Comparative Study of Material Laws Available in LS-DYNA® to Improve the Modeling of Balsa Wood

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Abstract

In order to compute the requirements for transporting packages in various situations using balsa wood as an energy absorber, a constitutive model is needed that takes into account all of the specific characteristics of the wood, such as its anisotropy, compressibility, softening, densification, and strain rate dependence. Completeness alone is not sufficient for the model, because it must perform appropriately in simulations that include many other non-linear situations, such as being subjected to friction, undergoing large deformations, and even failure.

To improve their existing modeling within LS-DYNA, CEA CESTA, in partnership with I2M of Talence, carried out a major experimental campaign both on standard characterization tests and on more complex tests representative of the behavior of real structures. All these tests have been modeled using different LS-DYNA material laws to assess their respective limitations and achieve optimal modeling within the framework of material laws currently available in LS-DYNA.

In a final validation phase, this optimized material law has been introduced in a finite element model representative of a real package to evaluate its effect relative to the initial law.

Keywords

Wood, Balsa, MAT_HONEYCOMB, MAT_MODIFIED_HONEYCOMB, MAT_WOOD

Introduction

Transport of nuclear material follows strict regulations. To avoid any nuclear potential risk to the environment, package must be designed to protect at any cost its contents. Depending on dimension and class of the package, several accident scenarios can be investigated regarding regulations: one of the most known scenarios consist of a free falling package from a certain height on a supposed rigid ground. Depending of the weight of the package and the height of falling, kinetic energy of the package just before impact with the ground can be increased from few kilojoules to several megajoules.

In these conditions, nuclear package builders use foams or natural material as wood in their design. Depending of their material properties, these materials have a relative low density and can absorb a large amount of energy as they are compressed. Combined with metal materials, builders produce package that respond to all of security criteria demanded by nuclear security authorities. Whether of wood or foam, the energy absorber parts stay generally confined within metal casing in nuclear package.

Consequently, as package builders use FE models to improve the design of their products and identify the most penalizing fall configurations, they need an accurate model of wood behavior used to absorb energy during crash. Significant work has been done at CEA CESTA in the late 1990s, leading to a first modeling of wood in LS-DYNA [1] [2]. This work was based on the *MAT_HONEYCOMB material law with available options at the time leading to neglect a number of physical phenomena compared to real behavior.

In this study, the main goal is to compare the current capabilities in LS-DYNA to improve modeling of balsa. A large set of new experimental tests (unit tests and representative small test like Brazilian test) have been as a starting point to improve wood model and to include additional physical phenomena in FE models. This comparative study will lead to an improved and more representative material law.

Wood behavior

General Points

Wood is a natural material, but there are lots of species in the world, each one having its own characteristics. However, some assumptions can be made regarding its mechanical behavior.

At a macro scale, it's a continuous and homogenous material. At its center, one can observe its growth circles all along its height. With these observations and by experience, wood can be supposed as a transversely isotropic elastic-viscoplastic material. The 3 main directions of material (Figure 1) can be identified as the direction of wood fiber (L), the direction perpendicular to the fiber, radial to wood growth rings (R) and the direction tangential to wood growth rings (T).

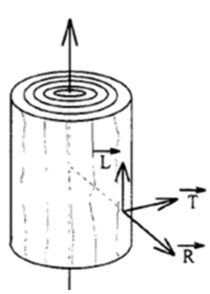

Figure 1: Orthotropic directions of a standard wood material [1]

As a result, 5 characteristic elastic constants can be extracted from experiment: Young modulus in L and R direction, shear modulus in LR plan and RT plan and Poisson's ratio.
If we look closer a wood specimen, at a micro scale (Figure 2), we can observe a cellular organization along wood fibers, with a structure similar to honeycomb.

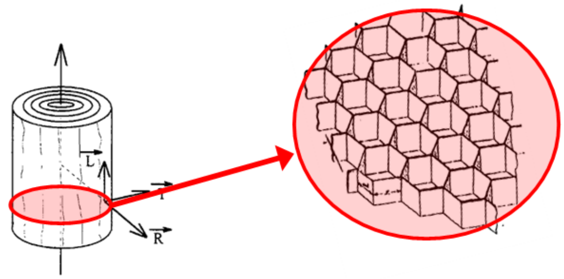

Figure 2: Honeycomb structure along wood fiber

As mentioned in the introduction, wood parts used in nuclear package are compressed during free fall on the ground. So, let's observe behavior of the wood in compression on an orthotropic direction of material (for instance L direction):

