CHARACTERISATION OF A CRUMB RUBBER MIXTURE FOR ROAD RESTRAINT SYSTEMS

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ABSTRACT

The need for studying new materials for the construction of road restraint systems arises from past design experiences and from road construction and maintenance demands. This is particularly true for the development of crash cushions. New materials shall comply with requirements of mechanical strength and energy absorption capability with regard to the shape and the class of the system itself (gating or not gating, redirective or not redirective). In particular, the behaviour of materials in the conformation assumed in the system when impacted shall guarantee:

- the respect of crash cushions performance parameters;
- the redirection-ability, if required;
- the avoiding of the detachment of any part or portion that could be hazardous during and after the impact;
- an easy repairing and/or substitution of damaged parts;
- the durability of parts before and after the impact.

This paper investigates the possibility that a crumb rubber mixture has to fulfil those requirements with the not negligible environmental advantage related with the use of recycled materials obtained from minced truck and car tyres.

The experimental phase consisted both in the static and dynamic characterization of the material also by means of a drop-dart equipment, as well as the numerical modelling of tests with the aim of assessing the values to be given to the mechanical parameters of the materials in the future simulations of impacts on road restraint systems' models.

Keywords: road safety, restraint systems, crumb rubber, crash cushion, LS-DYNA3D

1. INTRODUCTION

This study started by the two following statements.

A crash cushion is designed to reduce the consequences of the event by decelerating an out-of-control vehicle before it strikes a rigid roadside hazard.

Each year in Europe 250 million of exhausted tyres are dumped. In Italy the annual production of tyres is of 434.500 tons on a European full amount of 2.660.000 tons (source: ETRA, European Tyre Recycling Association, 2003). Of these enormous quantitative a 35% in Europe and a 66% in Italy is still now taken to the dump.

2. EXPERIMENTAL PHASE

The experimental phase concerned the characterization of a crumb rubber mixture produced with exhausted truck and car tyres and resin. The aim of this phase was to evaluate the capabilities of a waste material like crumb rubber when employed in the construction of road restraint systems in general and in particular, of impact attenuators. The experimental phase comprised either a mechanical characterization of the material with static and dynamic compression tests and a numerical analysis of the same tests performed by means of a worldwide utilized non linear finite element analysis software (LS-DYNA3D). The main phase was divided into several minor activities that involved, at different stages, the Civil Engineering Department (DISTART) of the University of Bologna (BO), the Mechanical Department of the Turin Polytechnic in Vercelli (VC) and the Technical Laboratory of the REMP S.p.A. in Fognano di Brisighella (RA).

2.1 Crumb rubber mixture and specimen production

The material proposed in this study is a vulcanized mixture of small rubber particles obtained from exhausted tyres and binding resin. A similar material has already been adopted for the production of kerbs and safety elements to be used in urban road construction. The elastomeric rubber particles are obtained by the industrial process of crushing and crumbing tyres. The resin used as binder basically consists of isocyanate modified with diphenylmethane diisocyanate.

The mixture production is easy. Crumb rubber at room temperature should be mixed with a target 10.5% of resin calculated on the weight of the rubber. This percentage is chosen on the basis of an aimed full resin coating of rubber particles which depends on the particle' size. When completely coated rubber particles look wet and sticky and the loose mixture assumes a viscous thinning behaviour under stirring. No hardening occurs at room temperature and within few minutes, but when the mixture is left to settle, vulcanization spontaneously begins depending on pressure and temperature.

A number of twelve specimen has been produced for testing. Specimen production is as easy as mixture production. Once the mix is poured into a mould it assumes its shape and settles. Compaction is not compulsory, but a regular and homogeneous action on the poured material surface is advisable to get a smooth and clean shape of the specimen. Compaction is significant when a certain material density needs to be achieved. For this study the target density of the hardened material was supposed to be the lowest possible to minimise the production process efforts (figure 1).

The most time consuming stage of specimens production is vulcanization. This process, that involves the reticulation of resin components under the action of pressure and temperature, starts when mixing is over. An accelerated vulcanization requires the specimens to be stored in a oven for at least 2 hours at more than 100°C. If oven pressure is set higher than atmosphere, the process is quicker depending, in particular, on the bulk of the vulcanizing material and on the thickness of the moulds.

