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GUIDE FOR NUMERICAL MODELLING OF DROP TESTING OF PACKAGES FOR THE TRANSPORT OF RADIOACTIVE MATERIALS

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ABSTRACT

To demonstrate compliance of package designs to applicable regulatory requirements [1], the good behaviour of the package under drop test conditions has to be justified. In order to do this, more and more analyses based on numerical calculations are performed to complete or replace drop tests with package specimens. These analyses are commonly used to:

- identify the worst drop conditions: angle, impact area, material properties taking into account temperature effects in the complete range of design temperatures, order of the sequence of drops (puncture drop before or after free drop test),
- justify the similarity between the specimens used for the drop tests and the worst package configuration,
- define stress fields for brittle fracture analysis,
- study the effects of the potential added features to the package at the time of transport (frame for example).

But such numerical models should be established with care, to ensure they do not lead to incorrect results. In this context, the French Institute for Radiation protection and Nuclear Safety (IRSN) has prepared a guide on transient dynamic calculation providing relevant modelling options and associated validation criteria. This guide has been built, using both the feedback experiments from the results of a large number of numerical calculations using LS-DYNA® calculation code [2] and purpose built benchmarks to determine about the most suitable options in case of doubt.

The main parts of this guide concern:

- the general principles for modelling and the consequences of numerical choices on the results (explicit or implicit calculation, simple or double precision, numbers of processors, symmetric or parallel processing, scale factor, speed),
- the specific options relative to meshing and elements formulation, material library, behaviour laws, contacts algorithms and bolt calculations,
- the quality results evaluation (Hourglass and penalty energies, sampling and filtering results).

The results show the high sensitivity of calculation options, in particular for the shock absorber (wood, foam) elements formulation, the method used for applying bolt initial stress, the size and the homogeneity of the meshing, the contacts and gaps management. The use of appropriate options has been proven to provide more accurate results with a finer depiction of reality.

INTRODUCTION

Numerical models are more and more used by applicants in order to perform safety justifications. Dimensions and masses differ from one design to the other but the speed range during regulatory 9 m drop tests is similar (impact speed of 13.5 m.s^{-1}, strain rate of about 50 s^{-1}). The accuracy of models depends on:

- physical validation (e.g benchmarks)
- appropriate selection of the input parameters.

Calculations have been performed in order to point out main parameters having an influence on the results accuracy and the duration of the calculation. In this objective, numerical models of several package designs have been created.

GENERAL PRINCIPLES

Some options have to be set before the creation of the model. The choices of numerical options are important as they could have a strong influence on the quality of the results or on the calculation run time. This last point is strongly related to the number of elements of the model (and thus its precision), but also the way the code evaluates the behaviour of the package. Some calculations algorithms are very time consuming for a just average result. As detailed hereafter, some options have to be preferred to others, when others have little influence on the results.

Scaling laws

Drop test are often performed with scale models, due to cost considerations. When scale models are used, a representativeness analysis is performed and dimensions, masses and energies are adjusted using the similarity laws. However, gravity cannot be scaled: accurate scaling of package potential energy however requires specific consideration since the scaled crushing of specimen represents a lack in the potential energy to absorb.
Two models have been created from a typical package design, one full scale, the other ¼ scaled. The drop test considered here is a 9 metre quasi-horizontal drop of the package with slap down effect. Thicknesses, clearances, masses, initial potential energies, cut-off frequencies and run times have been adjusted with the scale factor (impact duration is scale factor dependant). As all parameters but gravity between both models are identical, results are expected to be quite identical except if gravity has a significant influence. Results in figure 1 below show that the energy balances in both cases are visually similar. The maximal variation is up to 3 % during the slap down (free rotation) of the package. This error is due to the conservation of gravity, which physically shall not be scaled from one model to the other.

