NUMERICAL SIMULATION OF DYNAMIC DEFORMATION OF SPENT FUEL TRANSPORTATION PACKAGE FOR NUCLEAR POWER PLANTS IN ACCIDENTAL MECHANICAL IMPACTS

Dr. Alexander Ryabov, Dr. Vladimir Romanov, Dr. Boris Barkanov, Sergey Skurikhin

Sarov Labs, Sarov, Russia

ABSTRACT

The numerical simulation results and their analysis are presented for the dynamic deformations of TUK-117 package, intended for transportation of spent nuclear fuel from Nuclear Power Plants, subjected to the accidental 9-meter drops onto an unyielding surface at different angles. The main attention of the paper is focused on the analysis of container shock limiters deformation behavior. It is demonstrated that the maximal loading impacts the package at side drop. For the side drop, the maximal strain levels are determined for the different construction elements, including the cask's body and the bolts securing the sealing lid.
Construction dynamic behavior simulation was carried out based on LS-DYNA code, version 970 [1].

INTRODUCTION

TUK-117 package was developed for the transportation of 36 five-year aggregate exposure spent nuclear fuel assemblies of VVR-1000 reactor. One of the most important problems facing the design of the package is the problem of construction safety in accidental conditions. According to "Regulations of Safety Transportation of Radioactive Materials" of the International Atomic Energy Agency, the most severe mechanical accident is considered to be a 9-meter drop of the package onto a hard surface. The solution to the impact resistance problem for the package subjected to accidental drops is carried out based on modern computer numerical simulation technology.
The construction of the package [2] and its fragments are presented in Figures 1 and 2. The construction of the case consists of cylindrical shells (1, 2) and (3) fabricated from stainless steel, welded to coamings (4 and 5). In the bottom section there is a flat thick-walled bottom plate welded to the bottom coaming (4). The container is closed up by means of two lids. Inner lid (7) is set on the upper coaming and is fixed to it with a wedge split ring by means of studs. The inner lid is sealing. The outer lid (8) is attached to the coaming with studs. A particular feature of the container is that depleted uranium is used for anti-gamma-radiation protection. For that purpose, eight uranium rings (9) are placed into the cylindrical case. The siloxane caoutchouc (10) is used for anti-neutron protection. To reduce the mechanical loads onto the package in possible accidental drops the construction is equipped with two shock absorbers (11 and 12) installed at the bottom of the construction and at the outer lid. They consist of sets of alternating vertical flat plates of different height welded to short cylindrical skirts. The number of plates is 48, their thickness is h=30mm.
The purpose of the longitudinal fins (13) on the container is to increase the heat dissipation. They are used as side limiter as well. There are thermal bridges inside the fins. The space inside the fins is filled with siloxane caoutchouc. The spent fuel assemblies are installed in aluminum basket (14) placed inside the package container. The total weight of the container with the cargo is about 150 tons.
According to International Atomic Energy Agency regulations, a container must withstand 9 meter accidental drops from different angles onto an unyielding surface. Preliminary analysis has shown that the most representative cases of orientation for the dynamic stress analysis were as follows (φ is the angle between the container axis and the target surface):

- Axial drop ($\varphi=90^0$) onto the lid.
- Side drop ($\varphi=0^0$).
- Corner drop ($\varphi=67^0$) onto the lid with the center of gravity above the contact point.
- Slap down ($\varphi=67^0 \rightarrow \varphi=0^0$) after corner drop to the bottom.

The dynamic deformations of the package were simulated in frame of ISTC Project [2] based on Russian code DINAMIKA-3 [3] several years ago. The new results of simulations obtained by LS-DYNA code at Sarov Labs are presented in this paper.

THE COMPUTER MODEL

A 3D computer model of the construction was created for the numerical simulations. The model consists of about 850, 000 finite elements, both solid and shell type. The number of shell elements amounts to less than 5% of the total number of elements. The computer model is represented in Figure 1. The models of the top and bottom limiters are shown in Figure 2. The damping elements are made of stainless steel with the yield stress of 236 MPa. The studs are fabricated of steel with the yield stress of 850 MPa.

For numerical simulations of axial, side and corner drops the initial condition (at T=0 time point) is a uniform velocity field of amplitude 13.3 m/sec. The velocity vector is normal to the target surface. In the case of slap-down (corner drop after the first interaction with the hard surface and deformation of the container "corner" it turns round the corner contact area and collides with the obstacle again) the angular velocity is calculated analytically to save computer calculation time.