Figure 1 Laboratory specimens production

Four different cylindrical moulds have been used to produce the specimens. This was related with the possibility of testing the material in different test configurations and different stress levels. Table 1 shows the number of specimens produced for each mould's size.

Table 1 Produced specimens number and dimensions

# of specimens	Diameter (mm)	Height (mm)
2	150	130
5	150	180
3	100	120
2	120	170

2.2 Laboratory testing

Two main laboratory test series were set up at different stages: a series of quasi-static not-confined uniaxial compression tests and a series of dynamic not-confined drop-dart tests. Each series of test will be summarized hereafter. The static and dynamic compression test with no confinement are basic tests for the initial characterization of a material that shows such high potentialities in road safety and environment respect. The acquisition of mechanical parameters to be used in numerical simulations enables the researcher to design new devices of protection for road singularities without setting up real tests. The choice of the crash cushion shape will be, at the end, the key issue. On the basis of the complexity of the material model chosen for the crash simulations, different parameters are needed as input. For this reason, either static and dynamic tests were performed and mainly load-displacement compression curves were recorded.

Static compression tests have been primarily set up to investigate the actual behaviour of the material when loaded. High deformability, elasticity and low initial stiffness are desirable aspects for a crash cushion material. Hence, the easiest parameters to be recorded from these tests were the Elastic Young's Modulus (E_{st}) and the Poisson's ratio (ν). The final strength of the material was also to be observed with regard to the durability of the restraint system.

Figure 2 Static compression test: two instants (4s and 38s) of the same test

Tests were performed at 20°C – the material's stiffness increase with the decrease of temperature will not be discussed here – and a press speed control mode was set at 200 mm/min with an acquisition frequency of 20 Hz for both the load cell and the vertical LVDT. In Figure 2 the large horizontal specimen's deformations due to the typical high Possion's ratio of elastic rubbers and to the loading plates high friction is evident.

The main output of these tests is a load (N) – displacement (mm) curve from which stress (MPa) – strain curves can be easily worked out on the basis of the loaded area and the initial height of the specimen (L_0). Tests were done on specimens with different densities to investigate how this parameter may influence the initial stiffness. The graph in Figure 3 plots the average stress (MPa) – strain (deltaL/L_0) curves obtained from several tests on 2 different specimens (namely #2 - high density specimen and #11 – low density specimen).

In both cases the linear behaviour of the material is kept for up to 0.10 – 0.15 of the specimen specific deformation and for more. In particular, the low-density curve (#11) tend to show a linear behaviour until 0.20 strains. After this point curves tend to increase in stiffness. This is principally due to the horizontal swelling of the specimen caused by the high superficial frictions and to the material compaction under the increasing load. Friction causes the cylindrical lateral surface to bulge and curve resulting in an increase of strength that would not be recorded if the loaded specimen's surfaces are left free to deform and thus the lateral surface free to scale its radius. Initial density obviously plays an important role in plotting the slope of the curve during the test. An increase of approximately 50% in density (from 430 to 670 kg/m^3) leads to a triplication of the initial stiffness (from 0.27 to 0.95 MPa) with an increase of stress of more than 3 times when 40% of specific deformation is reached. This fact should be taken into account when crash-cushion's material production is concerned.