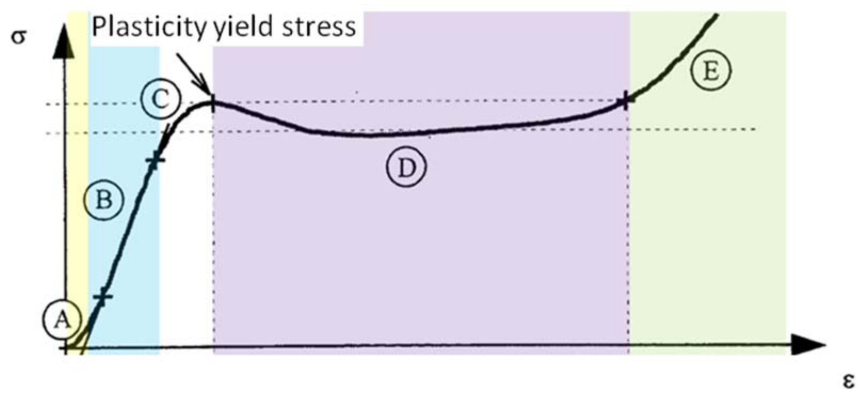

Figure 3: Standard behavior in compression for some woods

In Figure 3, three steps can be identified:
- a first globally elastic phase up to a peak stress corresponding to the yield stress (A + B + C)
- a second phase generally corresponding to a plateau, until all wood cells are completely crushed, possibly preceded by a softening behavior (D),
- a last phase corresponding to a compacted state after wood cells complete collapse (E).

Campaign test

To complete this theory, additional tests were made by University of Bordeaux. These unit tests permit to identify balsa behavior for each material direction, for standard loading case – tensile, compression and shear loads, at 2 strain rates.
All experimental tests assume an independent behavior for each material direction. Moreover, they have shown that balsa wood is sensitive to strain rate, in each material direction. As shown on following figure, stress can be scale by up to 6, depending of material direction we considered.

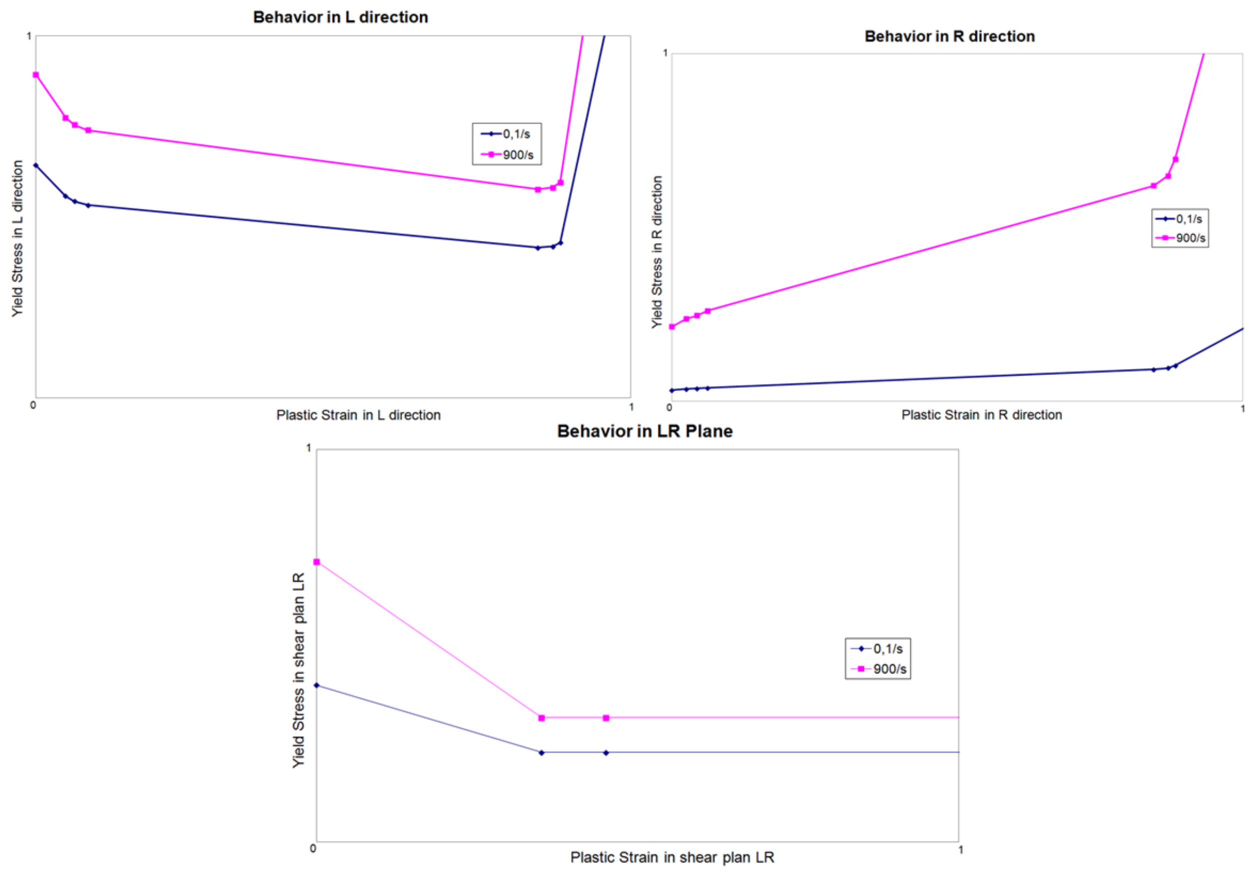

Figure 4: Yield stress curves for each material direction

Here we have only the behavior at two strain rates. Between these rates, we assume that Tagarielli formula [3] can represent the effect of strain rates upon stress/strain curve for each balsa material direction, for strain rates between $0.1s^{-1}$ and $900s^{-1}$. If σ_0 correspond to stress at $0.1s^{-1}$ strain rate, the stress σ at any strain rate can be identified by the formula below:

$$\sigma(\varepsilon_p) = \sigma^0(\varepsilon_p).\left(\frac{\dot{\varepsilon_p}}{\dot{\varepsilon_p^0}}\right)^m$$

As shown on Figure 4, strain rates effect is different for each balsa direction; consequently, the m exponent should depend on material direction.

