NUMERICAL STUDY OF THE MECHANICAL BEHAVIOUR OF TYPE B RADIOACTIVE MATERIAL PACKAGES IMPACTING REAL TARGETS

R.E. Vallée, L.I. Piot, I. BenHania
IPSN, BP 6, 92265 Fontenay-aux-Roses Cedex, France

(Most of this study has been performed in the framework of a Common Interest Program IPSN-COGEMA)

ABSTRACT

This paper presents (1) numerical drop impact simulations of type B radioactive material packages, (2) a comparison between the package damages caused by the 9m free drop onto a regulatory unyielding target and those caused by impacts on various targets, and (3) a mathematical model to evaluate the global mechanical behaviour of packages under impacts onto real targets.

Detailed finite element models of two packages (TN12 for the transport of spent fuel and FS47 for the transport of plutonium dioxyde powder) and of real targets have been developed to evaluate the structural integrity of packages during the drop impact accidents. Then, several mechanical impact simulations using the state-of-the-art numerical methods have been performed. The structural analyses were conducted by three dimensional analysis models using highly non-linear structural dynamic codes (DYNA3D, ABAQUS, and PAM-CRASH). The drop impact simulations included:

- impact of typical spent fuel shipping cask on various types of soils (clay, sand, and rock);
- impact of the TN12 and the FS47 on various metallic targets likely to be encountered during transport or handling;
- impact of the TN12 and the FS47 on a reinforced concrete structure;
- impact of packages on each other (TN12-TN12, FS47-FS47).

For each impact situation, several configurations, depending on the package orientation, the impact point on the target, and the drop height, have been simulated. These simulations point out the shock energy repartition between the package-target components, and highlight the high level energy absorption by the rack of the FS47, the frame of the TN12, and also by the target structure.

Results show that for the two packages studied, the simulated situations of handling accidents appear less severe than the regulatory drop tests.

INTRODUCTION

The aim of the study was to check how typical type B packages behave under a variety of severe handling mishaps among the most damaging likely to be encountered in real transport campaigns. Different types of packages are used in the transport of radioactive material. Two types of type B packages (TN12 and FS47) have been chosen, which are frequently used and loaded with high activity contents.

The TN12 package (cylindrical shape, 6150 mm length, 2500 mm diameter and weighing between 88 000 kg empty and 103 000 kg loaded) is used to transport spent fuel from reactor sites to the reprocessing plant.

The FS47 package (cylindrical shape, 2055 mm length, 742 mm diameter and weighing between 1380 kg empty and 1500 kg loaded) is used to transport powder of plutonium oxide from the reprocessing plant to the MOX fuel production plants.

The TN12 and FS47 packages have been modelled by finite element methods. Each finite element model has been calibrated in comparison with results of 9 meters drop tests onto an unyielding surface. In addition to package modelization, the frame of the TN12 and the rack of the FS47 have been modelled in order to take into account the environment of the package.

Four types of target structure have been studied : soils (clay, sand, and rock), various metallic targets, reinforced concrete structure, and the same package. Each target structure has been modelled with a specific law of behaviour. After simulation of the different impact configurations, an analysis of the validity of results is made and, if necessary, an improvement of the numerical model is performed and the calculation is repeated.

MESHING, CONTACTS AND MATERIALS

In a first phase, a simplified numerical model of a typical spent fuel package is made to simulate (with ABAQUS code) vertical drops and corner drops onto various type of soils. This simplified model takes into account the body and the shock absorbers with wood filling in a metallic envelope. The body and the envelope of the shock absorbers are modelled by 3D shell elements. Wood of shock absorbers is modelled by 3D volume elements. An isotropic elastic type law of behaviour (Young modulus E = 210 GPa, Poisson coefficient = 0.3) is used for the body of the package. The behaviour of the wood is considered as isotropic elastic-plastic. The mechanical characteristics of the wood are adjusted as the function of the orientation of the drop.

In a second phase, a complete numerical model of the TN12 package and of the FS47 package are made. As calculations are performed with two dynamic codes (DYNA3D and PAM-CRASH), two numerical models have been developed and calibrated for each package. Each numerical model is presented.