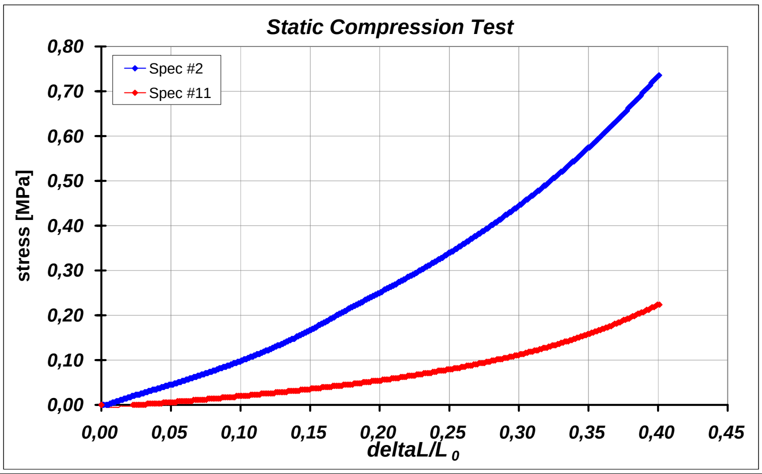

Figure 3 Static compression test: curves for different densities

Static compression test were stopped after 70-80 mm of displacement to prevent the equipments from damages as very high loads could be reached. Thus, specimen compression curves did not end with a failure. Specimens did not show any macroscopic failure at all, even if displacement reached almost half of their initial height (L_0). Furthermore, after unloading the specimens always regained their original shape within few minutes time. This is a clear indication of the considerable elastic behaviour of the rubber mixture itself and shows that the whole mixture production process does not affect significantly the rubber's original elasticity. In fact, after a single test the residual deformation measured with the loss in height of the 150 mm diameter sample was close to 0.4% and reached 1% after 4 compression test, each taken up to 70-80 mm of displacement.

A first hint drawn by these tests is that, for the produced material, elasticity is the predominant character and that deformability and initial stiffness can be adjusted on purpose during the material production varying its density. As quoted before the following parameters can be obtained from the recorded curves: Young's Modulus of elasticity: 0.95 MPa for the dense specimen (#2) and 0.27 MPa for the other (#11); Possion's ratio: worked out to be approximately 0.3 for each specimen.

Dynamic compression tests were mainly performed to investigate the capability of the material itself to absorb quickly-applied energy and to lead to the future design of attenuating devices. Hence, this research phase aim was to characterise the material under conditions reproducing road impacts, in particular according to loading speeds: the system is able to produce speeds up to 14-15 m/s. During the tests several data and information were collected such as a load-displacement curve and the specimen shape deformation after each tests. The mechanical parameters to be input in the LS-DYNA3D material model were also worked out from dynamic tests.

Figure 4 Dynamic test: tower, loading frame with dart, load cell and encoder for displacement measurements

The dynamic testing apparatus is a typical drop-dart equipment in use at the Mechanical Department of the Turin Polytechnic in Vercelli (VC). The drop tower compression equipment of Figure 4 is able to produce high loads at medium strain rates.

A 11 metres high tower guides a dart on his fall onto the specimen. Fall height can be adjusted depending on the desired final dart speed. Ground deformations are minimized by means of a 50 mm thick steel plate cast in a concrete foundation of high inertia. The impacting dart is basically a 50 kg mass steel beam with hooks and wheels for lifting and release. The theoretical impact kinetic energy is approximately 5000 J.

The specimen loading is not directly imposed by the dart and a specific steel frame has been designed for this purpose. A pre-load is therefore applied by the 22 kg frame head mass to the specimen. The frame carries also the recording devices such as a piezoelectric load-cell (max. load 220 kN and 30 kHz frequency) and an optoelectronic encoder (Figure 4). The data acquisition is left to a National Instruments card (800 ksamples/sec with 4 channels) controlled by a LabView software installed on a laptop.

Several specimens (100 and 120 mm diameter) were tested with 3 impacts each. Test conditions were kept identical for all tests. Test results show a similar dynamic behaviour if specimen size is taken into account. Hence, a representative average load (kN) - displacement (mm) curve - from tests of specimens # 9 (730 kg/m^3) and # 10 (700 kg/m^3) - is considered as basis for the following numerical modelling and is plotted (red) in the graph of Figure 5. In the same graph a curve (blue) plots the speed (m/s) of the loading frame head versus its displacement (mm) during the event.

The load-displacement curve is a typical rubber content material dynamic response. Three main steps can be traced on the curve. A first step where dynamic loading effects show a relatively stiff behaviour up to 15-20 mm; a second part where larger displacements rise (up to 40 mm) under small load increments; a third step where specimen compaction enables stiffness to increase together with rubber instant density. At approximately 80 mm of displacement, corresponding almost to half of the specimen height, the compression ends and speed drops to zero. The recorded load is close to 52 kN and the energy absorbed is approximately 2050 J. After that, the loading frame inverts his motion as the specimen returns to it part of the absorbed energy. A large portion of the theoretical dart's energy is dissipated in contacts and frictions during the event. This typical elastic behaviour of the produced material was expected and it will be taken into account during the retaining system design as no major reverse displacements should occur when the vehicle has eventually come to a stop.