Improve balsa FE model

Current state

As said in the introduction, balsa wood is already modeled in nuclear package FE using MAT_HONEYCOMB, since wood can be considered as a cellular material. This LS-DYNA law has been used over the past 20 years and has shown fairly good results for representing balsa behavior in nuclear package FEM. However, computer performance and LS-DYNA solver have evolved since that time.

In this trend, with the new experimental test made, one can consider to improve the current law used to model balsa, like adding strain rate effects and softening in compression on behavior. With all these information and regarding data obtained by CEA CESTA and University of Bordeaux, three laws were selected in LS-DYNA material library [4]:

- MAT_HONEYCOMB (MAT_026): as it's used currently, we could consider new improvement in input data to correlate new experiment data and new information;
- MAT_MODIFIED_HONEYCOMB (MAT_126): it's an update of MAT_026 and seems to have some useful abilities to model wood like balsa
- MAT_WOOD (MAT_143): as its name says, this material law is dedicated to model wood materials.

Next we will study and compare these three laws, for multiple tests:

- First step consist of reproduce unit tests for tensile, compression and shear loading and check behavior of each law regarding data obtained by University of Bordeaux;
- Secondly, some representative load case will allow to establish an improved LS-DYNA material law regarding the new available data;
- Finally, this new improvement will be compared to the current state of nuclear package model.

Unit tests

These unit simulations consist to impose simple load cases (tensile, compression, hydrostatic compression and simple shear loading) on one single element. The aim of these tests is to reproduce the behavior of each LS-DYNA material law for simple load cases and compare the results to experiment values.

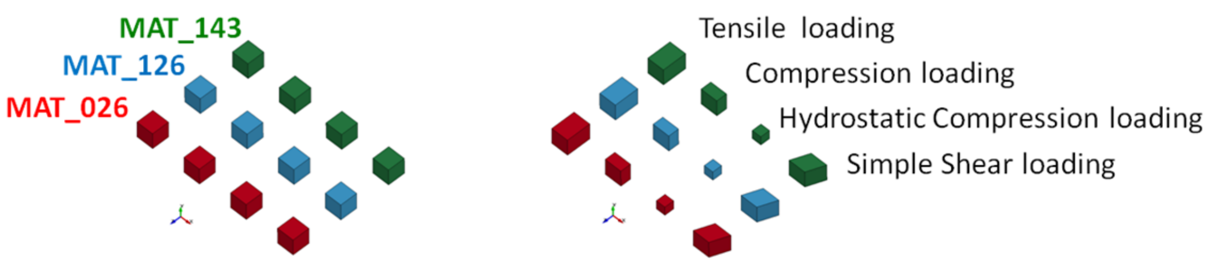

Figure 5: Unit simulation made on the 3 test laws

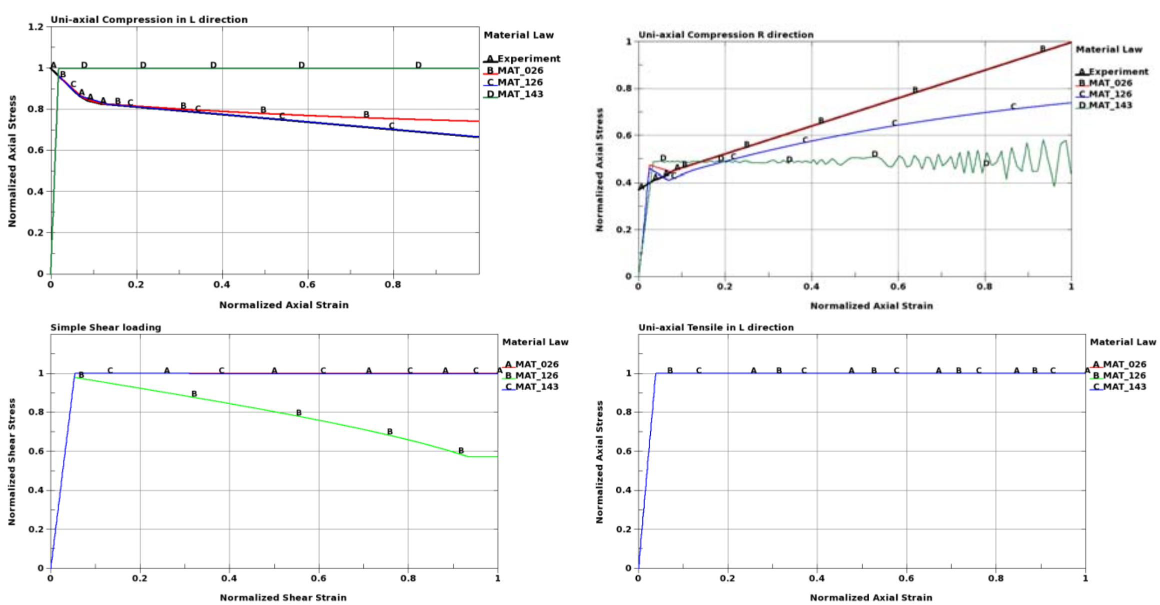

Figure 6: Some unit results on the three laws (Compression, Shear and Tensile loading)