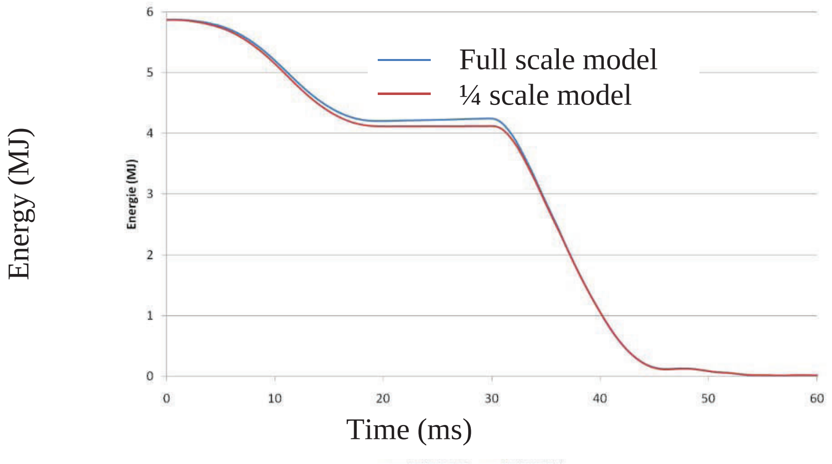


Figure 1. Comparison between full scale and ¼ scaled model energy balance

This calculation has been performed for other scale factors. The table 1 below shows no major incidence on accelerations. As a consequence, there is no indication against using scale factor models for 9 meters drop tests if global representativeness of the scale model is guaranteed and simplifications remain small.

Table 1. Maximal error on acceleration depending on scale factor

Scale	1:2	1:3	1:4	1:10
Max. error	-2,2 %	-2,9 %	-3,1 %	-2,9 %

Number of processors

It is expected that the more processors are used, the faster is the calculation. A sensitivity study has been performed in order to evaluate differences in the results (crushing distance and acceleration) of a numerical model of a package during a drop test. Results show that no significant difference can be brought out on acceleration profile. Furthermore, considering the option “negative number of CPU”, guarantees that the results will remain identical whatever the number of processors used for a very slightly longer run time.

It is then recommended to run calculation using the option “negative number of processors”, depending on what is available for calculation.

Single or double precision executable

Calculation can be performed using single precision executable or double precision one. Tests have been performed to show the differences between these two methods. Results show that for both crushing and accelerations values, the differences between the two methods are negligible. Nevertheless, double precision run times will be approximately twice as long as single precision run times. It is then recommended to promote single precision executable.

SPECIFIC OPTIONS

Element formulation

Each numerical LS-DYNA model is made of shell elements and solid elements described with different formulations. Among these, some are fully-integrated and some are under-integrated. These ones suffer from Hourglass mode, which is a nonphysical, zero-energy, zero strain and zero stress mode of deformation.

Calculations have been performed using three models with the objective of evaluating the differences between these models depending on the element formulation:

- model with under-integrated elements only,
- model with full-integrated elements only,
- model with the upper half using under-integrated elements, the other half with full-integrated elements (see figure 2).

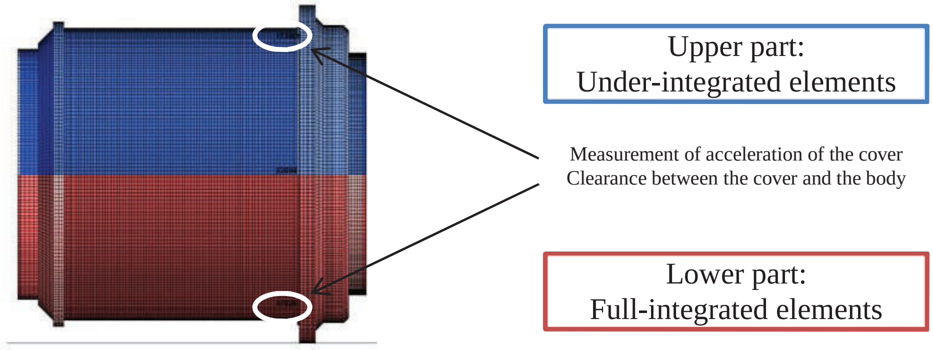


Figure 2. Model with upper half using under-integrated elements, the other half with full-integrated elements

The figure 3 below shows that in the case of under-integrated elements, the clearance between the cover and the body and the acceleration of the cover are underestimated compared to model using full-integrated elements. Despite the run time saving (20 %), it appears that the behaviour of the package is not well depicted. For mixed model, although the difference is low, it is not recommended to use such models which create interfaces that disrupt the propagation of load waves. It is then recommended to use full-integrated elements. Nevertheless, for some materials which are not often used in package design (e.g concrete), LSDYNA code preconizes the use of under-integrated elements.