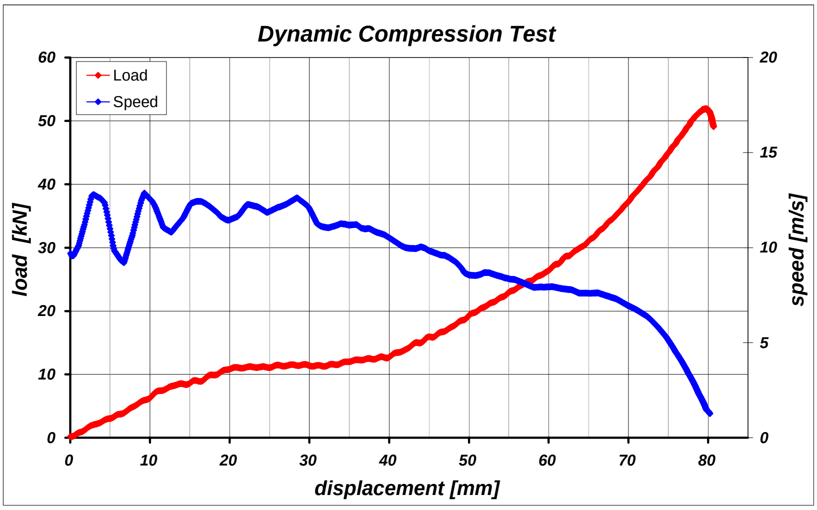

Figure 5 DCT results: load-displacement curve and speed-displacement curve

The initial frame head speed of approximately $11 \cdot 10^3$ mm/s is depending on the impacting dart mass and speed and to the head mass. After a waved behaviour the speed goes down reaching half of the initial value after 90% of the displacement. Within the next 10 mm of displacement speed falls quickly to zero.

After each impact the specimen elastically regain its original shape. A little residual deformation is recorded and the specimen height after three impacts decreased of about 3 mm, corresponding to 1.8% of the initial height. A couple of vertical cracks are also observed growing on the lateral surface of the specimens during testing. This cracks are the consequence of the tensions stress distribution on the specimen surface. Stresses reaches the material tension ultimate strength because of the large deformation affecting the sample when impacted. This fact suggests a further investigation on the fatigue behaviour of the material to assess its resilience when the number of impacting events is considered.

Loading rate stress dependency of the material should be noticed as no cracks appears on the specimens after quasi-static compressions. Higher strain rates lead to material tearing under dynamic loading. Judgement should be taken during crash cushion's design about the material volumes and thicknesses in order to reduce strain concentrations.

3. NUMERICAL SIMULATIONS

Numerical simulations comprised either static and dynamic compression tests. LS-DYNA3D is a f.e. modelling tool for reproducing dynamic impact events and it is used worldwide for crashworthiness problems. In this case, laboratory test were to be simulated and modelling of the produced material under static and dynamic loads was the key issue for the future design of a new low-maintenance crumb-rubber content crash cushion. Two different material models were chosen for the rubber specimens.

Static compression test required the modelling either of the rubber specimen and of the loading device; the last one was modelled by means of two independent rigid walls on the basis of the mutual materials' stiffnesses. Figure 6 shows the static model with all its elements: the problem symmetry allows the use of an half specimen model. Furthermore, the initial linearity of the load-displacement curves obtained from static compression tests suggested, in a first stage, the use of an elastic material model for the rubber specimen. Parameters to be introduced into the input file could be easily worked out from tests curves using the common elastic theory. Two mass densities were considered for two different simulations according to density differences. The values in Table 2 were chosen for the elastic parameters of the LS-DYNA3D elastic material models.

Table 2 Elastic material models' parameters

Specimen # 11	**Specimen # 2**
Mass density = 435 kg/m^3	Mass density = 670 kg/m^3
Young's Modulus = 0.27 MPa	Young's Modulus = 0.95 MPa
Poisson Ratio = 0.3	Poisson Ratio = 0.3

The specimen's mesh elements formulation is fully integrated to prevent from "hourglass" energy modes. Contact interfaces between the planes and the specimen are governed by the Coulomb's friction. A 3 second simulation was run for reproducing the material behaviour under uniaxial static compression. Symmetric degrees of freedom were assigned to all the specimen's section plane nodes. Gravity was applied to the system and a controlled velocity of 3.3 mm/s was given to the loading rigid wall. No masses were assigned to the planes as these were not involved in the real test kinematics: the loading plane should follow a prescribed motion.

