Numerical Simulations of Dynamic Deformation of Air Transport Package PAT-2 in Accidental Impacts

Alexander A. Ryabov, Vladimir I. Romanov,
Sergey S. Kukanov, Sergey G. Skurikhin

Joint Stock Company SarovLabs,
23/16 Varlamovskaya Road, Sarov, Nizhniy Novgorod region, 607190, RUSSIA
Tel: +7 83130 40802, Fax: +7 83130 44854
E-mail: alexr@socc.ru

Abstract

The PAT-2 package is designed by Sandia National Laboratories [1] for the safe transportation of plutonium and/or uranium in small quantities, especially as transported by air. The package consists of an outer container and an inner absorber. The outer container is made of 304 stainless-steel sheet metal. The inner absorber assembly consists of redwood and maplewood layers and is used for decreasing the mechanical loads onto the inner capsule with a radioactive material.

The PAT-2 package is resistant to high-speed jet aircraft crash. That was verified by the experiments. The package was tested in several orientations and subjected to impacts at a velocity of >129m/s onto a flat unyielding surface. Some obtained results of the package dynamic deformations are described in [1]. It is also noticed in [1] that the worst impact orientation could not be proven by the stress analysis before the tests. That's why it's very important to conduct a numerical simulation of the package behavior in high-speed impacts to compare the numerical results with the experimental data. Such a numerical expertise opening "an internal deformation world" of the construction behavior allows understanding the weakest and the strongest features of the design and can show the ways on how to improve the structure. It's also an additional experience of LS-DYNA® applications for such problems as well.

The computer model description and the numerical calculations results of the dynamic deformations of the package subjected to top-end, bottom-end, top-corner, bottom-corner and side impacts at a speed of >129 m/s are presented in the paper. Furthermore, U.S. Legislation (U.S. Public Law 100-203) also requires that the foreign shipments of plutonium through U.S. airspace be able to withstand a worst-case aircraft crash, therefore the requirements for packages used for these applications is expected to be even more severe [2]. In accordance with this requirement, the stress analysis of the package at arbitrary impact speed of 200 m/s was performed using the computer model of PAT-2.

Introduction

Development of a protective container for air transportation of radioactive materials is a difficult engineering and scientific problem because of strict requirements to such constructions. In according with these requirements air containers must withstand accidental impact to a hard surface at the velocity not less than 90 m/s. Deformation of the construction in these conditions is an extremely complex and highly nonlinear process. Distinctive features of the process are high levels and rates of plastic strains in the construction's metal parts, orthotropic properties of wood layers, friction in contact interaction between the construction elements, etc. There is a cost effective way for the solution of these difficult problems - it is an application of computer codes for numerical simulations of the dynamic deformation of the structures [6, 7]. Solving such a complex problem with high fidelity takes a deep verification of the code. This verification should be done by comparison of the numerical results and experimental data. Going this way one can prove the methods of numerical simulation and get the best solutions.

This paper presents one of these proving steps – modeling of wood compression under intensive high-velocity loading. Numerical simulations of dynamic deformation of air transport package PAT-2 in high-velocity accidental impacts at different angles are carried out and obtained results are compared with experimental data in order to check the reliability of developed wood model.

Package and Tests Descriptions

The PAT-2 packaging comprises three basic parts: a protective overpack assembly of grain-oriented redwood and maplewood with an embedded titanium inner assembly and a double-walled outer stainless-steel drum, an iron-base superalloy containment vessel and a stainless steel capsule within the containment vessel [1]. Components of the package that do not need to be removed for access, to load and unload contents, are bonded in place with a high-strength flexible epoxy adhesive. Figure 1 shows a section view of the PAT-2 package and its essential elements.