The complete numerical model of the TN12 package includes the meshing of the shell, the bottom, the plug, the ring flange, the plug cover, the neutron shielding, the trunnions, and the shock absorbers. The copper fins are not modelled, but their weight is taken into account. The shell, the trunnions, the neutron shielding, and the wood in the shock absorbers are modelled by 3D volume element. The shell elements are used to model the metallic envelope.

For the numerical model (50 000 volume elements) of the TN12 package developed with DYNA3D, the content (basket and fuel assemblies) is modelled either by a rigid cylindrical inside the cavity, or by nodal mass linked to the body. For the numerical model (17 000 volume elements) developed with PAM-CRASH, the weight of the content is modelled by modification of the specific weight of the body.

The law of behaviour for steel and aluminium pieces is elastic-plastic. The law of behaviour for the neutron shielding is isotropic elastic linear for the PAM-CRASH model and elastic-plastic for the DYNA3D model. The mechanical behaviour of the wood is modelled by non- linear orthotropic law. The fixing bolts of the closure system are modelled by rigid elements.

Two complete numerical models have been performed for the FS47 package (one for DYNA3D and one for PAM-CRASH). The body and the closure system are modelled by volume elements (48 000 for DYNA3D and 16 000 for PAM-CRASH).

IMPACTS ONTO SOFT AND HARD SOILS

Nine different targets were studied in order to cover as wide a range as possible of natural ground surfaces which might be encountered during transport: clay, sand and rock, each having three levels of hardness: soft, semi-hard and hard. A bilinear elastic-plastic law is used to model these materials with a yield strength defined by a Mohr-Coulomb criterion ($\tau = c + \sigma_n.\tan \phi$), except for the rock for which a Von Mises criterion was used.

Ground surface	E (MPa)	ϕ (°) or σ_e^* (MPa)	c (MPa)	ν
Clays	50 - 150 - 300	0	0.1 – 0.3 – 0.8	0.3
Sands	50 - 250 - 500	15 - 25 - 35	0	0.3
rocks *	2500 - 34000 - 30000	10 - 26 - 70	X	0.3

Table 1 : numerical values for behaviour laws

Three drop orientations were analysed: vertical, on an edge and horizontal. The drop heights used were 9 m, 20 m and 40 m in turn. Only the typical spent fuel package was studied with the main results being as follows.

For vertical drops:
For the 3 types of sand, the 3 types of clay and the soft rock, the behaviour of the package is practically the same and only changes very slowly with drop height: at 9 m, the wooden cover compressed by around 10 mm while indentation of the package into the target varies between 80 and 510 mm. The kinematics of the impact are essentially governed by the hardness of the target. For the semi-hard and hard rocks, the behaviour of the package is characterised by the wooden cover being compressed by 45 mm when dropped from a height of 9 m where this compression increases rapidly with drop height: the kinematics of the impact are governed by the damping ability of the wood and the drop height resulting in the same compression (60 mm) of the cover as the drop from 9 m onto an unyielding target is 13.5 m.

For corner drops :
The impacts on sand and clay lead to a moderate compression of the cover and greater indentation of the package into the ground than for vertical drops (corner effect). For a drop

height of 9 m, impacts on rock lead to a cover compression of 380 mm, similar to that found when a package is dropped edge-first onto an unyielding target. The relationship between drop height and cover compression is no longer relevant when there is full compaction of wood.

Note: for particularly soft soils, a drop which does not produce any mechanical damage to the package may however, due to the indentation into the ground and the thermal power released by the contents, cause an unacceptable temperature rise.

IMPACTS ONTO METALLIC TARGETS

Five targets representative of the environment of the packages during transport were studied: the lower spacer beam of a crane, the bilge of a ship, the side of a ship, the side rail of a railcar (*wagon*), the axle of a railcar (fig. 1) and the trunnion supports (fig. 2). The first 4 are deemed to be non-piercing: these are mechanically welded structures made from ordinary steel plate, the thickness of which is typically 25 mm. However, the railcar axle, which is a solid part, and the trunnions supports, made from thick plate (40 - 70 mm), are deemed to be piercing targets. In all cases, a bilinear elastic-plastic law is used to model the target steel.