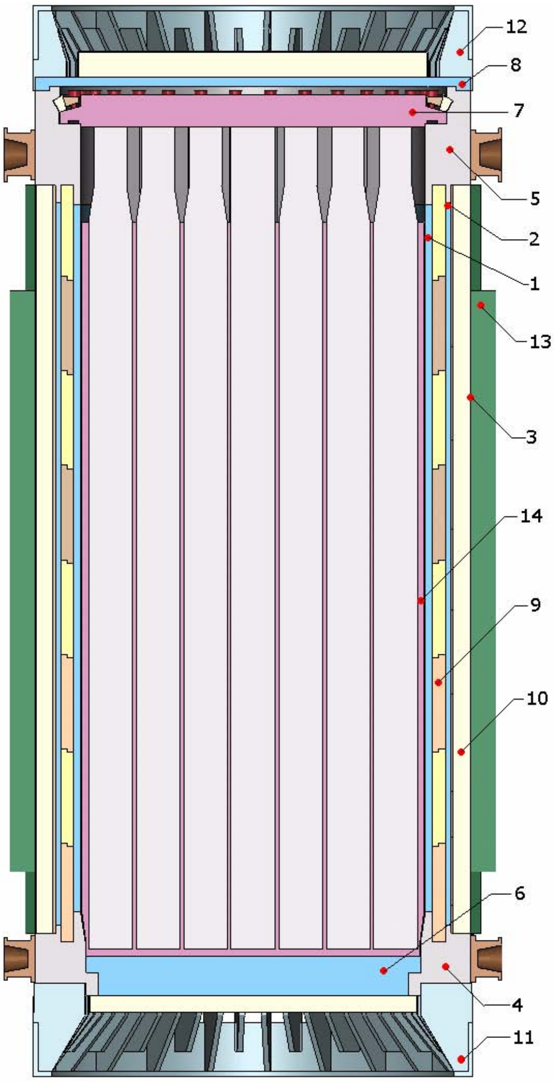

Figure 1 – The Computer Model of the Package

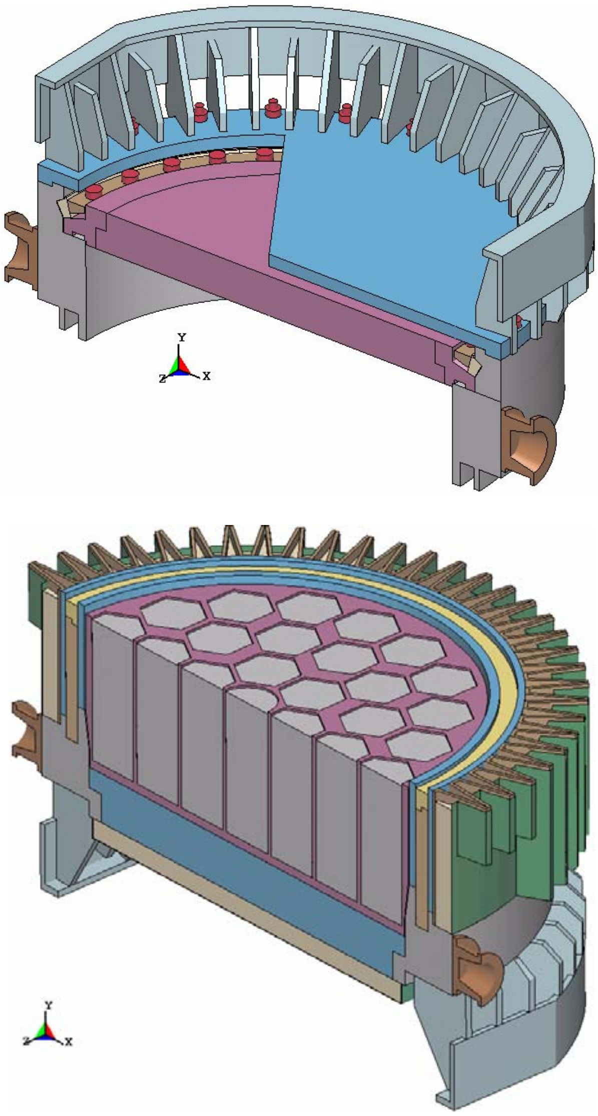

Figure 2 – The Fragments of the Computer Model

ANALYSIS OF THE RESULTS

A large amount of the information has been obtained by the numerical simulations of the package deformation in the various orientations of the drop. A portion of this information is presented and analyzed below.

