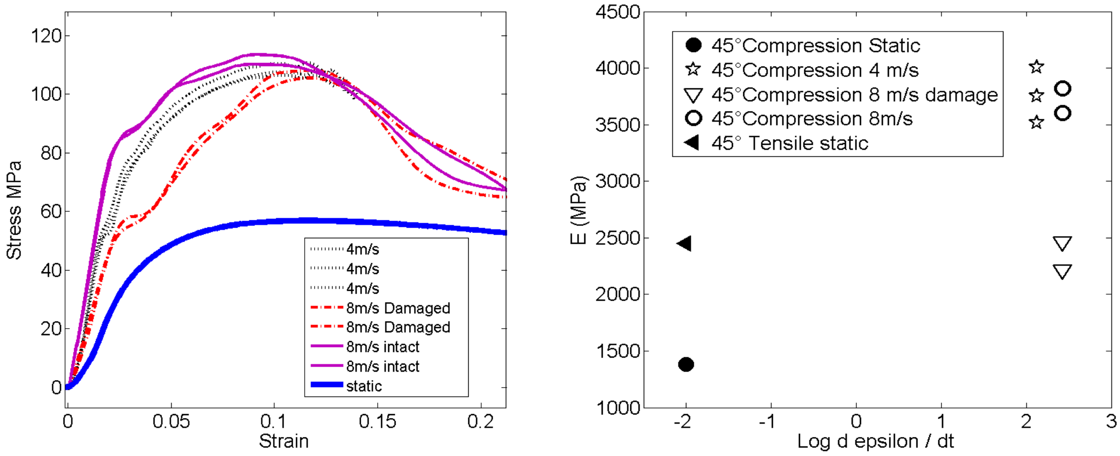

Figure 8. Compression ±45° specimens results. Right modulus evolution with strain rate.

3.5 Testing campaign conclusion

The Twintex is a material showing a quasi-brittle behaviour when fiber orientation is 0°. However material properties are lower in compression but an impact speed raise can restore partially those properties. 45° Specimen are much softer and stiffen quickly with strain rate. They present lower properties in compression at low speed.

5 Simulations results

5.1 Traction simulation

Reproducing the tensile test in the simulation is interesting compared to a simple model calculation at integration point because it takes into account structural modification in the specimen (figure 9).

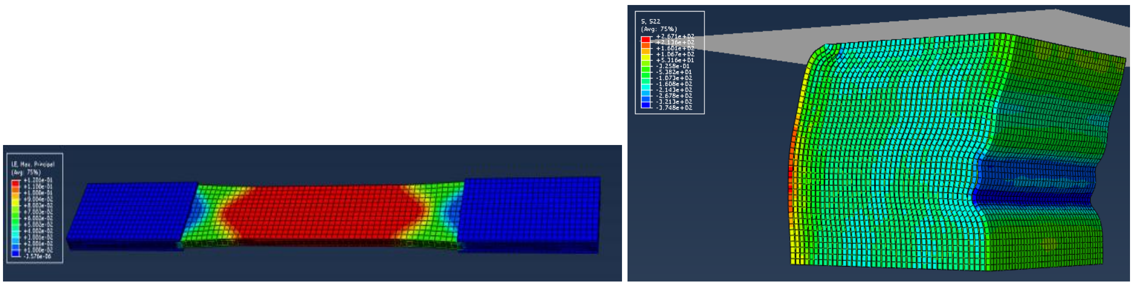

Figure 9. Simulation visuals, principal strain plot. Left Tensile, Right Compression.

The correlation with experiment is good. Aluminum wedges have been brought to the model to correctly represent boundaries, simpler conditions badly affect results.

5.2 Compression simulation

Impactor and Hopkinson bar surfaces interacting with specimen are modeled by two analytical rigid plates. The plate for the receiver is encastred and the impactor plate receives a mass and an initial speed. This make the hypothesis receiver bar movements are negligible. A general contact conditions is included. Empirical observations from damaged specimens (figure 1) and video show obtained failure mode with our model (figure 9) are comparable to reality. Friction coefficient sensitivity is observed and can make switch from a failure mode to

another: for example the top can slide on one side or have no perceptible movement resulting in slightly different deformed shape but comparable crush energy.
Model shows a good correlation with experiment for both modulus and failure strain staying within a 15% error range (figure 10) we find acceptable for crash test. However post failure behaviour show too high stress for 0° specimen (40% error range).