	Target	height	Frame	Packaging orientation
Non piercing	Spacer beam of a crane	3 m	yes	horizontal and /> to the target
	Bilge of a ship (full)	19 m	yes	horizontal
	Bilge of a ship (empty)	19 m	yes	horizontal
		19 m	yes	+10° from horizontal
	Side of a ship	6 m	yes	horizontal and /> to the target
		6 m	yes	-10° from horizontal /> to the target
		6 m	yes	+10° from horizontal /> to the target
	Side rail of a railcar	5 m	no	horizontal and // to the target
Pierc.	Axle of a railcar	5 m	no	vertical, bottom impact
		5 m	no	CG vertically above impacting point
	Trunnion supports	5 m	no	horizontal

Table 2 : impact configuration studied for TN12

For impacts on piercing targets, and regardless of the orientation used, the characteristic parameters of the impacts are similar. More than 96% of the impact energy is thus dissipated into the target and the frame, the impact duration is more than 100 ms and the maximum acceleration of the package is less than 70 g : the stresses within the packaging and in the cover bolts are always low in relation to the allowable values. The secondary effects which may result from the destruction of the targets were not studied.

For drops onto piercing targets, the numerical model of the TN12 was improved in order to incorporate the connections between the various components of the closure system: the gaps and the bolts were modelled and the contacts controlled (penalty method). On the covers, the mesh was improved and a failure criterion was used. Finally, the model allowed the failure risks of the various bolts to be analysed.

The two package orientations tested for a drop onto a railcar axle give similar results: only 10 - 30% of the impact energy is absorbed by the target, the remainder being absorbed by the package. The impact duration is approximately 55 ms and the maximum acceleration of the package is 30 g. The railcar axle pierces the damping cover and causes local plastic deformation in the closure system (5 - 6%). The stresses on the bolts, slightly higher for a vertical drop, do however remain below the failure limit.

The impact on the trunnion supports actually led to three simulations in order to provide a best estimate of the effect of the bolt model on the calculation results. The impact had the following characteristics: 55% of energy absorbed by the target, impact duration of 60 ms and acceleration of 45 g. The trunnion support pierces the damping cover and causes local plastic deformation. However, unlike the previous case, the stresses on the bolts of the plug cover (secondary confinement barrier) contain a high element of shear, such that one of the 12 cover bolts was destroyed; the ring flange bolts (primary confinement barrier) do not show any sign of failure, but a new model taking into account the failure of the cover bolts would be needed to confirm the behaviour of the ring flange bolts.

	Target	height	Rack	Packaging orientation
Non piercing	Spacer beam of a crane	3 m	yes	vertical, bottom impact
	Bilge of a ship (full)	19 m	yes	vertical, bottom impact
	Side of a ship	6 m	yes	vertical, nearly centred bottom impact
		6 m	yes	vertical, centred bottom impact

Table 3: impact configuration studied for FS47

In all these impact configurations the FS47 packaging is undamaged. In return, its rack behave as a mechanical damper and is strongly damaged, particularly during impact on the bilge of a ship. The most critical impact configuration for the packaging is that on the side of a ship, subject to a perfectly centred impact.

IMPACTS ONTO A REINFORCED CONCRETE STRUCTURE (PIER)

The target models used to simulate impacts on natural ground surfaces are too simple to be applied to reinforced concrete structures, as each has its own behaviour. The case of impacts on concrete therefore had to be dealt with using a specific example. The case chosen is that of the Flamands pier within the port of Cherbourg, France, this being the point at which all MOX fuel and vitrified wastes leaving France by sea and spent fuel entering France are loaded or unloaded.

The pier consists of around a dozen pillars, measuring 36 x 30 m, supported by piles. A single pillar has been modelled in detail, based on the as build drawings. From top to bottom, the pillar consist of a cover slab, a layer of backfill material, a thick slab and a network of beams, caps and piles anchored into the rock; the overall height is 20.8 m. In the impact zone, the mesh was increased and reinforcements are explicitly modelled by beam elements; however, neither the failure of the reinforcements nor the loss of cohesion between the steel and the concrete were taken into account. In addition, a law specifically for analysing reinforced concrete foundations subject to dynamic loading is used. Overall, the pillar consists of 160 000 elements and 115 different materials, essentially due to the very varied reinforcing materials used in the various parts (fig. 3).