The Axial Drop ($\varphi=90^0$) onto the Lid

The time dependence of the container overload is presented in Figure 3. Analysis of Figure 3 illustrates that the duration of the deceleration process is roughly 15 -16 ms. The container overload does not exceed 100g. The displacement via time curve is shown in Figure 4. During the deceleration process, the top limiter deforms approximately by 130 mm, which is nearly 35% of its initial height.

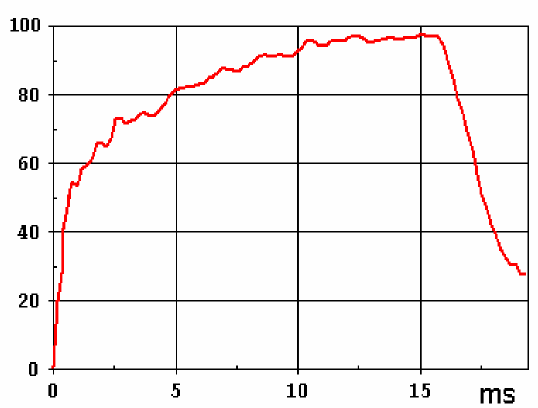

Figure 3 – Integral Package Overload via Time

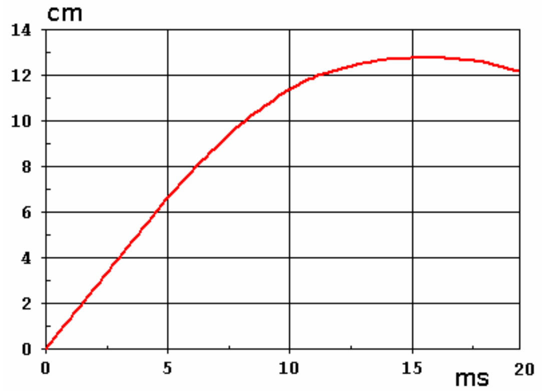

Figure 4 – Container Displacement via Time

Figure 5 illustrates contours of effective strain ε_i in the top limiter. It can be seen in local zones that the effective strain reaches the level up to ε_i~63%, which exceeds the stainless steel allowable elongation δ~50%. This allows assuming the possibility of some local cracks in the top limiter elements.

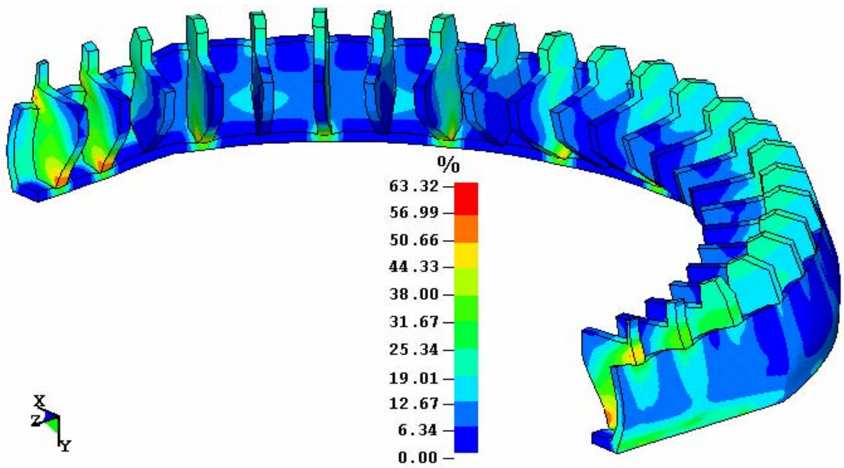

Figure 5 – Contours of effective strain in the top limiter

The Side Drop ($\varphi=0^0$)

Package overload behavior by the use of time and deformed shape of the longitudinal fins after a side drop are presented in Figures 6 and 7, respectively. During the side drop, the lifting trunnions protruding from the longitudinal fins are the first to experience deformation. Within this time interval T= (0-2) ms, when the trunnions deforming the maximal overload is about ~15g. After the first fin closes on the target surface the container overload increases and reaches 140g. The absolute displacements of the package's points in cross-section that goes through the trunnions are about ~ 112 mm. The change of the height of the most loaded fin is 75 mm.