As we compare the results of each load case for the three possible laws (Figure 6), some statements can be made:

- In uni-axial compression along fiber direction (L), MAT_WOOD behavior is elastic-perfectly plastic: the parameters used for this law haven't permitted to reproduce softening in compression before full compaction;
- In simple shear loading, only MAT_126 reproduces the experimental behavior, as its inputs use directional strain instead of volumetric strain (for MAT_026). In this later case, as simple shear doesn't produce volume modification, volumetric strain is constant all along loading. So yield stress (define in function of volumetric strain) can't vary.
- In tensile load, all laws produce the same results, as we have supposed a perfectly plastic behavior of balsa wood in tension.

From these first results, the two honeycomb laws (MAT_026 and MAT_126) present the best fitting with experiment data. MAT_WOOD doesn't seem being able to represent balsa wood behavior in our case. Literature about MAT_WOOD shows more experiment on tensile loading than on compression test. Moreover, there is little information regarding modeling confined wood using MAT_143. Parameters available in LS-DYNA material card (in user mode input) can only tune transition between elastic phase and compression state, for compression loading. As far as we know, there is no option to represent softening during compression along wood fiber direction. New development around this MAT_WOOD law could take into account this behavior in compression.

On the contrary, MAT_026 and MAT_126 can represent softening behavior in compression along fiber direction as they use curves to pilot yield stress of each direction. The first unit tests confirm the correct use of MAT_026 material law to represent balsa wood behavior in FE package models. However, MAT_026 law can only represent one strain rate effect for all material directions: strain rate along fiber direction is supposed identical to the other wood direction, say R direction. Furthermore, behavior of each material direction is independent of each other. But they share the same volumetric strain in stress-plastic strain curve, so they are not really unlinked, as volumetric strain is the trace of the strain tensor. In the case of balsa, studies have shown that the behavior of each direction can be assumed completely independent of others, as we consider static loading or strain rate effect.
On the other hand, with MAT_MODIFIED_HONEYCOMB, stresses are computed with axial strain, in each material direction. Moreover, strain rate effects on stresses can be set independently for each direction. In our case, as we assume a complete independent behavior between each direction, MAT_126 seems to be the best option to model balsa wood.
Additionally, MAT_MODIFIED_HONEYCOMB provides an alternative method (named bellowed MAT_126 3rd mode) to define the yield stress surface. In this case, yield stress is given by the following equation:

$$S(\beta,\varepsilon_v) = \sigma^{LCA}(\beta) + \cos(\beta)^2.\,\sigma^{LCB}(\varepsilon_v) + \sin(\beta)^2.\,\sigma^{LCC}(\varepsilon_v)$$

Where:

- $\sigma^{LCA}(\beta)$ is yield stress in LR plan function of β angle
- $\sigma^{LCB}(\varepsilon_v)$ is yield stress offset in L direction, function of volumetric plastic strain ε_v
- $\sigma^{LCC}(\varepsilon_v)$ is yield stress offset in R direction, function of volumetric plastic strain ε_v

This alternative method can overcome one limitation of MAT_126: if we check off-axis behavior in (LR) plane (yield stress function of β angle between L direction and considered direction - Figure 7), the maximum yield stress is not at β=0° but around β=5°. Using $\sigma^{LCA}(\beta)$ with the alternative method of MAT_126, we can pilot wood behavior in the (LR) plane in order to have maximum yield stress at β=0°.

