Proceedings of the 19th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New Orleans, LA, USA

Impact Limiter Development and New Material Investigation for Spent Fuel Transport Casks

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ABSTRACT

Impact limiters are designed to limit the deceleration experienced by transport casks when subjected to 10 CFR 71 mandated 30 foot (9 meter) drop onto a flat, essentially unyielding surface. TN Americas (TNA) uses impact limiters made of balsa and redwood to absorb the energy from a 30 foot (9 meter) drop.

Its energy absorption capabilities along with ease of machinability make wood an ideal material for impact limiter fabrication. As wood is a natural material, the average crush strength varies greatly for a given density. Recent experience during fabrication has shown that the range of average crush strength (ACS) has changed over time and varies depending on the region of procurement.

Engineered materials are explored to see if other benefits can be gained along with reliable procurement. It is determined that due to the lower variance engineered material can result in a smaller impact limiter and lower decelerations onto the transport cask.

INTRODUCTION

10 CFR 71 regulations require that the containment boundary of a transport package is able to withstand a 30 foot (9 meter) free drop onto a flat, essentially unyielding surface. Impact limiters are designed to limit the deceleration experienced by a cask and its contents during impact. TN Americas (TNA) uses impact limiters made of balsa and redwood to absorb the energy from a 30 foot (9 meter) drop. The light weight and high energy absorption capabilities of wood make it an ideal material for impact limiter fabrication.

This paper presents the lessons learned during wood impact limiter fabrication at TNA and the effect it had on design and licensing. Additionally, the benefits of engineered materials as an energy absorber are investigated and compared with wood. Finally, future design suggestions are proposed.

BACKGROUND

TNA uses wood in many impact limiter designs based on its ability to effectively absorb energy. The cellular microstructure of wood is comprised of long prismatic cells (fibers, grains) of honeycomb shape [1] which give it this characteristic. Wood fiber sizes and densities vary by species. Additionally, weather and climate can affect these characteristics within a single wood species. Low-level magnification micrograph cross-sections of redwood and balsa are shown in Figure 1 [2]. Variations in the grain structure shown in Figures 1(a) and 1(b) illustrate differences between these two wood species.

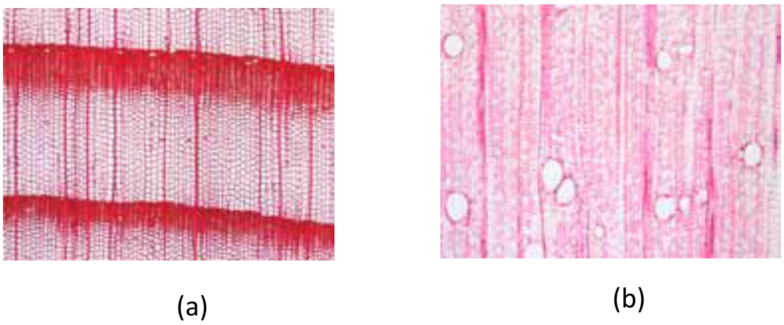


Figure 1 Low-level cross section magnification (a) Redwood (b) Balsa

The mechanical properties of wood (including strength and stiffness) vary by direction. For this reason, wood is typically modelled as an orthotropic material. The longitudinal direction, also referred to as the parallel direction, is parallel to the fibers while radial and tangential directions are perpendicular to fiber direction.

The energy absorbing characteristics of Balsa Wood were studied in depth by Marc Borrega and Lorna Gibson [3]. By crushing Balsa Wood samples in the longitudinal direction, they determined that a majority of Balsa Wood energy absorption during crushing occurs as the cell walls collapse. Figure 2 shows that this event transpires due to buckling followed by folding of the cell walls. This phenomenon was also observed by Vural and Ravichandran [1] and Da Silva and Kyriakides [4].

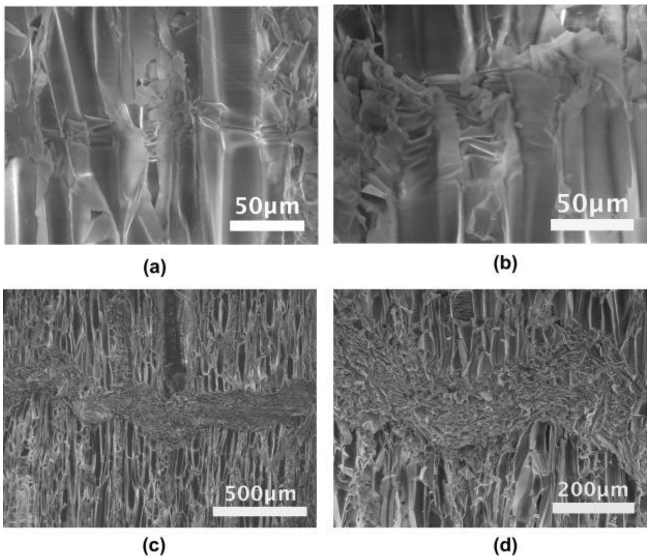


Figure 2 SEM micrographs of LD balsa showing (a and b) the initiation of failure by local buckling in axially crushed fibers (3.3% strain) and (c and d) the evolution of failure at 8.1% compressive strain

In structural mechanics, buckling and collapse of members are highly dependent on the cross-sectional properties and lengths of members being considered. For this reason, the mechanical properties of natural wood can exhibit a significant amount of variance.