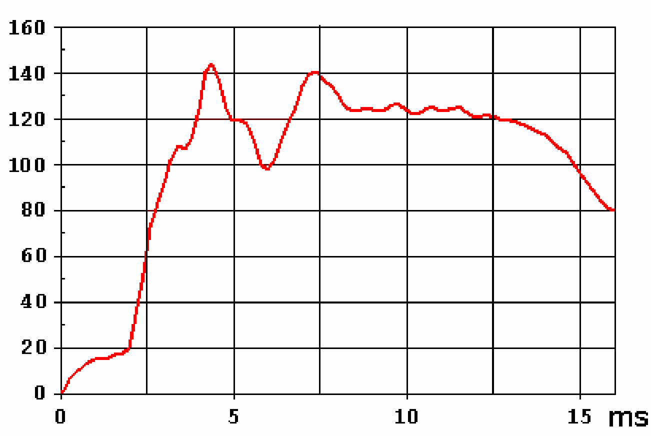

Figure 6 – Integral Package Overload via Time

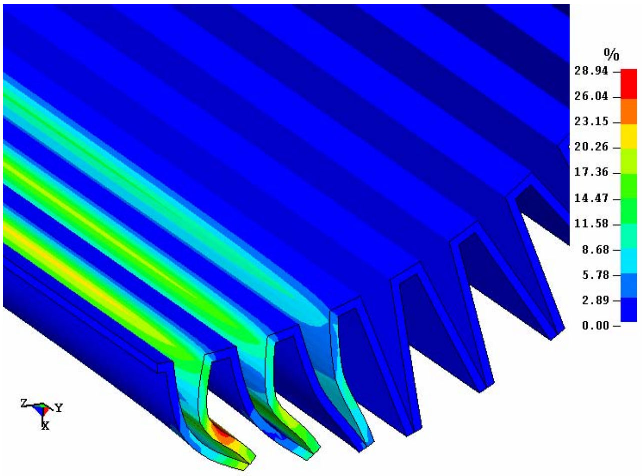

Figure 7 – The Contours of the Effective Strains in the Fins

The number of the fins contacting the unyielding surface is equal to 6. The maximum value of the effective strain ε_i ~30% is localized in the first fin contacting the obstacle.

The Corner Drop (φ=67^0) on the Lid with Center of Gravity above the Contact Point

In Figure 8, a general view of the container impact zone is represented for this case of drop. The container overload is ~55g, which is half as much as the axial drop. The package deceleration duration increases by approximately 2 times and amounts to 33 ms (Figure 9). The container displacement value is 250 mm (Figure 10), which is 1.9 times higher than the deformation after the axial drop. Analysis of the results shows that 10 vertical flat plates of the bottom limiter are involved in the damping process (Figure 11). The cylindrical shell is twisting and the vertical gusset plates are bending. The short vertical plates close on the lower ring plate of the limiter. The maximum deformations in the middle of the vertical plates amount to values of 96%. This indicates that the absorber failure in the impact zone.