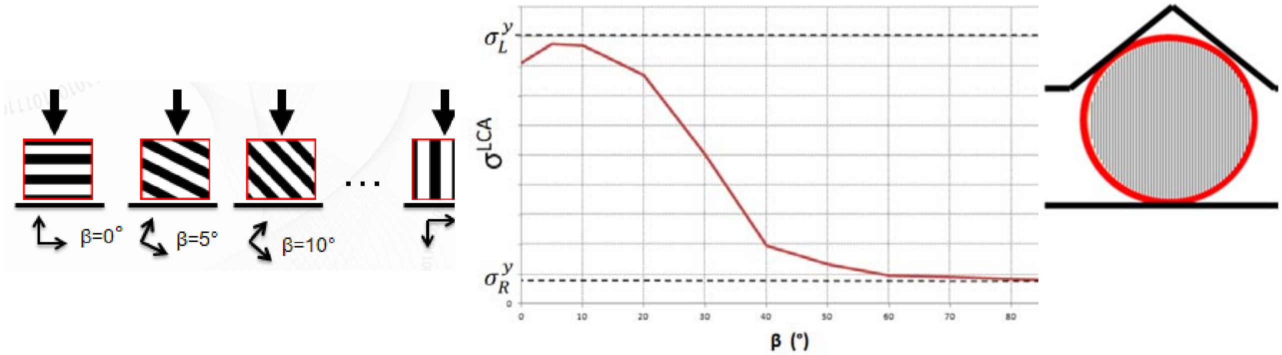

Figure 7 : Out-of-axes unit compression on MAT_126

However, without more information specifying behavior in function of volumetric strain for each material axes, this version of MAT_MODIFIED_HONEYCOMB was not studied. Future experiments will permit to optimize balsa modeling with this modification of MAT_MODIFIED_HONEYCOMB and improve balsa behavior model in FEM nuclear package.

Representative loads: Brazilian and punching tests

As we obtained two potential LS-DYNA laws to improve balsa representation in nuclear package FEM, additional experiment needs to be set. Here, the experiment must represent the same load on wood as it will be on nuclear package. Regarding multiple tests available in the nature, CEA CESTA chooses to adapt the Brazilian test to wood characterization. The load induced on wood sample in this type of test is relatively similar to the one wood parts will undergo in nuclear package.

Their tests consist of a balsa disc circled by a strip of aluminum located between a fixed V shaped jaw and a moving plan that crushes the wood block. Aluminum strip is glued to balsa disc. Velocity of the moving plan is low enough to suppose quasi-static loading. Parameters that will be used to compare material laws are

- Crushed surface area near moving plane
- Contact force between moving plane and the wood sample function of plane displacement.

In order to simplify measurement, one can assume that it's a 2D Plane Strain problem. In this case, we measure crushed width in the 2D plane of the initial circle of wood.

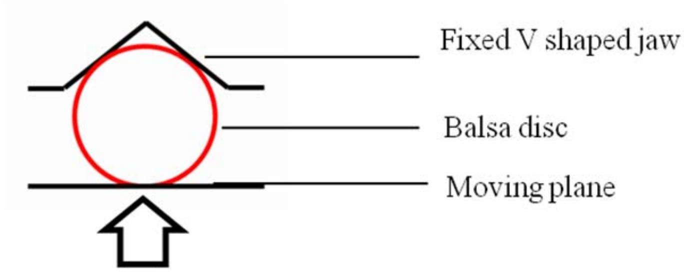

Figure 8: Diagram of a Brazilian test used to characterize balsa

Three designs were tested (Figure 9): in the first one, balsa disc has wood fiber direction parallel to moving plane; in the second one, fiber direction is normal to moving plane. In the third test, fiber direction is parallel to moving plane but there is a hole at the center of the balsa disc (reinforced by an aluminum cylinder).

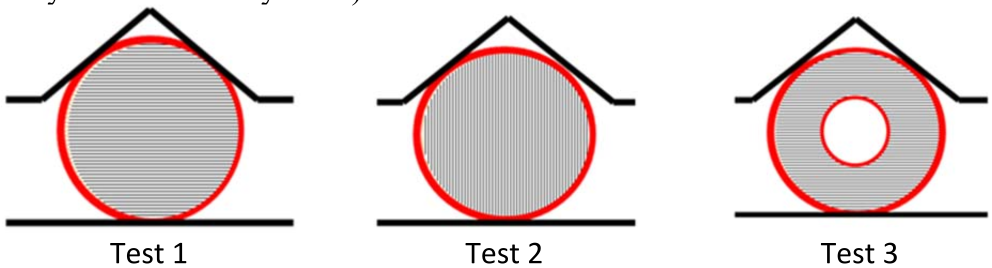

Figure 9: Three Brazilian tests used to characterize balsa behavior

Additional tests were also made. They consist in punching some rectangular balsa bloc at different fiber orientation with various impactors at an imposed initial velocity (Figure 10). The aim of these test were to identify the strain rate effect on wood behavior. For confidentiality reasons, the results are not presented in this paper.

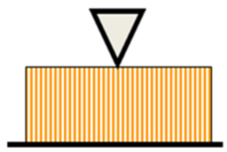

Figure 10: Example of punching test

Thereafter, we will only discuss of the results obtain by experiment and with FEM using MAT_026 and MAT_126 for the first design of Brazilian test. As said before, two parameters will be used to compare FEM results to experimental data:

- Crush width near moving plane: as we supposed 2D Plane strain problem, the crushed surface is reduce to its width.
- Contact force between moving plane and wood sample, function of plane displacement.

Regarding crush width of balsa disc on moving plane at the end of the loading, the FE model using MAT_MODIFIED_HONEYCOMB gives better result (relative error with experience lower than 1%) than the one with MAT_026 (+9%) (Figure 11 and Figure 12). As said before, MAT_HONEYCOMB uses volumetric strain to described behavior in each direction, whereas MAT_MODIFIED_HONEYCOMB uses axial strain for each direction. There is no dependency for each direction in MAT_026 and simple shear loading in elements doesn't lead to stress increase: contact force between moving plane and balsa disc increase slowly in MAT_026 case than in MAT_126 model.