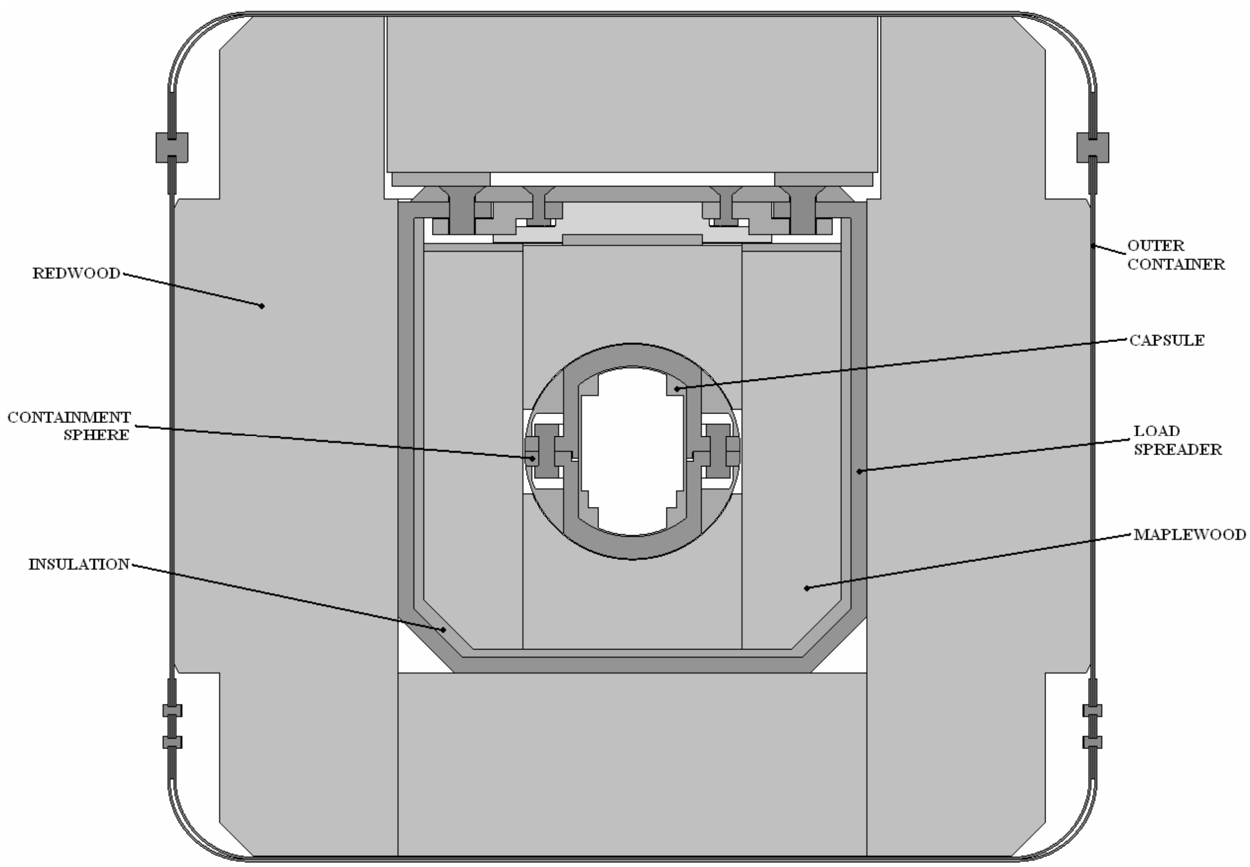


Figure 1. Section View of the PAT-2 Package

In accordance with NUREG-0360 requirements the package was subjected to impact test. The PAT-2 packages were accelerated to a minimum of 129 m/s as measured by redundant photometrics, and the velocity vector of package motion was perpendicular to the face of the unyielding target. Packages were impacted in five crash attitudes:

1. Top end impact (0º attitude)
2. Top corner impact (45º attitude)
3. Side impact (90º attitude)
4. Bottom corner impact (135º attitude)
5. Bottom end impact (180º attitude)

Attitude was controlled to within ±10º and was measured by redundant photometrics. After the impact, the crush, puncture, double-slash, fire and immersion tests were conducted in the order given. The radiographs of the deformed packages were made before the fire test. After the immersion test the packages were disassembled to check the content integrity.

Computer Model

A 3-D computer model of the construction was created for the numerical simulation. The model consists of about 985,000 solid finite elements and is represented in Figure 2. As it can be seen from the figure, the model considers all the essential elements of the package, including insulation, rivets, bolts etc. Preliminary bolt tightening is not allowed for. Weld seams are not singled out as separate computational subdomains. It is assumed that mechanical characteristics of the weld seam material are the same as those of the main material, and the attenuation constant of each weld is assumed equal to 1.