Results confirmed that the adopted material parameters were correct as vertical and horizontal deformations well reproduce the specimen real behaviour (Figure 6). The material model elasticity characterizes the outputs as stresses uniformly increase within the specimen when vertical displacement increases. After 1 second of simulation mean stresses on the top surface element reach approximately 0.020 MPa, whilst at the end of the simulation are linearly increased over 0.050 MPa. The stresses distribution within the bulk of the specimen is symmetrical and correctly denotes higher central stresses. LS-DYNA3D's output stress-strain curves obtained as averages from the core elements of the top surface can be compared with regression lines worked out by real tests curves. Figure 7 shows the comparison between test and simulation' results for the two different rubber densities (specimen # 2 and specimen # 11).

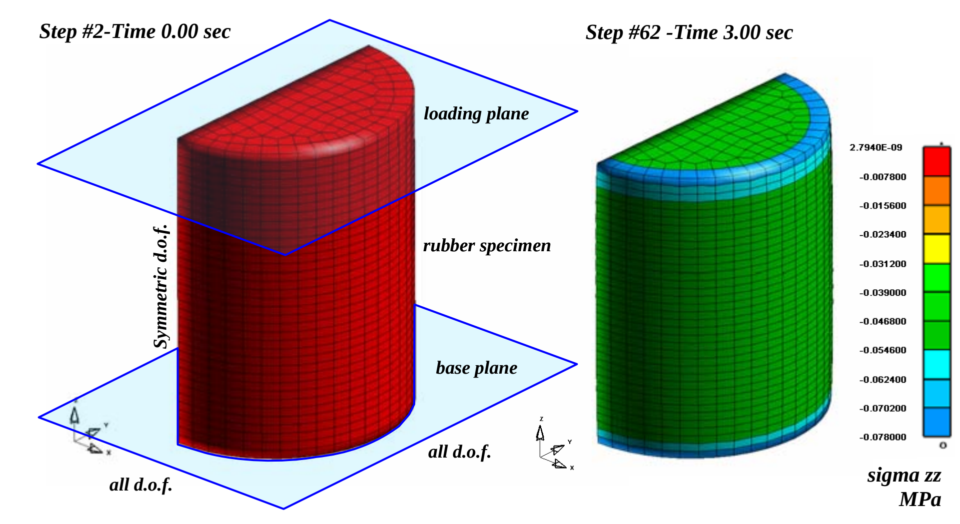

Figure 6 LS-DYNA3D static model and its final deformation after 3 sec (spec.# 2)

During the 3 second simulation, the comparison between regression lines of the laboratory curves and LS-DYNA3D model curves is excellent. This fact endorse the major elastic behaviour of the crumb rubber. Longer analysis taken up to 20 seconds revealed that the LS-DYNA3D material model well represents the real test even for very large deformations. In fact, as the lab test curves shown in figure 3 tend to increase with the square of specific deformation, also the simulation curves bend showing higher stresses rates for constant deformation rates. This similarity proofs that the model is correct and is able to detect the real specimen behaviour with regard to its shape, following the quadratic increase of stresses mainly due to the lateral surface bulging.