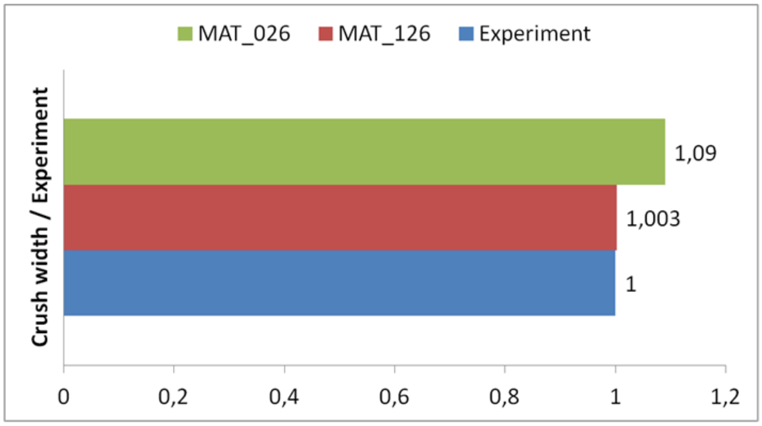

Figure 11: Comparing crush width with experiment

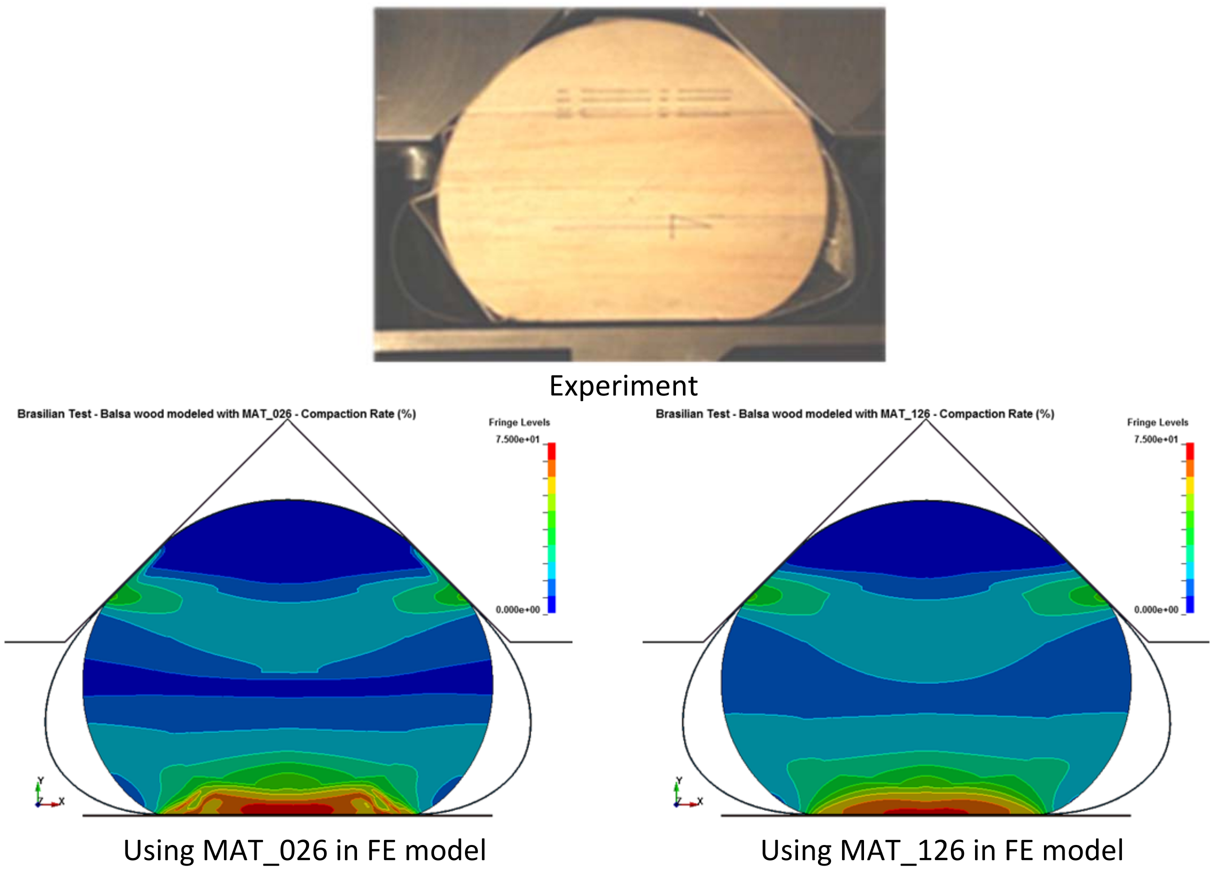

Figure 12: Deformed shaped of Brazilian Test – Experiment, MAT_026 FEM and MAT_126 FEM

Concerning contact force versus plane displacement, the two FE models are close to the experimental curve. For high displacement, as the glue between wood disc and aluminum band is not directly represented – we just set a standard contact with high frictional ratio, experiment curve is a bit lower than LS-DYNA models results.