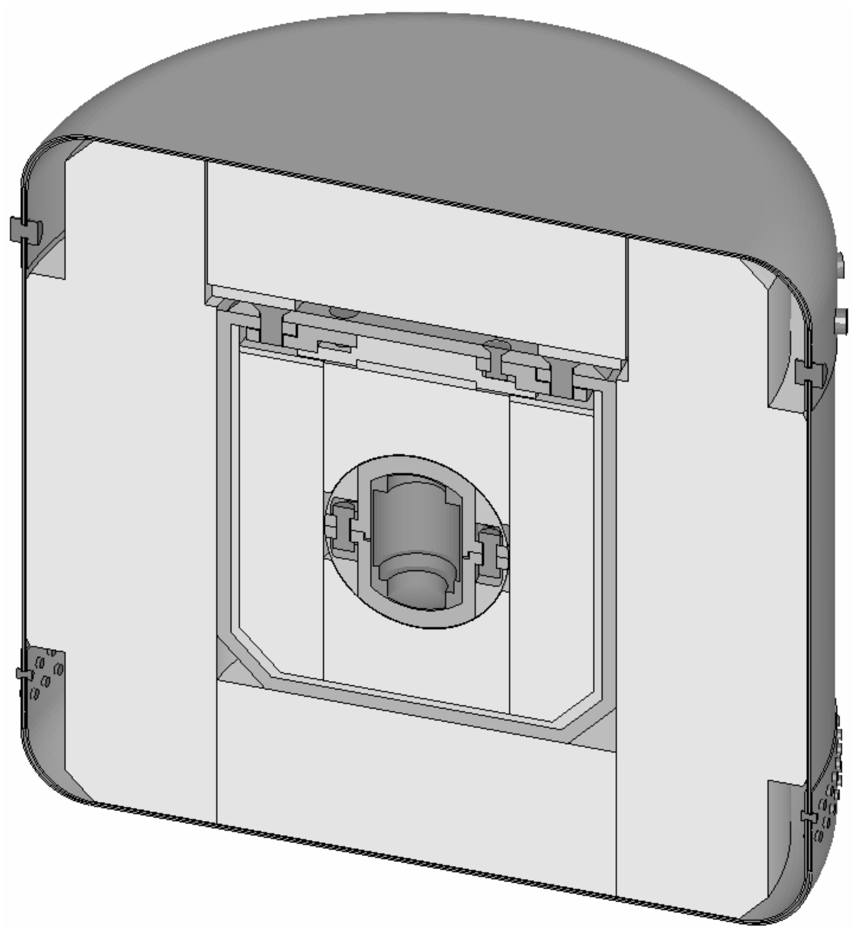


Figure 2. Computer Model of the PAT-2 Package

The initial condition for numerical simulations is a uniform velocity field of amplitude varied in range of 132-139 m/s. The velocity vector is normal to the target surface.
Material model MAT_PLASTIC_KINEMATIC with corresponding properties is used for all the metallic parts of the package.

Wood Material Model

Wood is an orthotropic material [3] and has three orthogonal axes of symmetry: longitudinal, radial, and tangential. The longitudinal axis L is parallel to the fiber (grain); the radial axis R is normal to the growth rings (perpendicular to the grain in the radial direction); and the tangential axis T is perpendicular to the grain but tangent to the growth rings. These axes are shown in Figure 3. The stiffness and strength are greatest in longitudinal direction. The mechanical properties in the two other directions are nearly equal. It is known [4] that at scale of some millimeters wood is a cellular solid: cell walls often with the shape of hexagonal prisms enclose pore space. The relative density (d_0/d_s) where d_s is the density of cell wall material can be as low as 0.05 for balsa. Because of these characteristics, the behavior of wood under compression is similar to the behavior of other cellular materials such as foam or honeycomb.
Nowadays the classic approach is using of elastic-plastic type of material to represent wood. As

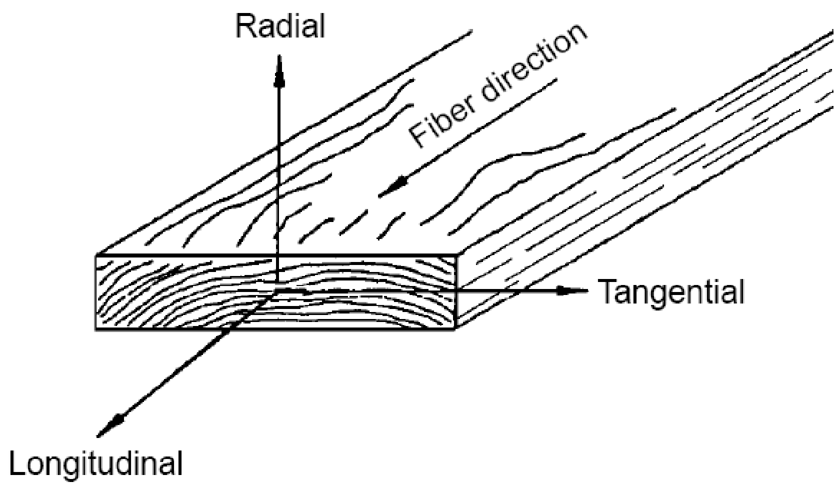


Figure 3. Three principal axes of wood with respect to grain direction and growth rings.