Jet Propulsion Laboratory (JPL) also performed over a hundred tests to understand variances in balsa crush strength. The correlation between density and average crush strength of Balsa Wood are shown in Figure 3.

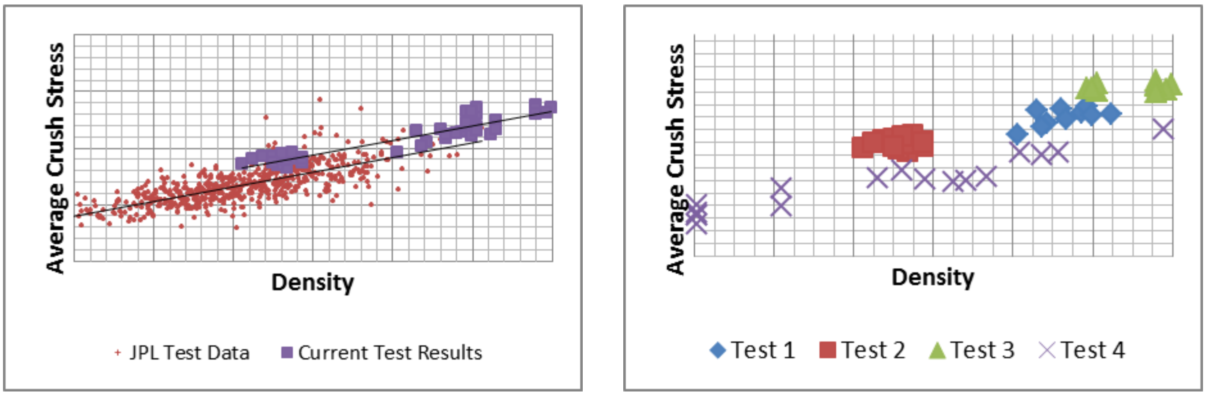


Figure 3 Balsa crush strength data (a) JPL test results and current test results (b) Test results from different regions

Large variations in ACS exist for a given density. For example, for a density range of 8-9 pcf, the average crush strength (ACS) is approximately 1,500 psi with a standard deviation of 300 psi. Impact limiters are designed for both ends of the ACS spectrum. Low end values ensure the impact limiter does not bottom out during the drop event while the high end values aid in calculating a conservative deceleration. Inclusion of ACS variations due to temperature effects presents a challenging design environment.

FABRICATION EXPERIENCE

The original TN-RAM Cask and impact limiter system were designed over 30 years ago. Recently, TNA fabricated a TN- RAM Cask which required new wood impact limiters to protect it during transport. Revisiting the design brought along many challenges, including issues related to wood procurement. Constraints on wood availability resulted in higher ACS per density than tests from the original design built 30 years earlier. Because of this, the license specification became over constrained.

For TNA, material acceptance tests also proved challenging. For TN-RAM wood impact limiters, acceptance testing involves specific requirements for density, moisture, and ACS. A comparison of past and present tests reveals that values for ACS for a given density are higher now than data obtained for either the original design or JPL tests. Direct comparisons of recent results from acceptance test versus JPL results are shown in Figure 3(a). Note that the new results (in purple) trend higher than data from JPL (in red).

Due to a rise in popularity, Balsa Wood is now being grown and sold in more parts of the world than ever before. And, since its mechanical properties are dependent on many factors including weather and climate, it is expected that balsa trees growing in different parts of the world will experience a much wider variations in density and ACS. Figure 3(b) shows test results for ACS and density for Balsa Wood from different regions of the world. While the density to ACS follows a similar tend as before, it adds to uncertainty to an already wide spectrum.

ENGINEERED ENERGY ABSORBING MATERIAL INVESTIGATION

Some engineered materials present better ACS variation control than naturally growing woods, making them good energy absorbing materials used for impact limiter design. The following is a discussion of 3 engineered materials in wide use today.

Aluminum honeycomb (AH)

As an engineered material, Aluminum Honeycomb (AH) is easily machined without cell reinforcement, fully vented (thus allowing volatiles/pressure to escape), and stable during shipping and handling. Like wood, the ACS of AH depends on orientation. Several mechanical properties are controlled during the manufacturing process to vary the crush strength from 500 psi to 5000 psi.

Several vendors are able to control the variation to +/- 15% of the target ACS. It has already been used in several impact limiters, including TNA’s MP187 design [6]. However, since AH is metallic based, it is heavier and more expensive than the wood. Figure 4(a) shows Trussgrid AH from Alcore Inc [7].

(a) aluminum honeycomb **(b) plastic foam** **(c) carbon foam**

Figure 4 Engineered material

Plastic foam

The most popular plastic foam is polyurethane. It is typically prepared by the reaction of addition, condensation or cyclotrimerization. The main advantage of plastic foam as an energy absorbing material for is that it is quasi-isotropic material. Therefore design of foam impact limiters are easier to design than anisotropic materials like wood or AH. Another advantage is that foam can come in a large range of densities, which also means a large range of ACS can be used in the design.