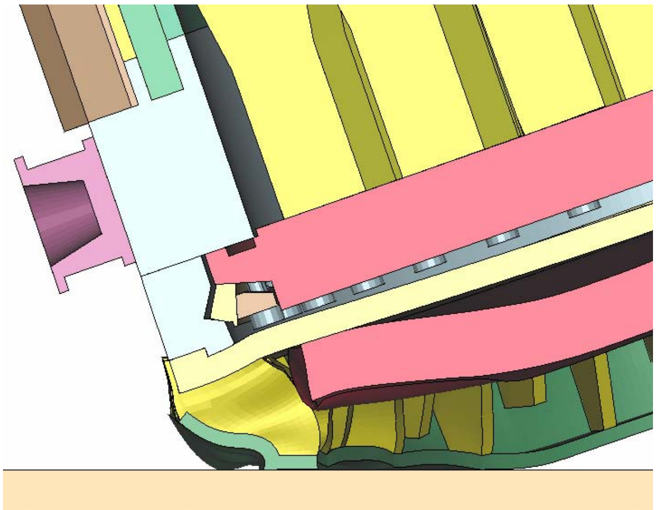

Figure 8 – The Deformed Shape of the Construction

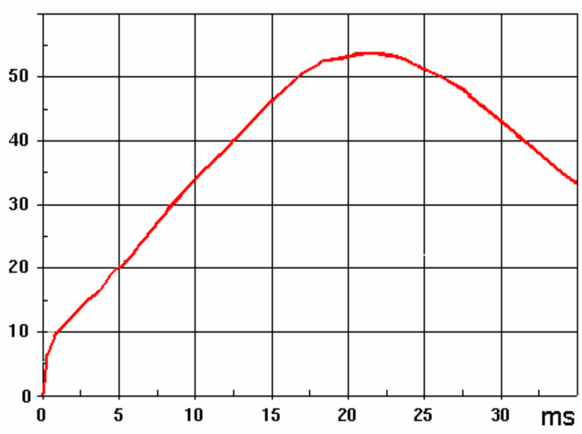

Figure 9 – Integral Package Overload

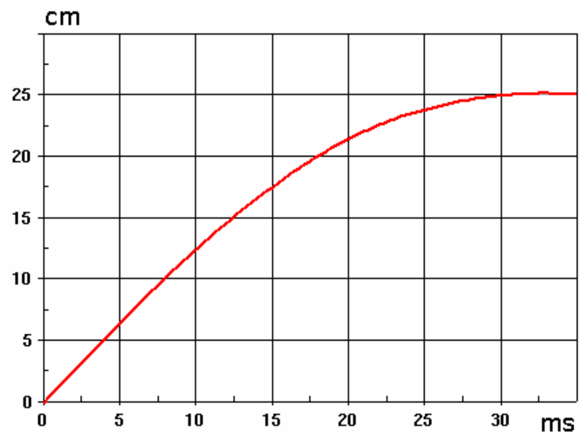

Figure 10 – Container Displacement via Time

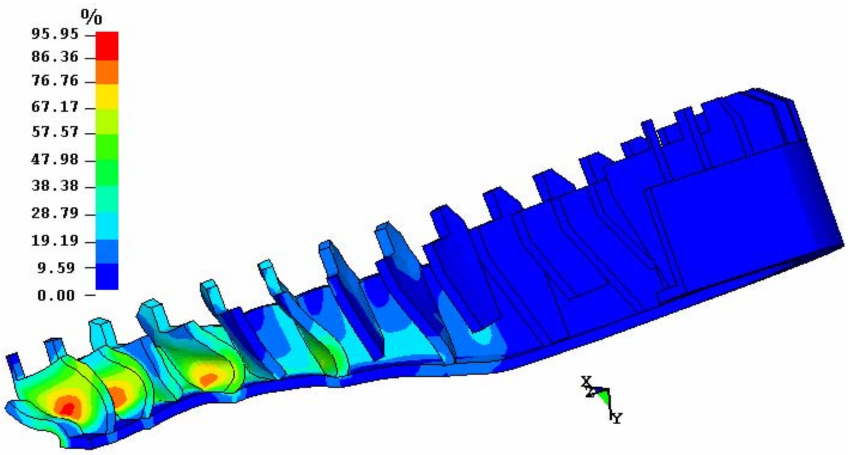

Figure 11 – Contours of Effective Strains

Analysis of the results allows concluding that the top limiter is about twice as compliant in case of the central corner drop as in case of the axial drop.

Slap-Down (φ=67^0→φ=0^0) after the Bottom Corner Drop

Initial impact velocity field, caused by the rotation after corner drop is presented in Figure 12.