it is noticed in [4], the main drawback of the elastic-plastic model when it is used to represent wood is that it is an isotropic material model that does not take into account the possible porosity of the material. This implies that the plastic volume is constant. That means that when the material is crushed over the yield stress in one direction of orthotropy, its section is increasing in order that the volume remains the same as at the beginning of the plastic phase. Also there is no changing of wood properties after full compaction of wood pores. Therefore, the classic elastic-plastic approach is unsuitable for wood.
As it is mentioned above, the behavior of wood is similar to the behavior of cellular materials. Because of this fact, it was decided to choose LS-DYNA® material model MAT_HONEYCOMB as the basis of wood material model.
Analysis of existed experimental data of wood behavior in compressions at different direction [3-5] shows that at every direction it can be approximated by trilinear curve, showed in Figure 4. As it can be seen from the figure, the curve consists of three linear parts:

1. Elastic (from point (0;0) to point (ε_{yield};σ_{yield}))
2. Plastic (from point (ε_{yield};σ_{yield}) to point ($\varepsilon_{compaction}$;$\sigma_{compaction}$))
3. Compacted (after point ($\varepsilon_{compaction}$;$\sigma_{compaction}$))

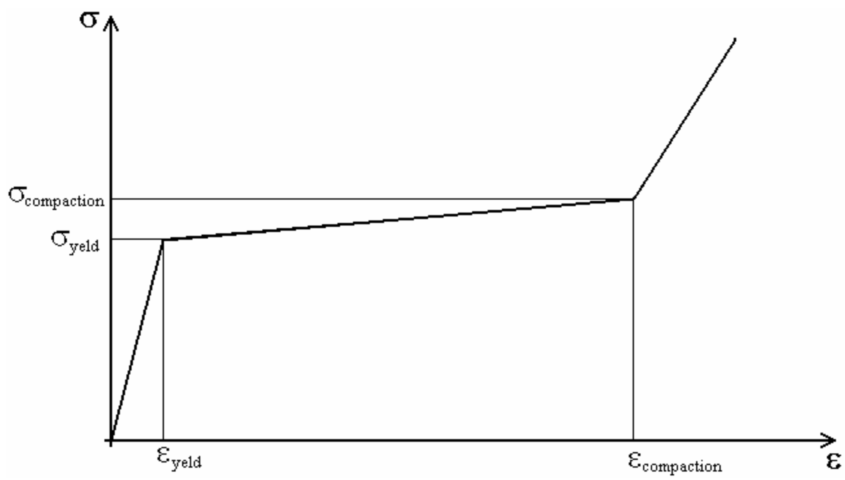
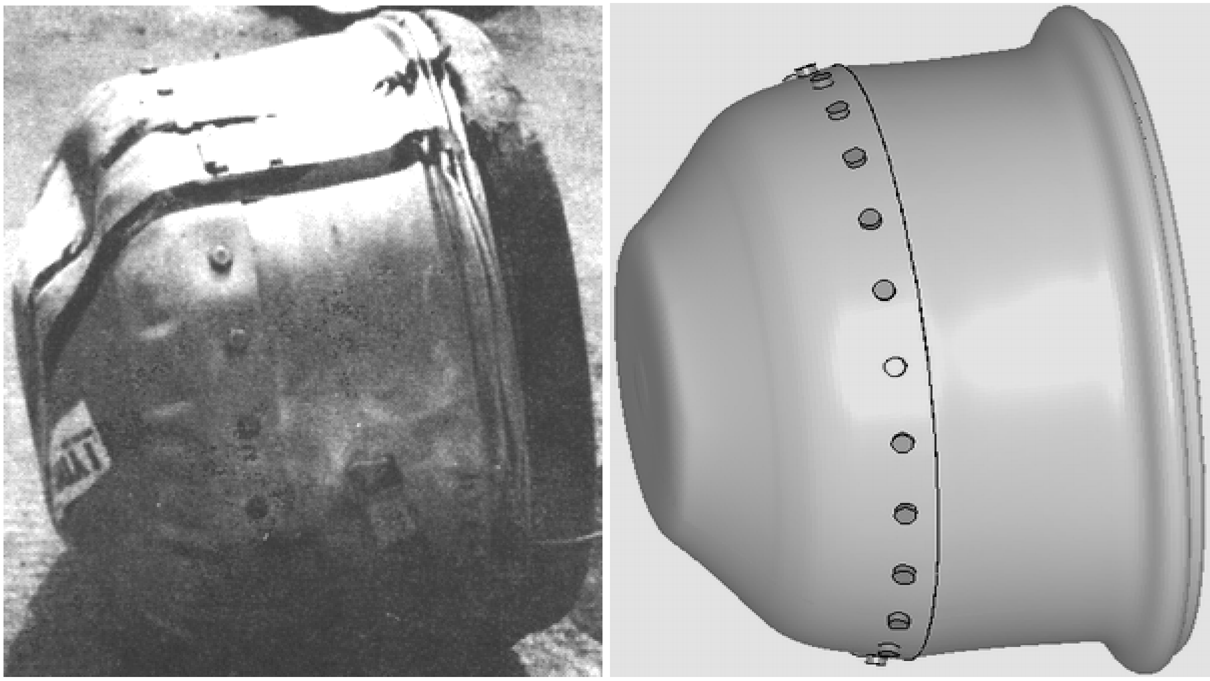