The main disadvantage for plastic foam material is its strong temperature dependency of ACS, resulting in a lower working temperature than other materials. Another weakness includes a relatively low compressive lockup strain during compression when compared to wood.

Figure 4(b) shows a sample of Polyurethane Foam. For Polyurethane Foam, typical mechanical properties are:

- Density: 15 - 30 pcf
- ACS: 1500 - 3500 psi

- Lockup Strain: 40 - 50%

Carbon foam

Carbon Foams generally fall into two categories: graphitic and non-graphitic. Compared to graphitic Carbon Foam, Non-Graphitic Carbon Foam are generally stronger, but possess lower thermal conductivity and cost far less to manufacture. Carbon Foam is also inflammable and incombustible.

Figure 4(c) shows the sample of carbon foam from CFOAM Inc. Typical mechanical properties of carbon foam are:

- Density: 10 - 30 pcf
- ACS: 500 - 3000 psi

PERFORMANCE COMPARISON BETWEEN ENGINEERED AND NATURAL MATERIALS

Model setup

Figure 5 shows a transport cask system model used for the performance comparison. The characteristic parameters are:

- D1 = 90 in, D2 = 96 in, L1 = 50 in, L2 = 20 in, D3: to be decided
- Loaded Cask weight W = 250,000 lbs

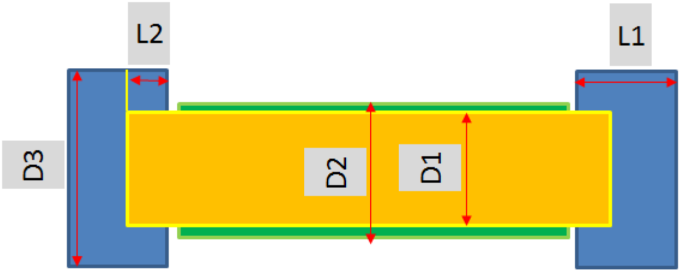


Figure 5 Diagram of Transport Cask System Model

Material property

For wood and engineered materials (EM), the same nominal properties are used:

- Density: 20 pcf
- ACS: 2000 psi

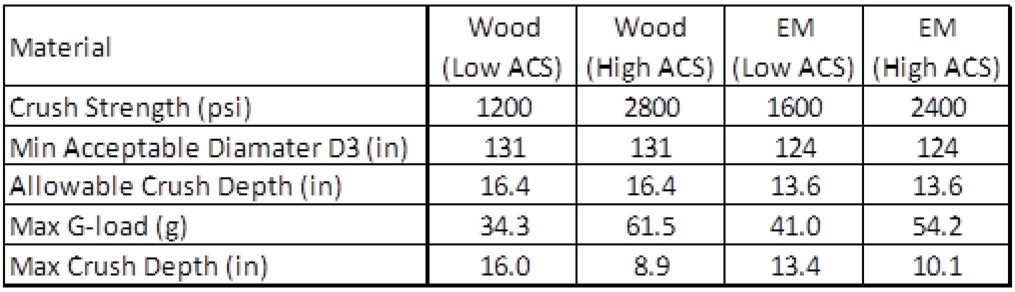
The ACS variation for each material is:

- Wood: ±40%
- EM: ±20%

Initial design and predicted performance result

In-house software was used to optimize each impact limiter design. For each simulation, the materials with the lowest ACS were modeled. The minimum acceptable impact limiter diameter, D3, was then determined by iteration. Later, the highest ACS for the material was applied to determine the maximum acceleration (G-load) for a given design. Table 1 shows the summary of results for all simulations.

Table 1 Summary of performance prediction



Material	Wood (Low ACS)	Wood (High ACS)	EM (Low ACS)	EM (High ACS)
Crush Strength (psi)	1200	2800	1600	2400
Min Acceptable Diamater D3 (in)	131	131	124	124
Allowable Crush Depth (in)	16.4	16.4	13.6	13.6
Max G-load (g)	34.3	61.5	41.0	54.2
Max Crush Depth (in)	16.0	8.9	13.4	10.1

Data from Table 1 indicates that engineered energy absorbing materials resulted in a smaller minimum acceptable diameter (D3 = 124 inch) and lower maximum G-load (54.2 g) than their wood counterparts (D3 = 131 inch and 61.5g, respectively).

CONCLUSIONS

Based on the foregoing discussion, the following suggestions could be made:

- Over-constraining material property definitions should be avoided.
- Engineered materials inherently possess an advantage over wood when attempting to control variation related to ACS. Therefore, they are recommended as the first choice for future impact limiter development, especially when a smaller size is desired.
- New impact limiter designs (using engineered materials) should consider weight and cost evaluations when determining material applicability.

ACKNOWLEDGMENTS

Authors would like to thank following for information supply and for review comments: Daran Ossinger, Yueh Kan Shih, and Prakash Narayanan.

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