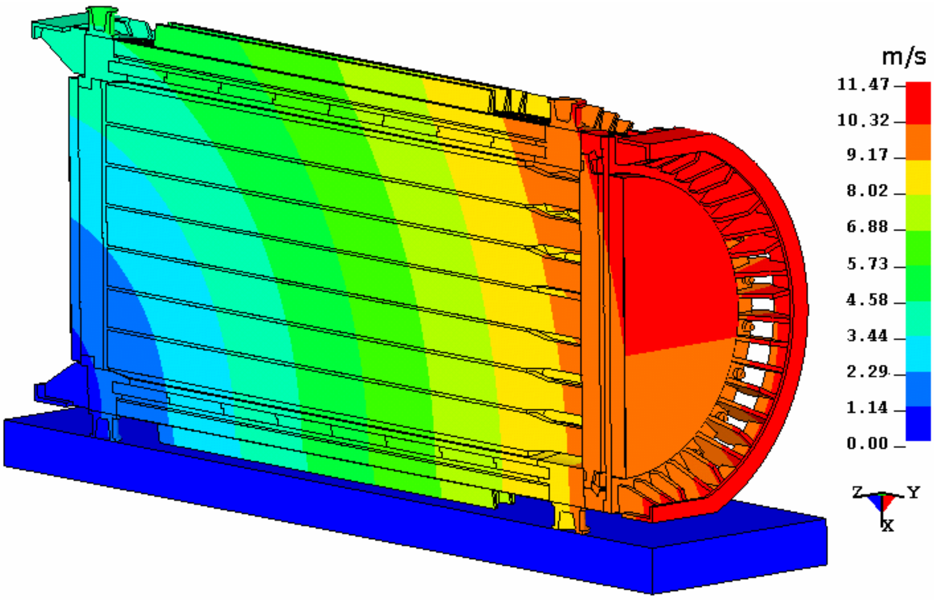

Figure 12 – Initial Velocity Contours

Analysis of the numerical simulation results demonstrates that the maximum package overload value 60g (Figure 13) is close to that in the case of the corner drop and is approximately 1.7 times less than it is as in the side drop. The maximum deformations are localized in the same side fin as for the side drop. However, the maximum deformation level of the fin is about 15%.

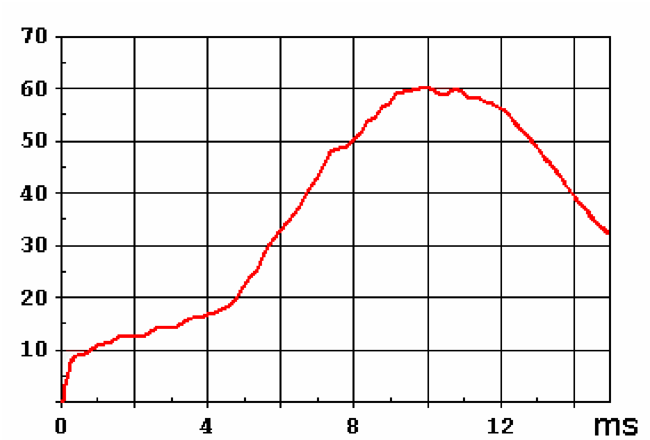

Figure 13 – Integral Package Overload via Time

Table 1 presents the maximum values of the package overload in different orientations of the drops.

Table 1

φ°	90	0	67	67→0
n^{max}, g	100	140	55	60

As shown in Table 1, evidence is given that the level of the container dynamic reaction does not exceed 100g except for the case of side drop.

Let's consider the container elements in the most loaded case – the side drop. Table 2 presents the maximum values of the effective strain ε_i^{max} of the most stressed elements of the construction.

Table 2

	Outer shell	Load-carrying shell	Inner shell	Inner lid studs
ε_i^{max}, %	0.5	1.05	0.9	1.3

Analysis of the results shows that the maximum deformations in cylindrical shells are localized in the butt-ends areas where the shells are connected to the top and bottom coamings. In the connecting inner lid, the most loaded studs are located opposite the impact zone. The maximum level of the effective strain is ~1.3% and is determined by shear deformations. The maximum deformation levels are less than the elongation (ultimate strain) of the shells and studs materials that are ~45% and ~10-15%, respectively. Therefore, it can be concluded that the package withstands 9-meter accidental drops of different attitudes.

CONCLUSIONS

A detailed 3D computer model of TUK-117 package was developed and its dynamic behavior in accidental mechanical loadings was investigated by the computing simulations. The numerical results allow concluding that the package meets the safety requirements in accidental 9-meter drops.

1. Axial shock absorbers provide the level of package loading not exceeding 100g.

2. The worst loading case for the package is a side drop, when the maximal overload reaches the level of 140g, thought to be the most stressed elements of the construction withstand this impact.

3. In instance of a corner drop onto the lid, the side fins are twice as compliant as in instance of side impacts. This leads to reduction of the load by 2 times and increase of the container displacement by 2 times. The top absorber elements can fail during the corner drop.

REFERENCES

1. LS-DYNA. Version 970. User manual.

2. Project #963, International Science and Technology Center, Moscow, 2000.

3. V.G. BAGENOV, A.I. KIBEC, Numerical simulation of three-dimensional problems of dynamic deformation of elastic plastic structures by finite elements method. Proceedings of the Russian Academy of Sciences Mechanics of Solids, 1994, No 1, p. 52-59.