For the TN12, five different drop attitudes from a height of 8 m were tested first, in order to determine the most damaging point of impact and orientation. However, the results showed that the concrete suffered a large amount of damage in all cases: many reinforcements undergo plastic deformation with the maximum deflection reached being up to 1 m and the slab is probably pierced. The damage to the package is low compared to that caused by a regulatory 9 m drop, and there is no risk of radioactive material being released. Three additional simulations were therefore carried out with a package in the horizontal position, centred on a beam and from three drop heights: 6m, 4m and 2m. It seems that there is a real risk of piercing the pier for a drop height of 6 m and that from 2 m and above, the damage caused may require the pillar to be totally rebuilt (fig. 4).

For the FS47, four drop simulations from a height of 8 m in different configurations showed that a drop onto a corner in the middle of a bay (travée) is the most damaging, for both the package and the concrete slab: the package causes a 200 mm indentation in the slab and the plastic deformation at the bottom of the package reaches 15%. A new simulation was then performed using this orientation but by increasing the drop height to 50 m (giving $v = 113 \text{ km.h}^{-1}$), which is the maximum lifting height. The amount of damage is the same as for the 8 m drop; the package causes a 400 mm indentation in the concrete and the package is distorted to the same extent as for a regulatory 9 m drop.

IMPACT OF PACKAGES ONTO EACH OTHER (TN12-TN12, FS47-FS47)

The simulations of impact of packages onto each other have been performed with DYNA3D software. Three configurations for the TN12 and two configurations for the FS47 of drop of 16 meter height have been studied.

The first simulation for the TN12 packages considers each TN12 with their frame, in horizontal position, and their longitudinal axis parallel with each other. The frames absorb 50% of the total energy of the drop. The body and the closure system of the TN12 packages are undamaged.
The second simulation considers one TN12 without frame that drops on the other TN12 with frame. Both are horizontal, but their longitudinal axis are perpendicular (fig. 5). In this configuration, an ovalization of several millimetres of the shells of the TN12 packages is observed. Nonetheless, the ovalization does not depend on the modelization of the content (by rigid cylinder or by nodal weight), but a modification of the law of behaviour of the neutron shielding (from a perfect isotropic elastic law to the perfect isotropic elastic-plastic one) increases the ovalization of the shell with a factor 10. An improvement of the knowledge and of the modelization of the mechanical behaviour of the neutron shielding is needed to assess the potential deformation of the content.
The third simulation considers one TN12 without frame in oblique attitude that drops onto the closure system of the second TN12 in horizontal position, with frame. The frame absorbs 53% of the impact energy. The TN12 package that drops is undamaged, but the closure system of the plug cover of the second TN12 is damaged with a 4 % deformation, without damaging the leaktighness system.
Furthermore, for the TN12 package that drops, a height of drop equivalent in comparison of the 9

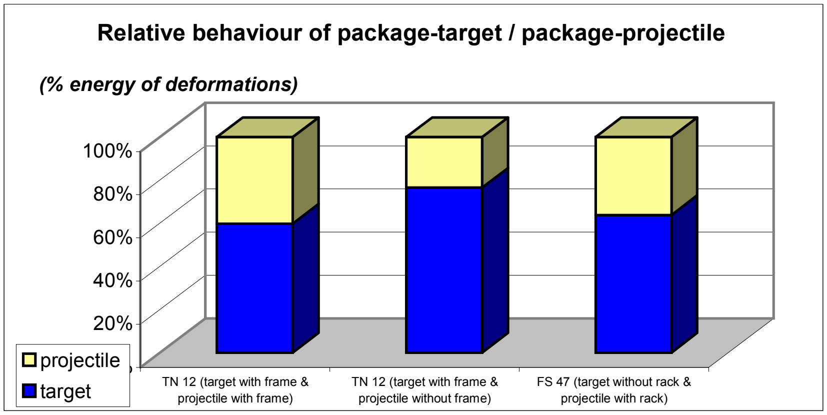
meter regulatory drop test has been calculated. The first configuration is retained. The comparison criteria are the acceleration, the deformation of the trunnions and impacted surfaces, and the absorbed energy. A height of 50 meters is necessary to get identical levels of acceleration, deformation and energy to those calculated for a regulatory drop test.

For the first simulation of the FS47 packages, one FS47 package drops in vertical position, without rack, on the other FS47 package, with his rack. The shock absorber and the rack of the FS47-target are destroyed and absorbed 99 % of the impact energy. Nonetheless, its closure system is undamaged.