Figure 4. Trilinear approximation of wood behavior in compression.

As it was noticed above, the mechanical properties in radial and tangential direction are nearly equal, so the same curve is used for both of this direction. Thus, only two curves should be defined to describe the wood behavior in compression.
Unfortunately, there is a lack of wood properties for such wood model. To fill up a gap in the properties the following way is used. Initially, the existing properties for redwood and maplewood are set as given in [3-5]. The missing properties are set equal to properties of woods with similar densities. Calculation of PAT-2 bottom end impact is performed with using of these properties and obtained residual thicknesses of wood layers are compared to experimental data. According to the results of the comparison, the properties are changed and the calculation is repeated with the new properties. After a number of iterations, calculated and experimental residual thicknesses of wood layers become the same. After that, numerical simulations of the others directions of PAT-2 impacts are carried out in order to prove the reliability of obtained maplewood and redwood properties.

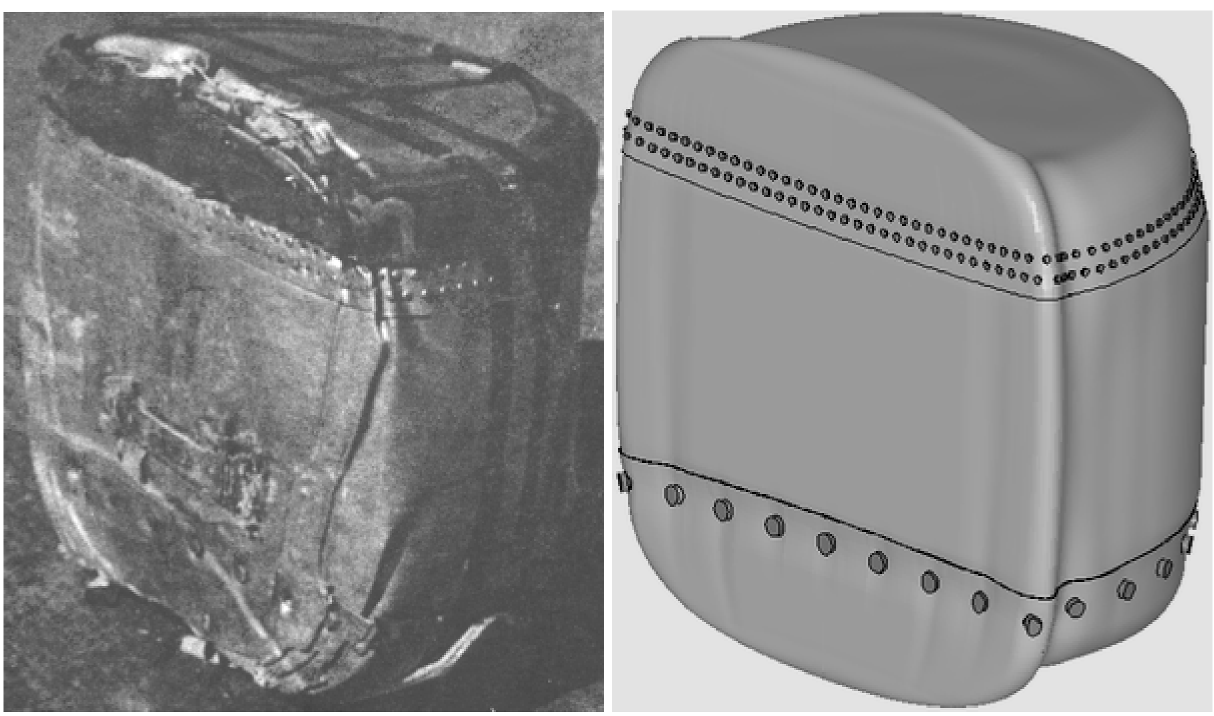
Numerical Results

A large amount of the information has been obtained from numerical simulations of the package deformation in the various orientations of the impact. Some of this information is presented and analyzed below.
Comparison of calculated and experimental deformed shapes of the package after bottom-end, side and bottom-corner impacts are shown in Figures 5-7 correspondingly. As it can be seen from the figures, generally the numerical simulation results and experimental data are well agreed. There are some differences between them, especially in numbers of folds, appeared on the outer container after impacts. This problem could be resolved by a mesh refining in the fold areas, but in frames of this work it is not essential, because the main goal of the work is developing of wood model.