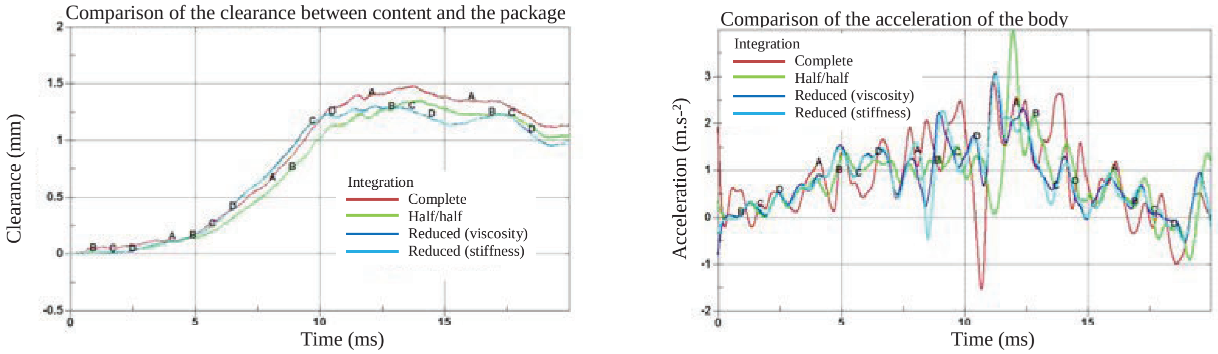


Figure 3. Comparison between under-integrated or full-integrated element formulation

Bolt modelling

The safety of packages transporting radioactive materials is based, among others, on containment of radioactive substances. In this objective, gaskets are used in association with bolts. Numerical computing is now powerful enough to precisely evaluate the bolt deformations and the gasket seating surface displacements. Nevertheless, some models consider no bolt or only rigid connections, which do not consider bolt stiffness or preload. In order to take into account actual response of bolts to mechanical loads, at least beam elements or even solid elements have to be used in the model in order to provide information on the risk of tightness loss.

Concerning the modelling of the part of the bolt located in the threaded hole, the calculations performed show that the maximal stress value is quite the same (see figure 4 next page) when this part is taken into account or not, but the stress field is different. When the threaded part is not taken into account, a disruption appears in the stress field and in the wave propagation by consequence. Modelling the engaged part of the bolt has only few influence on the stress level in the bolt, but leads to a better depiction of the behaviour of the shell.