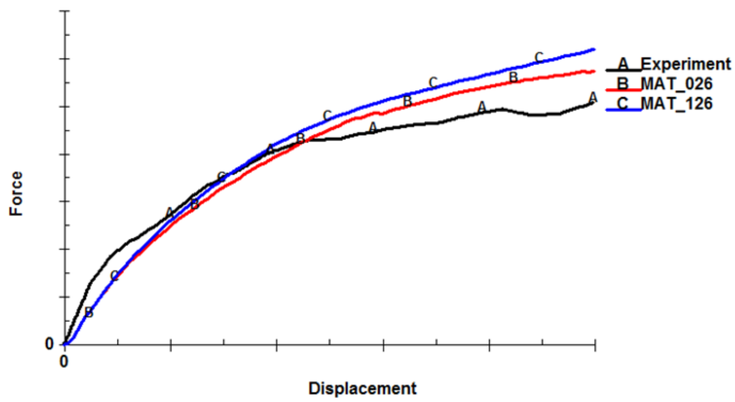

Figure 13: Contact force versus Plane displacement – Comparing Experiment to FE models

The same trends can be observed for the other two Brazilian test designs: MAT_126 shows best results regarding experiment than MAT_026.
Regarding these 2 results – crushing width and contact force – LS-DYNA law MAT_MODIFIED_HONEYCOMB seems a good candidate to improve wood behavior representation in nuclear package FEM. Furthermore, as explained previously, it also allows user to define strain rate effect for each direction. Final step of this paper will compare results obtained with the current model of nuclear package (using MAT_026 to model balsa) to the results generated by a FE model using MAT_126 for balsa parts.

Improved balsa law vs. current law in a package FEM

In this last step, we compare current MAT_026 law to MAT_126 law for modeling balsa wood in a generic nuclear package. Here we use a type B nuclear transporting package with an axi-symetric geometry (Figure 14).

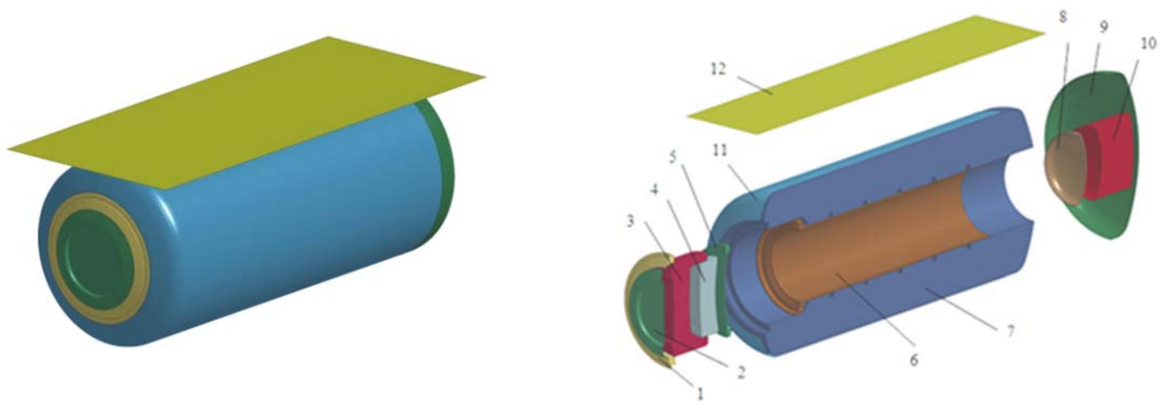

Figure 14: Geometry of the nuclear transporting package used for this study

We consider here a package impacting a rigid wall modeling the ground from a height of 9m. In order to avoid useless computation, we model the package just upper the rigid wall and generate initial velocity all over the FE model. Assuming a free fall from 9 meters, initial velocity will be 13.5m/s for all nodes of package.
As shown on the figure above, parts identified as 3, 4, 5, 7 and 10 are constituted of balsa material: in this configuration, kinetic energy induced by free fall can be absorb in every possible falling direction. In the case of a free fall from 9 meters height, about 53% of initial kinetic

energy is absorbed by wood parts (Figure 15), which weight is about 30% of the total mass of package.

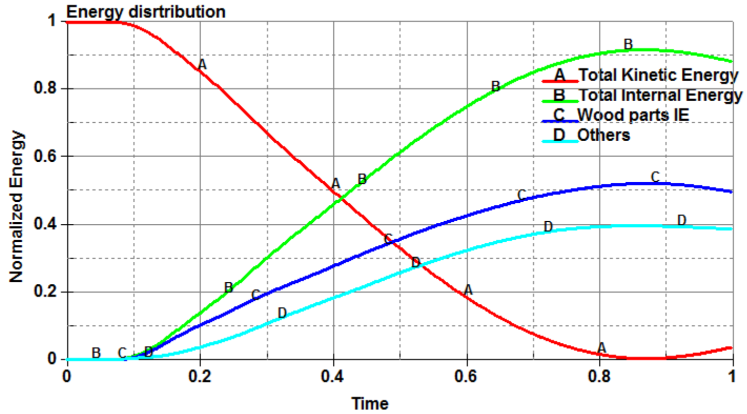

Figure 15: Energy distribution between package entities

To complete this comparative study, we run 2 package models: one is our reference and it use MAT_HONEYCOMB to model balsa behavior. It's the current model used by CEA CESTA. The other one uses the information above with MAT_MODIFIED_HONEYCOMB to model balsa. As you can see below, results are similar between these two models: regarding plate displacement (Figure 16) and acceleration (Figure 17), differences between the two models don't exceed 8%, the second model showing higher values for these two parameters.