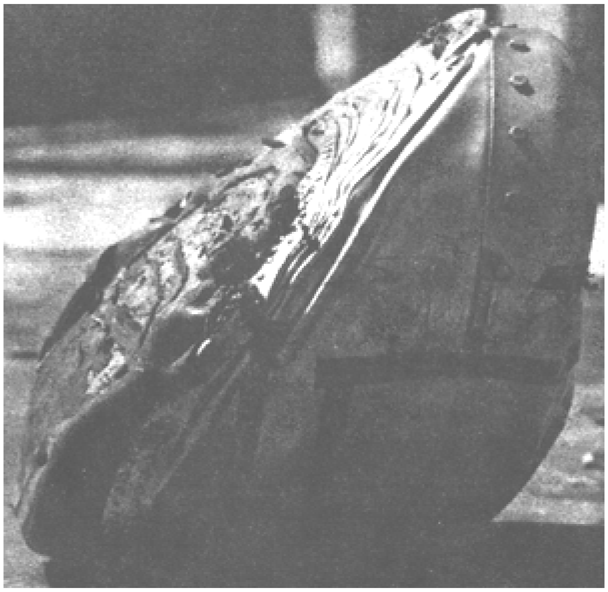
Experimental Calculated

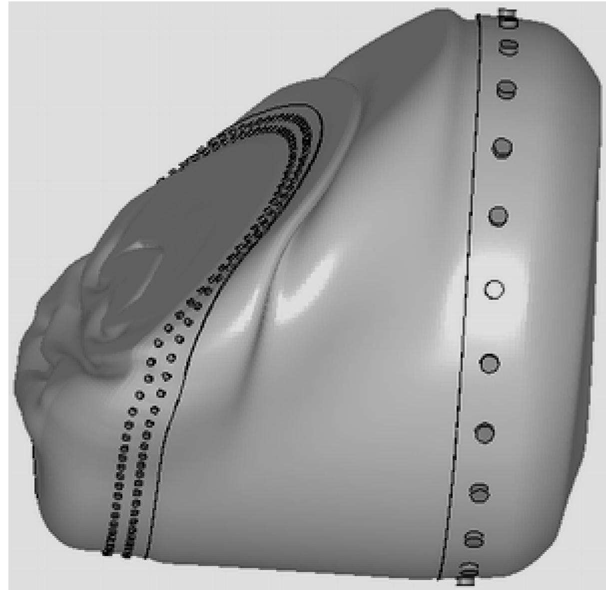
Figure 5. The deformed package after bottom-end impact



Experimental Calculated

Figure 6. The deformed package after side impact



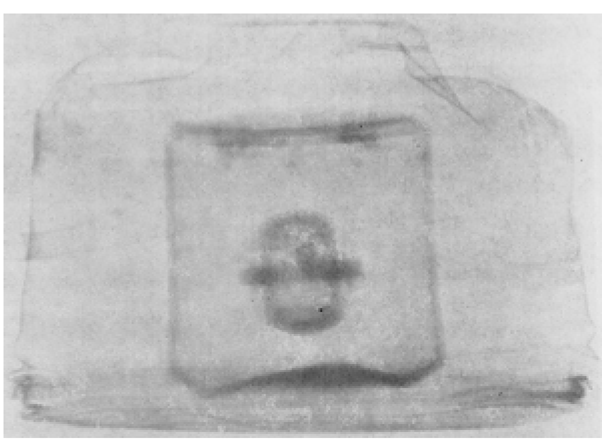


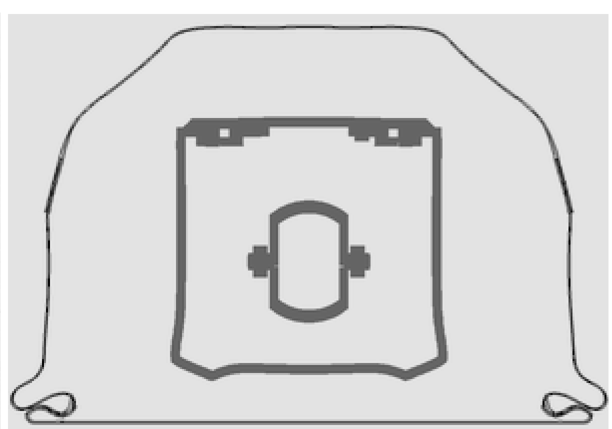
Experimental Calculated

Figure 7. The deformed package after bottom-corner impact

Figures 8-10 show both calculated section views and experimental radiographs of the package's deformed shape after bottom-end, bottom-corner and top-corner impacts correspondingly. It should be noticed that the radiographs were taken after the impact, crush, puncture and double-slash tests, whereas calculated section views show the package's deformed shape after impact only. Because of this fact, there are some differences between the pictures, but generally the calculated and the experimental results are really close.