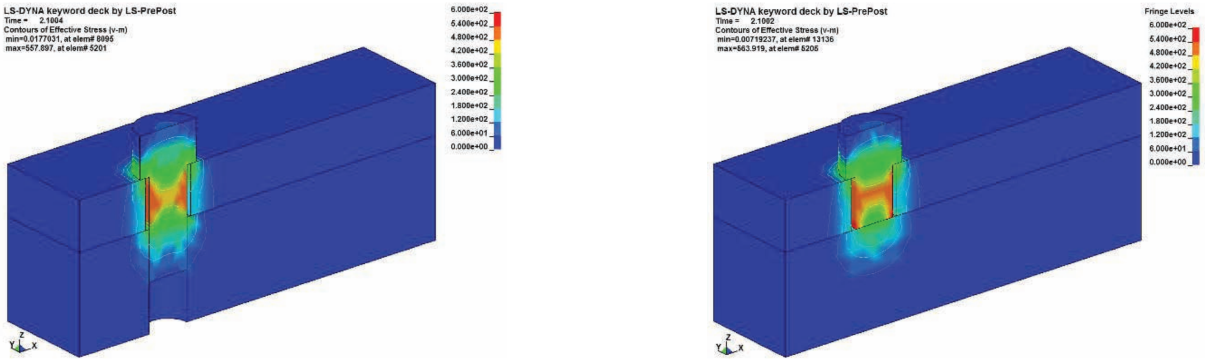
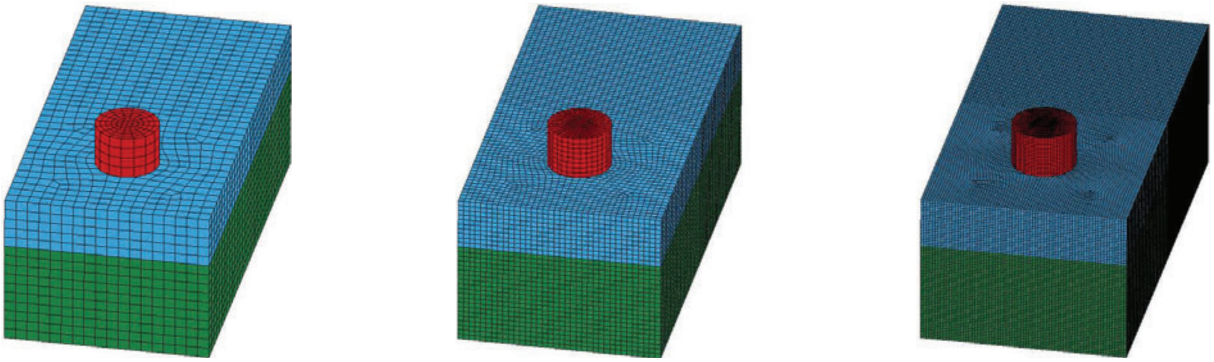


Figure 4. Stress field when threaded part of the bolt is modelled (on the left) or not (on the right)

It is commonly accepted that the more detailed the meshing, the more precise the results. But a too fine meshing induces long run times. Several calculations have been performed using different sizes of elements in order to identify the best compromise for the meshing size.



5 mm 2.5 mm 1.25 mm

Figure 5. Three models with different sizes of elements

Preload has been applied using direct initialization, and stress has been evaluated in each case. The results presented in figure 6 on the next page show that the stress field is slightly different. A significant influence can be observed on the maximal stress value. Nevertheless, this difference has no impact on the bolt behaviour as the highest values are nonphysical values located under the bolt head and near the beginning of the engaged threaded part of the bolt. Indeed they are explained by purely numerical stress concentration due to simplification of the model.

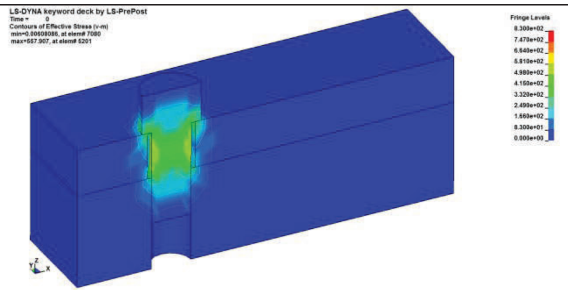
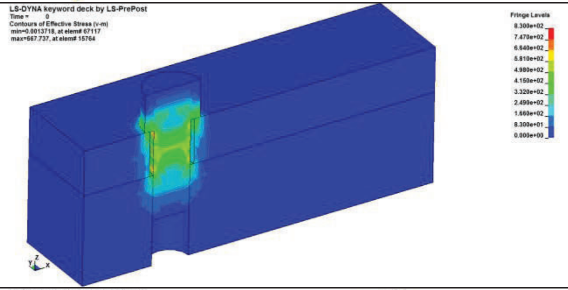
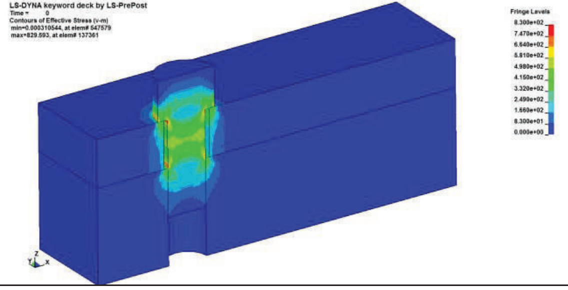
5 mm		σ_{max} = 558 MPa
2.5 mm		σ_{max} = 668 MPa
1.25 mm		σ_{max} = 830 MPa