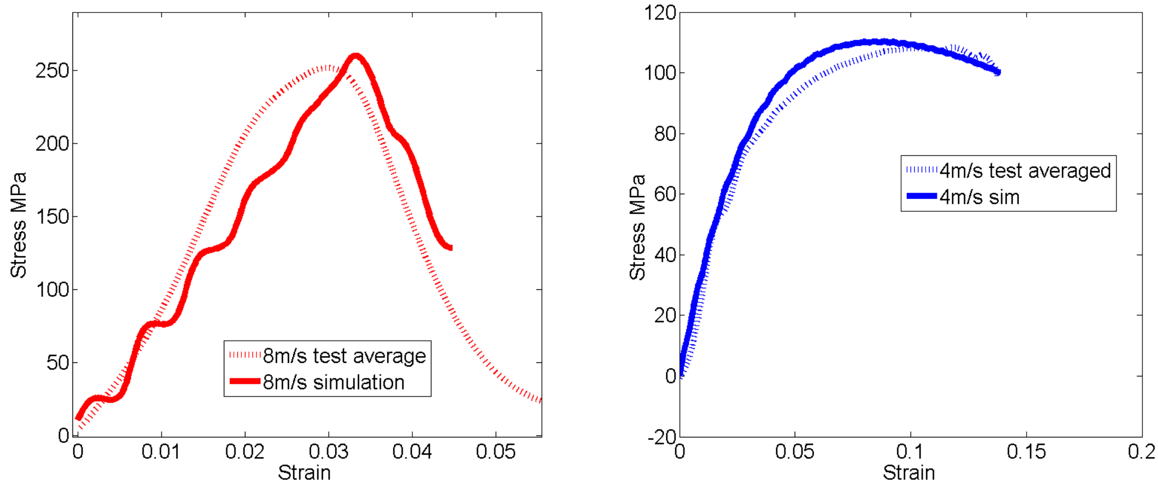

Figure 10. Model results. Left compression 0° 8m/s. Right Compression 45° 4 m/s.

6 Discussion

Compression specimen showed lower stresses than tensile one but raising loading speed results in higher stresses. Our interpretation is that ply buckles in compression as shown on figure 1 and so contribute less to the resistance of the composite structure. When speed raise inertia reduce lateral movement freedom and limits buckling so the qualities seen in traction on the material are recovered. Each fiber can also buckle by itself and modify modulus/strength with speed sensitivity but we don’t have any way to measure that for now.
For 45° specimen high speed modulus is 170% higher than static test and is also 34% more important than traction modulus. This means buckling lock is insufficient to justify this effect. Our proposition to explain this stiffening is that the polypropylene matrix is stiffer at high strain rate resulting in higher stresses on 45° specimens. The stiffening effect could already be "capped" at 4m/s explaining the similar results between 4m/s and 8m/s.
ABAQUS simulation shows a good correlation with our tests. No distinction is made in the material law between compression and traction so the material law is not written to fit arbitrarily compression results. Shear stiffening with speed is capped at 35%. This kind of simulation takes into account large movement and masses comforting us in our assumption that the stiffening is largely due to inertia effects.

7 Conclusions

This work is promising concerning future simulation of cars crash absorbers. We showed our model is already working on structure showing complex behaviour like the cube during crushing and that we are able to identify it on a reasonable amount of testing data. The actual model handle fracture within the ply very roughly and the model has to be checked and eventually improved on this point. The computational cost remains small for a full 3D model as it is able to run on a desktop computer in a few hours (depending directly on loading speed). The next step will be to compute larger structure. This should be possible thanks to the parallelizable mathematical structure of explicit formulation. Some points remain to be investigated. For now there are distortions problems when going further into the compression calculation. A simpler law (pure elastic/plastic with isotropic hardening) allow to go beyond this point with a good visual correlation (figure 11) so a solution has to be find for our current model, and handling correctly element deletion seem to be the key.

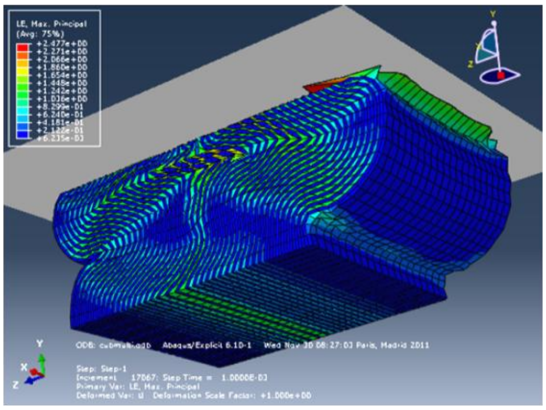

Figure 11. Simple law 0°

Model validity after failure and identifications methods have to be improved. Recently delaminating elements calibration is done by an invert method on compression results with a validity check in traction but an alternate way to measure those parameters is needed and we are investigating using a double cantilever beam fixture or a flexion system [1]. Finally I would like to sincerely thank Franck Pasco and Pierrick Guegan for the energy invested in this work and for sharing their skills in instrumentation and mechanical testing in general.

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