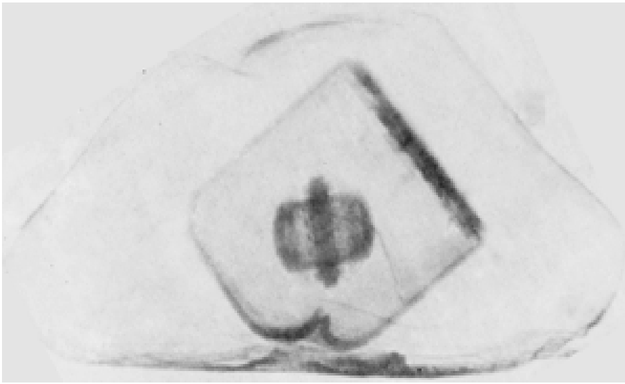
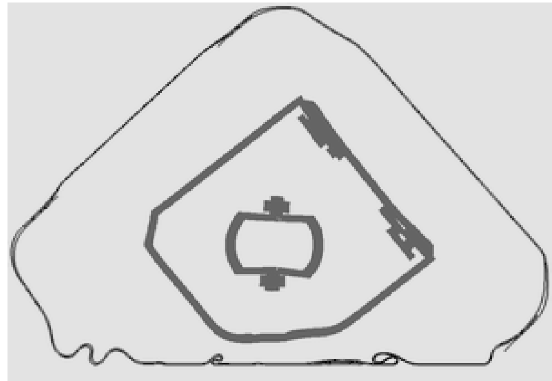
Analysis of the pictures shows that maplewood and redwood layers are significantly deformed from the side of impact, whereas in the other areas wood layers are almost not deformed. So, to verify the developed wood model it is enough to compare experimental and calculated residual thicknesses of wood layers in impact area only. The results of the comparison are presented in Table 1. The table demonstrates that the experimental and calculated residual thicknesses are well agreed. Inaccuracy of the calculations is not exceeded 16%, so it can be concluded that the developed wood model accurately describes wood behavior in high velocity compression.





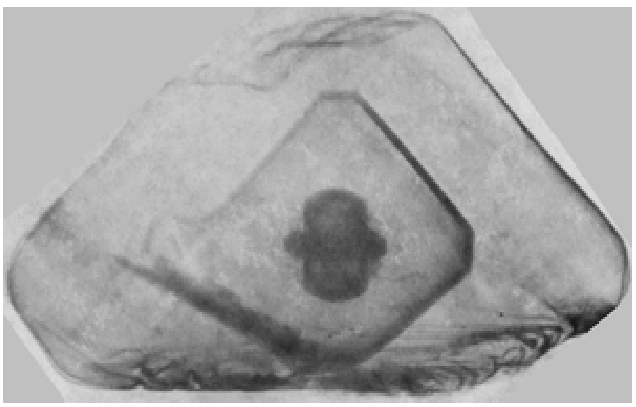
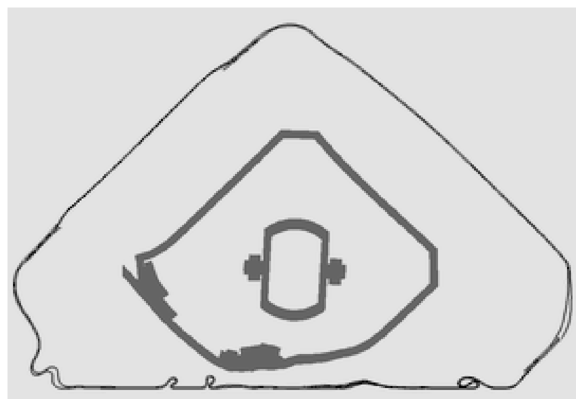
Experimental Calculated