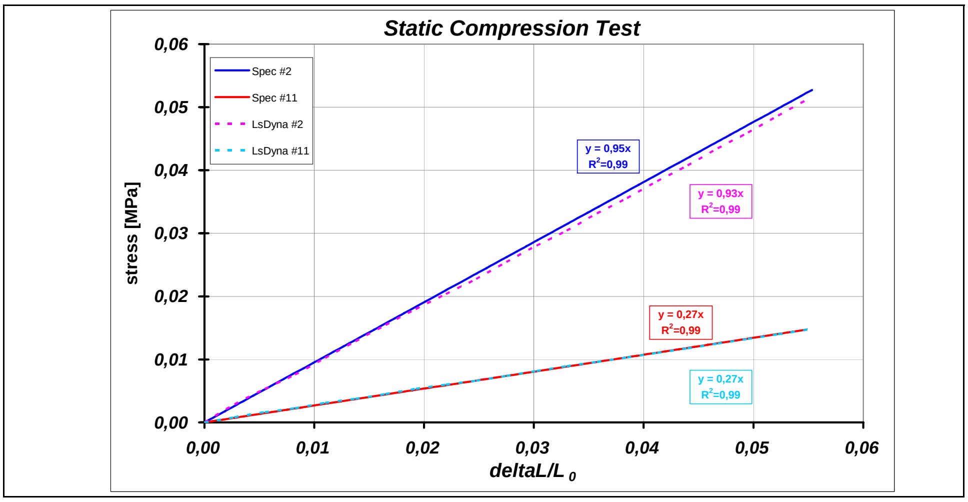

Figure 7 Laboratory and LS-DYNA3D static curves for different densities

Small errors are to be imputed to the lacks of the material model in describing the viscous component and the yield tensile strength of the real rubber specimen which will actually suffer of small plastic deformations after each test. Even the slight increase in density due to the expulsion of the air trapped within the rubber particles can not be reproduced with the elastic material model adopted. For these last reasons the material model should not be employed in crash-test simulations as very large deformations may occur depending on the cushions' shape. However, the static tests'simulation phase demonstrated that the rubber material itself, at low strain rates, is highly elastic and that its model could be easily adopted for the early crash-cushions'design when best densities and shapes are to be evaluated.

Performing dynamic compression tests' simulations was simpler than real drop-dart tests. The impact event on real specimens can be divided up into two stages: loading and unloading. At this research step only loading stage was considered and the elapsed time from the first triggering displacement of the encoder up to the maximum one was calculated via recorded time histories. As very short time and a simple geometry are to be simulated, computational time were not a key issue and a full cylindrical model could be therefore produced. This enabled an easier and more accurate calculation of load-displacement curves to be superimposed with the real ones. Hence, the model (fig. 8) comprises a cylindrical specimen (120 mm diameter, 170 mm height) and two rigid planes: one fix and one vertically moving. The rubber has been modelled with the LS-DYNA3D material n°181 Simplified Rubber/Foam that requires as input a series of parameters and a load curve obtained from static-compression tests performed on a real specimen (Table 3). The specimen mesh is fully integrated to avoid "hourglass" energy.

The bottom rigid plane is massless and constrained in all his d.o.f. as it does not interfere with the impact dynamics. Only the friction between the base rubber face and the plane is considered: a 0.9 Coulomb coefficient is assigned to the contact. The top rigid wall is moving vertically at an initial velocity of $11{\cdot}10^3$ mm/s. The assigned speed is taken from the mean value of the loading frame head measured from the encoder time history. A mass of 22 kg is given to the wall to take into account the mass of the frame head and the fact that the dart-frame head interaction will reduce the dart speed, i.e. the frame head will act alone on the specimen. A Coulomb friction coefficient of 0.9 is assigned to the top plane contact. Gravity is applied to the whole model and the simulation is recorded for a 12 milliseconds time interval during which the loading impact phase is complete and the reverse displacement of the top plane starts.

The obtained results are satisfactory and validate the capability of the software to model the new material under dynamic events. Simulated stress-strain conditions well represent the real ones and the geometrical deformations of the specimen corroborate the model. With regard to load-displacement curves, the correspondence between experimental and simulation ones is optimal for most of the event (fig.9).

Table 3 Simplified Rubber/Foam model parameters (ton, mm, s, N, MPa units)

RO	**K**	**MU**	**G (1)**	**PR**
7E-10	313	0.4	1000	0
SIGF(1)	**SGL**	**SW**	**ST**	**Load Curve**
0.1	178	132	132	Frc- displ.

(1) – for frequency independent damping.

After 35 mm of displacement the simulation curve almost superimposes the experimental one matching the specimen behaviour till the end of the event. The initial spike of the LS-DYNA3D curve is due to the rigid contact between the plane and the specimen and would be nullified with non rigid loading planes. This will require further model refinements. The difference in peak load value is less than 8% and the final displacement differs of less than 2%. The overall impact energy absorption is respected if the rigid contact one is not taken into account.