Figure 6. Von Mises stress field in bolts for three sizes of elements

This study shows that since the mesh size is adapted in order to reduce the bolt faceting, maintain resistant surface and then keep bolt stiffness, it is not necessary to use a smaller mesh size to depict the behaviour of the bolt.

<u>Shock absorbing covers behaviour laws</u>

Modelling shock absorbers is a major point in numerical modelling of packages transporting radioactive material content as this component is designed to dissipate most of the impact energy.

Crushing properties of materials used in shock absorbers such as wood or foam are obtained by specific material tests; they have an important influence on the quality of the results. LS-DYNA provides typical material behaviour laws but they are useless if the requested parameters are not known and cannot be provided. Therefore, the first step consists in performing preliminary material crush tests.

Once performed adapted laws for the calculations can be used. For example, to model foam in shock absorbers the table 2 on next page proposes some adapted laws depending on the type of foam:

Table 2. Laws associated to different types of foam

Absorber characteristics	Density $\rho < 200$ g/l Poisson coefficient $\nu = 0$				$\rho > 200$ g/l $\nu > 0$
Type of absorber	Reversible		Irreversible		Irreversible
Type of law	Elastic and strain rate dependent	Visco-elastic	Isotropic	Anisotropic	
Law #	57-83	73 (62)	63-163 (53-75)	26-126-142	(75)
Typically used for	Seat foam	Comfort foam	Padding foam (PU)	Strand foam Aluminium Honeycomb Wood	Structural foams PU-based Epoxy-based
Note : brackets mean that the law is not the most relevant one					

Another major point is that the absorber materials (usually wood or foam) are placed and sometimes glued in steel casings. The numerical contact between the casing and the absorbers is also important. The casing is usually modelled by shell elements whereas the absorber material is modelled with solid elements. Several methods exist in case of absorbers glued to the casing, to model the interface between the absorber material and the casing (merged contacts, contacts with or without clearance, tied contacts, cohesive elements). A sensibility study has been performed and the deformation results are presented on the figure 7 below.