Figure 8. Radiograph of the package after bottom-end impact

Experimental Calculated

Figure 9. Radiograph of the package after bottom-corner impact

Experimental Calculated

Figure 10. Radiograph of the package after top-corner impact

Table 1. Residual thicknesses of wood layers

Impact Orientation	Thickness of Maplewood Layer (mm)		Thickness of Redwood Layer (mm)	
	Experimental	Calculated	Experimental	Calculated
Bottom-end	29	31	30	29
Bottom-corner	38	36	17	18
Side	34	36	12	13
Top-corner	37	32	12	12
Top-end	30	31	20	21

Analysis of the experimental data shows that the package is the most damaged in the case of top-corner impact, so it was decided to repeat the calculation of top-corner impact at impact velocity of 200 m/s. The main goal of this simulation is testing of developed wood model with higher strain rates. At the same time, this calculation allows checking if the package meets the U.S. Legislation requirements for the foreign shipments of plutonium through the U.S. airspace [2].
The package's deformed shape after the top-corner impact at velocity of 200m/s is shown in Figure 11. As it can be seen from the picture, the developed wood model works well for this case too. Analysis of the numerical results and the package's deformed shape shows that the deformation of the package is significant and it seems that the content does not keep its integrity.

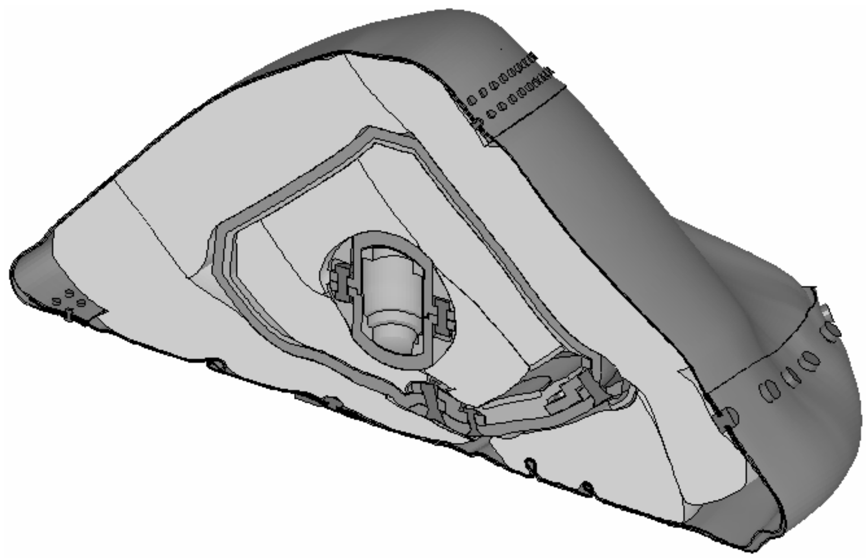


Figure 11. Cutaway view of the package after 200m/s top-corner impact.

Summary and Conclusions

Material model for numerical simulation of wood behavior in compression has been developed basing on the existing experimental data and LS-DYNA® MAT_HONEYCOMB material model. Numerical simulation of dynamic deformation of air transport package PAT-2 in accidental different orientations impacts onto a flat unyielding surface at a velocity of >129m/s was performed using the wood model. Comparison of experimental data and numerical results shows that they are well agreed, so it can be concluded that the developed wood model accurately describes wood behavior at high strain rates.

References

1. J.A. Anderson, E.J. Davis, T.A. Duffey, S.A. Dupree, O.L. George, Jr., Z. Ortiz PAT-2 (Plutonium Air Transportable Model 2), Safety Analysis Report, Sandia Laboratories, 1981.
2. United States Public Law 100-203, Title V – Energy and Environment Programs, Subtitle A – Nuclear Waste Amendments, Part – Miscellaneous, Section 5062, December 22, 1987.
3. Forest Products Laboratory. 1999. Wood handbook—Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.
4. C. Adalian, P. Morlier Modeling The Behaviour of Wood During The Crash Of A Cask Impact Limiter, PATRAM'98 Conference Proceedings, Vol.1
5. A.P. Bolshakov, N.N. Gerdjukov, E.V. Zotov, S.A. Novikov, Yu.I. Scherbak Damping Properties of Sequoia and Birch Under Shock Loading, PATRAM'98 Conference Proceedings, Vol.1
6. A. A. Ryabov, V. I. Romanov, G. I. Sotskov Numerical Simulations of Dynamic Deformation of Air Transport Fresh Fuel Package in Accidental Impacts, WM'03 Conference, February 23-27, 2003, Tucson, AZ.
7. A. A. Ryabov, V. I. Romanov D. V. Roschikhmarov Optimization of Protective Container Subjected to Thermal and Impact Loads. WM'04 Conference, February 29- March4, 2004, Tucson, AZ.