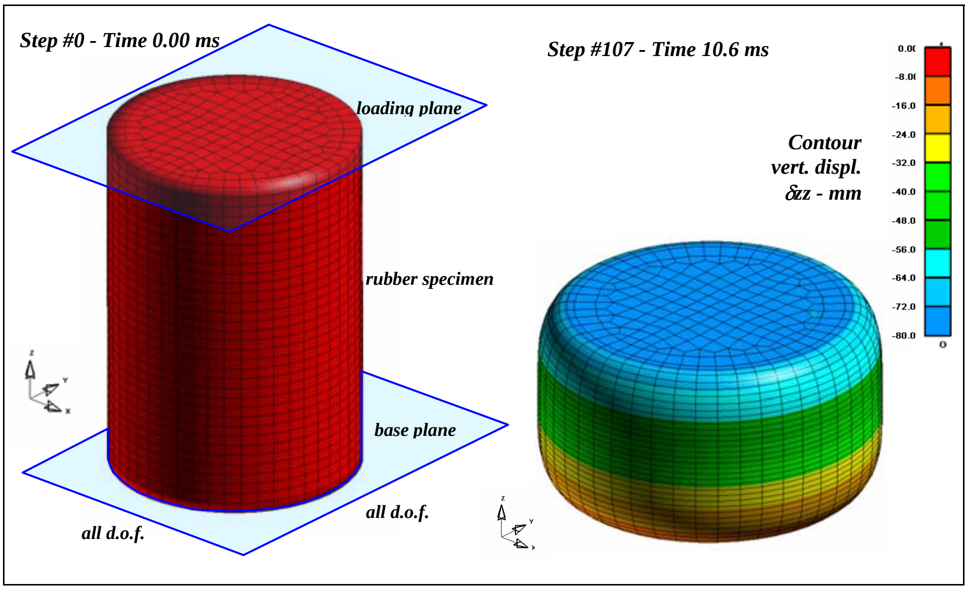

Figure 8 LS-DYNA3D dynamic model and final deformation after 12 ms (spec.#9)

4. CONCLUSIONS

In this study a reuse of rubber tyres waste is applied to the production of crash cushions. An experimental investigation was held to look at the attitudes of the new material and to work out its mechanical characteristics to be used in the numerical analysis. Laboratory static compression tests were performed on rubber specimens vulcanized in a oven. On the same set of samples a series of drop-dart tests were conducted under a loading tower.

The Simplified Rubber/Foam material model well describes the behaviour of the proposed rubbery material at this very first stage. With a model refinement based on other dynamic testing, a complete definition of the input parameters could be employed when a full attenuating roadside device modelling will be considered. The developed material model will help in the design of thicknesses and shapes of the attenuating rubber elements as well as of their assemblage to form the final restraint system. The usefulness of numerical simulations in these choices is therefore undoubted.

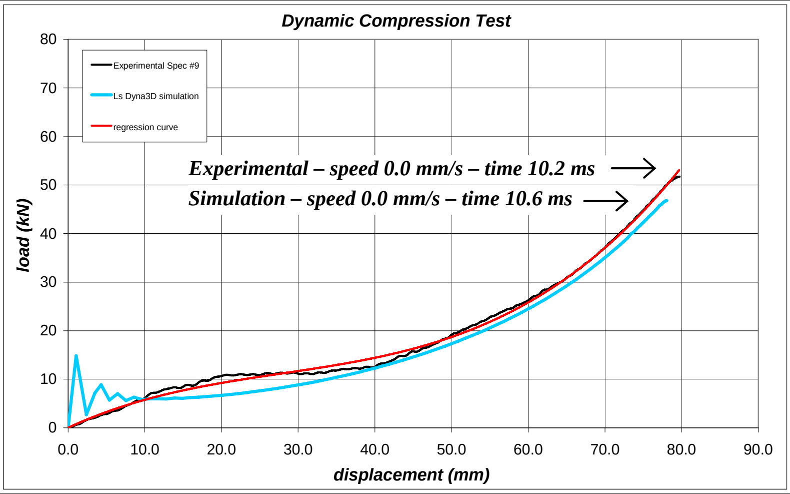

Figure 9 Laboratory and LS-DYNA3D curves for dynamic tests (spec.#9)

All the crash test configurations required for the UNI EN 1317 certification could be modelled and the system's characteristics could be varied to meet the acceptance criterion. The highly elastic nature of the produced material suggests the design of hollow elements with relatively thin walls able to exhibit large deformation without bouncing back the impacting vehicle. The use of other elements such as posts or geosinthetics is desirable when constraining potentially detached parts of the impacted system is needed. Further investigations should consider the material durability with reference to climate actions and to the reuse of some already struck parts.

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