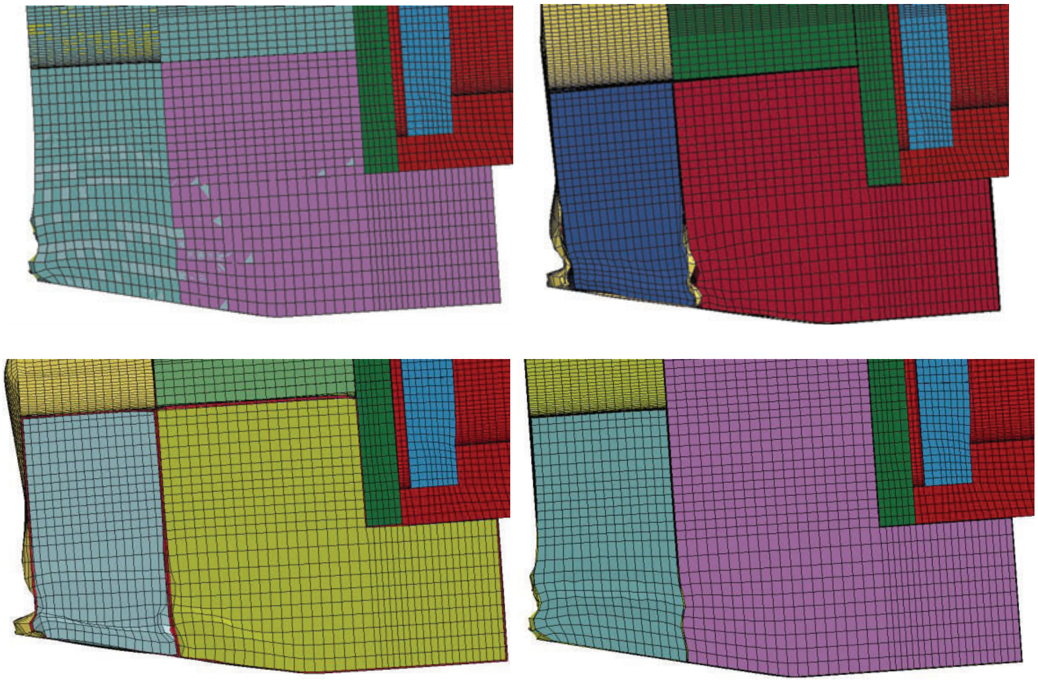


Figure 7. Deformations on casing with merged elements (top left), unmerged with no clearance (top right), cohesive elements (bottom left), tied (bottom right)

Except for the merged elements, each case shows two lobes in the casing, which is close to reality. Regarding accelerations, figure 8 shows that merged elements overestimate the acceleration, as well as tied elements.

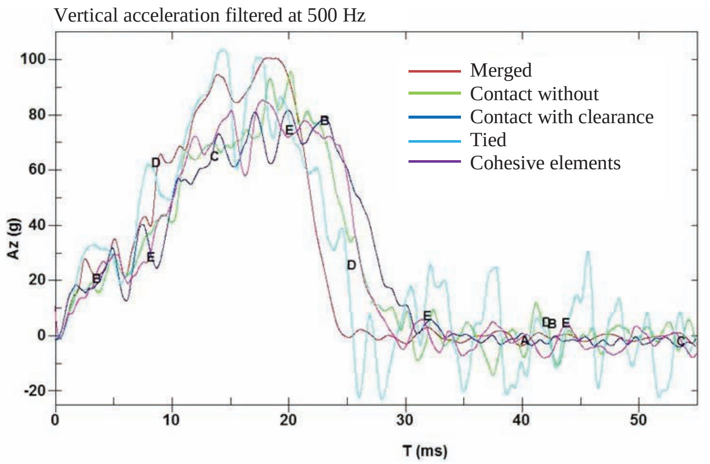
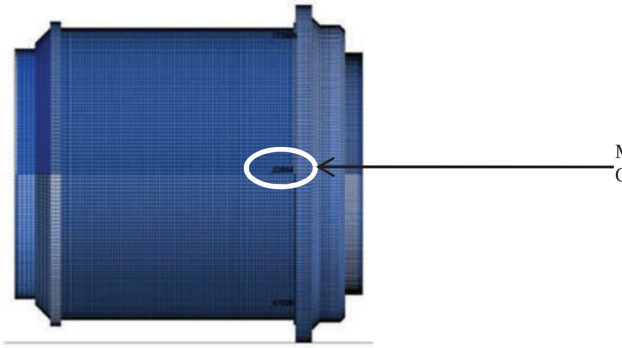


Figure 8. Accelerations of the package obtained with different cases of contact elements of the shock absorbing cover

As a conclusion for this aspect, merged or tied elements tend to underestimate deformations whereas they overestimate accelerations. In order to keep a good depiction of reality, it is then necessary to use cohesive elements though this method is quite heavy to implement and needs specifics test to define the strength of the glue.