For the second simulation, one FS47 drops in oblique attitude on the shock absorber of the second FS47 with rack. The impact point is centred on the closure system (fig. 6). In this case, the FS47-target absorbs 70% of the impact energy, mainly with his shock absorber. Moreover, a part of the closure system is damaged, but the modelization is not precise enough to determine whether or not the leak tightness is lost.

As for the TN12 packages, an equivalent height has been determined for the FS47, for each configuration. The criteria are the same. For the first configuration, a height of 35 meters allows finding the same damages, and for the second configuration, a height of 40 meters is calculated.

The graph indicates the spreading of absorption of impact energy between the package that drops and the package that is the target. We can see that the package-target absorbs about 2/3 of the energy, and the other one 1/3.



CONCLUSION

Many configurations of impact have pointed out that the packages maintain their integrity and that the additional equipments (frame, rack) improve the absorption of impacts and increase the safety margins.

The consequences of drops of packages, with their additional equipments, are often limited and below those of the regulatory impact test. The real target and the frame or the rack absorb the main part of the impact energy.

For the two packages studied, the regulatory drop tests appear more severe than the likely handling accidents that have been simulated.

Fig. 1: impact of a TN12 on a railcar axle

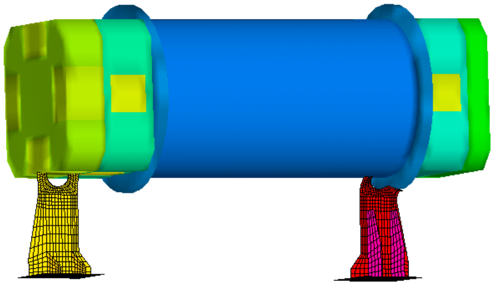


Fig. 2: impact of a TN12 on trunnion supports

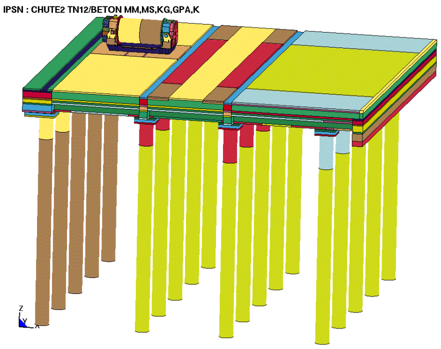


Fig. 3: impact of a TN12 on a pier

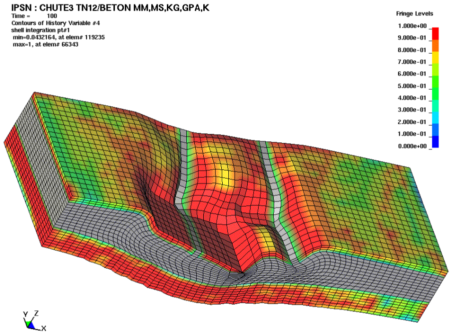


Fig. 4: damaged on the pier after a 8 m drop

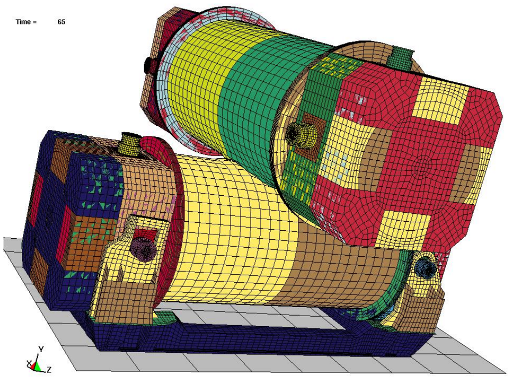


Fig. 5: impact of a TN12 onto a TN12

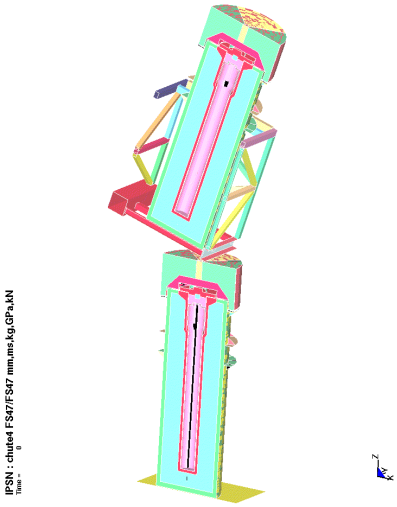


Fig. 6: impact of a FS47 onto a FS47