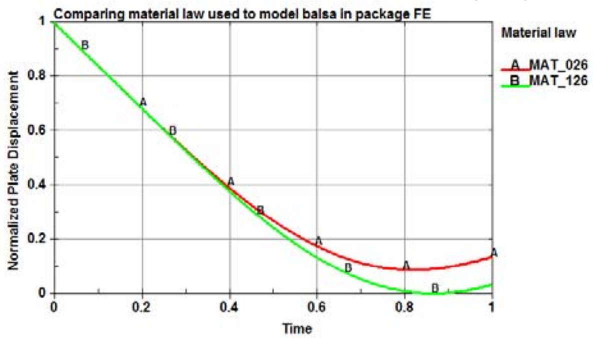

Figure 16: Comparing plate displacement

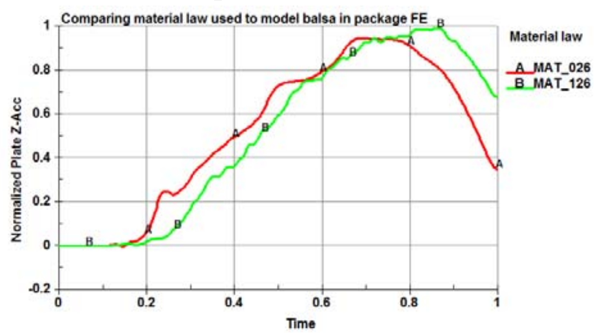

Figure 17: Comparing plate Z-Acceleration

If we check force impact of package over the rigid surface modeling the ground (Figure 18), the two finite element models give relatively coherent results. However, the energy absorption is lower in MAT_MODIFIED_HONEYCOMB case than in MAT_HONEYCOMB FEM. In this last case, the package bounces off the ground faster, as we've seen on acceleration history.

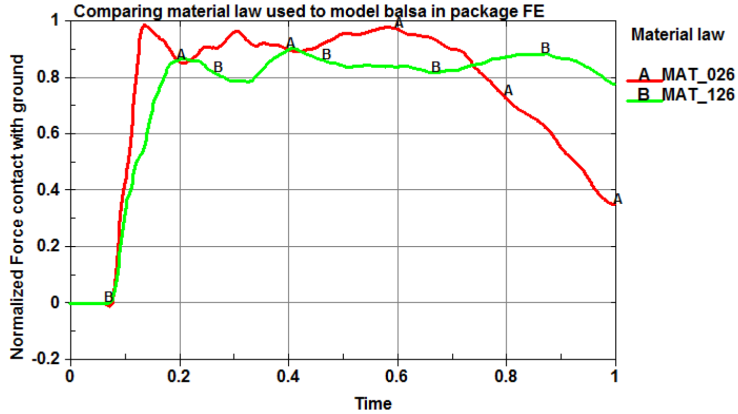

Figure 18: Contact force with the ground

This study highlight the new possibilities of modeling of wood in FE models of nuclear package, and check the consistency with the models currently in place under the same loading conditions, due to new test campaigns material characterization.

Adding strain rate effects on MAT_126 law gives some new results, as we considered speed effects on wood behavior for a free fall package, which is not a quasi-static problem. However, the confidentiality of this study doesn't allow us to present the results.

In the case of the models presented here, the two laws used to model the balsa in packages give relatively similar results.

Conclusion

This paper aims to investigate the possibility in LS-DYNA to represent balsa wood behavior in nuclear package FE models. Three laws were initially investigated: MAT_HONEYCOMB, MAT_MODIFIED_HONEYCOMB and MAT_WOOD. As simulation of unit tests showed, the current state of MAT_WOOD doesn't seem able to represent balsa wood in confined compression and shear.

Currently used by CEA CESTA in their package FEM, MAT_HONEYCOMB shows suitable results to model balsa regarding data we got with experimental tests. However, it seems to overvalue crush width compared to MAT_MODIFIED_HONEYCOMB. This one gives appropriate results for loading cases presented here. With this law, user can define material behavior in each direction independently of the others, even for strain rate effects on stress curves. There are also other options with MAT_126 which allow defining wood out-of axes behavior in transversal plane (LR plane). Yet, it requires defining stress in function of volumetric strain as in the case of MAT_HONEYCOMB. Any future experimental campaign will permit to improve the input data for MAT_MODIFIED_HONEYCOMB.

Acknowledgement

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