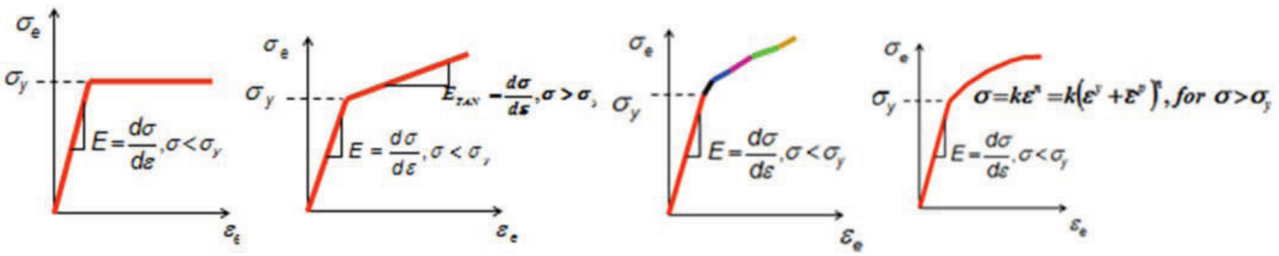
<u>Steel behaviour laws</u>

Data about linear materials such as metals are easy to obtain in literature but they are often imprecise in the plasticity domain and even more frequently not available for strain rate effects. Calculations have been performed using different plasticity laws and rate effects (Cowper Symonds coefficients) using a model of package with metallic shock absorbers, in a case of a drop with the package in a horizontal position.



Measurement of acceleration of the cover
Clearance between the cover and the body

Figure 9. Model used for the study of steel behaviour laws



Elastic/plastic law Bilinear law Piecewise linear plasticity Curve

Figure 10. Different ways to model plasticity domain for metallic materials

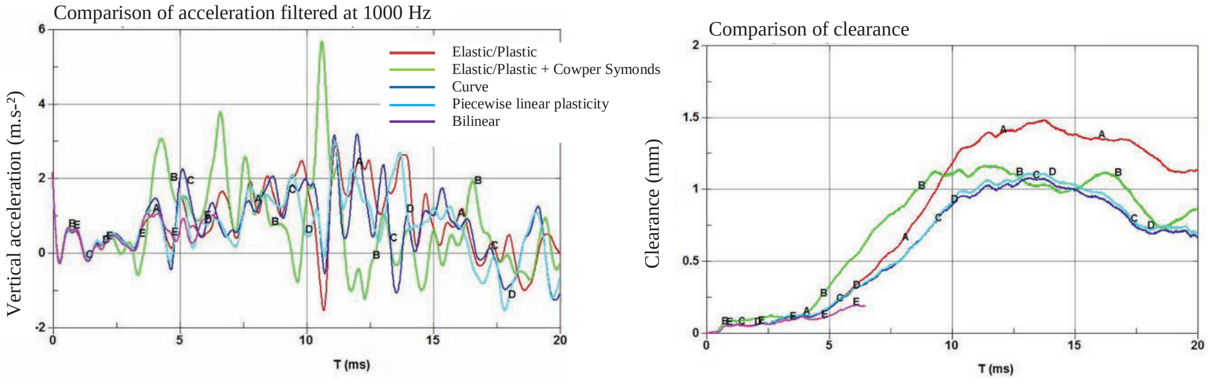


Figure 11. Acceleration and clearance for plasticity in metallic materials calculation

The results show that the classic elastic/plastic approximation overestimates the clearance and acceleration by about 25 % towards the "piecewise linear plasticity" law. A particular care must be taken in extrapolating the curves beyond the points obtained experimentally. In general it is highly advisable to limit the use of experimental data to the point of necking. Beyond this point, an extrapolation must be performed. Both options classically used - linear slope zero or non-zero extrapolation - are not satisfactory because it leads to localize the deformation in the first case and not to limit the stress in the second case. Power law like extrapolation with a C1[1] continuity is generally recommended. Regarding the modelling of the rate effects, simulations show that in the range of impact velocity, taking into account the rate effects affects only very partially both stress and accelerations. However the use of non-optimal parameters in a simple Cowper-Symonds type law may lead to seriously disrupt the signals of acceleration. If the rate effects are taken into account, it is preferable to define a table of curve for various strain rates in the suitable range.

RESULTS EVALUATION

The explicit solver of the LS-DYNA code provides easily results even if wrong parameters are used. This makes the explicit method very adaptable and evolutionary but the user shall validate the results numerically as well as physically.

Some solutions exist and have to be applied.

The energy balance has to stay stable (no creation or loss of energy). If under-integrated elements have been used, it is strongly recommended to check that the Hourglass energy is below 10 % for each part of the model. Also damping energy and rigid wall energy which are nonphysical energies have to be negligible compared to physical energies.

In order to cover the whole response spectrum of the package, sampling frequencies have to be much higher than natural frequencies of the package. In this objective, a modal analysis may be used taking into account the whole package and drop configurations. A study has been performed to highlight the importance of cut-off frequencies. For the example presented in figure 12 on next page, natural frequencies have been evaluated to 521 Hz for the first bending mode (left) and 303 Hz for the first lobe mode (right) in the case of a drop of the package in horizontal position.

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[1] C1 continuity : at the interface between two curves with C1 continuity, the curve is continuous (no point is missing), and the slope is the same for each side (no angular point)

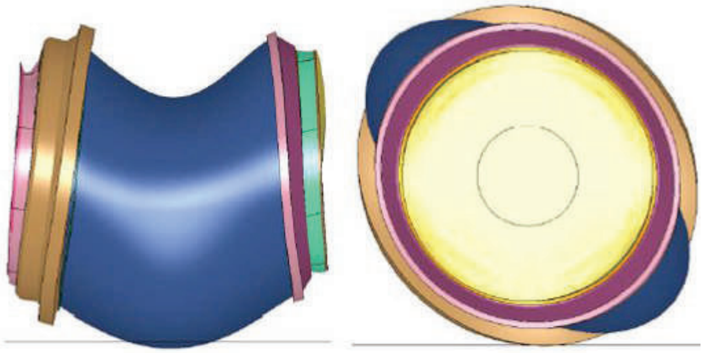

Figure 12. First natural frequencies for a package

Different acceleration profiles have been calculated for this drop configuration depending on the cut-off frequency. The results shown in figure 13 confirm that for cut-off frequencies below the natural frequencies the signal is much degraded and is not reliable.

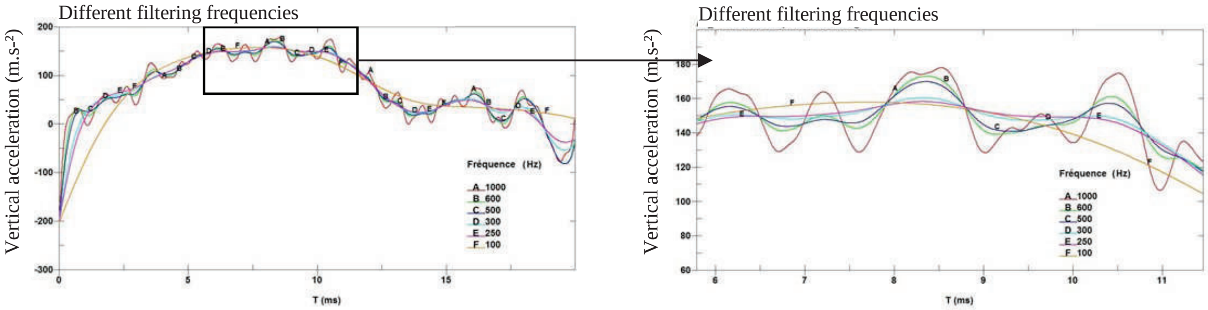

Figure 13. Filtered accelerations using different cut-off frequencies

CONCLUSIONS

LS-DYNA code is a powerful tool to simulate package dynamic behaviour modelling, but users have to be very careful with options in order to obtain physically credible result. The French Institute for Radiation protection and Nuclear Safety (IRSN) has prepared a guide containing present-day good practices to be considered to achieve a robust model and obtain reliable results.

In particular, it has been shown that using options such as explicit model, shared memory parallel processing (SMP), single precision executable and complete integration elements leads to rather good results with reasonable calculation duration.

It remains however important for users to validate the obtained results of numerical calculations, for example by comparison with real drop tests results and analysis of calculations results in terms of energy balances, accelerations and deformations profiles. This guide cannot supersede to engineer analysis, but to highlight good modelling practices. Moreover, it should be progressively enriched taking into account evolution of knowledge gained from assessments of the analyses that will be submitted by package design approval applicants.

REFERENCES

[1] Regulation for the Safe Transport of Radioactive Material (IAEA, TS-R-1, Edition 2009)
[2] LS-DYNA Keyword User's Manual v971, January 2012