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# NUMERICAL AND EXPERIMENTAL EVALUATIONS OF THE EFFECTS OF A PACKAGING SYSTEM FREE DROP

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## ABSTRACT

A safety management of the radioactive wastes unavoidably involves the pre-treatment, the treatment, conditioning, storage and disposal of all categories of radioactive wastes, including transportation activities. An essential component for any safe shipment is thus a robust safe and reliable system (or "cask") constituted by a massive sealed steel and concrete canisters to provide both structural strength and radiation shielding.

The casks or packaging systems, used for the transportation of nuclear materials, especially the spent fuel elements (SPE), are designed according to rigorous acceptance requirements, such as the ones provided by the International Atomic Energy Agency (IAEA), in order to provide protection to human being and environment against radiation exposure and contamination particularly in a reference accident scenario that may include, as it is well known, several types of test conditions as drop, puncture, fire and submersion tests.

The present study deals with the evaluation of the structural response and performance in free drop test conditions of a new Italian packaging system that should be used for the transportation of low and intermediate level radioactive wastes.

To the purpose the carried out numerical and experimental analyses are presented and discussed. The experimental tests were performed at the University of Pisa, by dropping a full scale solidified waste packages (with simulated inert content) into a flat unyielding surface in order to demonstrate and assure the structural integrity as well as to check the induced damaging effects, in the conditions foreseen in the previously mentioned IAEA recommendations.

To simulate and determine the progressive damage, during the impact conditions, numerical models of both the considered cask and target surface have been set up and implemented in a rather refined way, taking into account suitable material properties and constitutive laws.

The comparison between the obtained experimental and numerical results highlighted that, although rather severe local deformations, the whole packaging system was capable to withstand the impulsive dynamic loading generated during the drop test without unacceptable loss of safety feature and that the numerical approach is able to reproduce with high reliability the test situations.

## INTRODUCTION

Before a package is first used to transport radioactive material, it shall be confirmed that it has been manufactured in conformity with the design requirements set forth by the International Atomic Energy Agency (IAEA) in [1] and/or relevant national regulations (in Italy [1], [2] and [3] must be considered).

The integrity of packages is crucial for a safe disposal, storage and transport of radioactive material (RAM or R$W): to certify these packages the manufactures (or "applicant for approval") are required to demonstrate that they can withstand loads, that could occur under normal operation and accident

conditions [4][5], and meet the safety requirements in terms of performances of containment, radiation protection and criticality-safety (if necessary). These full-scale tests (or corresponding validated numerical simulations) are defined by IAEA [1].
The present paper summarizes the drop tests performed, at the Scalbatraio testing station [6] of the University of Pisa, on a type IP-2 package (an Italian packaging system provided by Sogin) in standard conditions for normal transport. In addition, a numerical analysis (by ANSYS© code [9]) aimed at the evaluation of the structural response of the packaging system and effects/damages caused by the impact conditions, are presented and discussed.
The present paper is articulated so that it will be:

- shown that the design of prototype package is able to withstand normal transport conditions with specifically reference to drop test conditions;
- demonstrated that no cliff effect, failure or sudden collapse of the package occurred;
- explained how compliance with all the regulatory requirements lead to high performances (e.g., in many cases, as it was demonstrated in the present one, the need to meet radiation exposure criteria induces to design a thick package, with mechanical resistance fulfilling the other requirements).

## Regulatory Requirements For The Safe Transport Of Radioactive Materials

The IAEA SSR-6, 2012 [1] set the standards for the high duty packages used for the transport of RAMs, under both normal and accident conditions, and specify appropriate qualification tests.
The package as well as its lifting attachments, for handling and stacking operations, shall be designed, taking account appropriate safety factors, in relation to its mass, volume and shape that it can be easily and safely transported.
The qualification tests in [1] are severe to cover normal and accident situations which can be realistically envisaged so that safety is guaranteed throughout the lifetime of the package. Typically, they are:

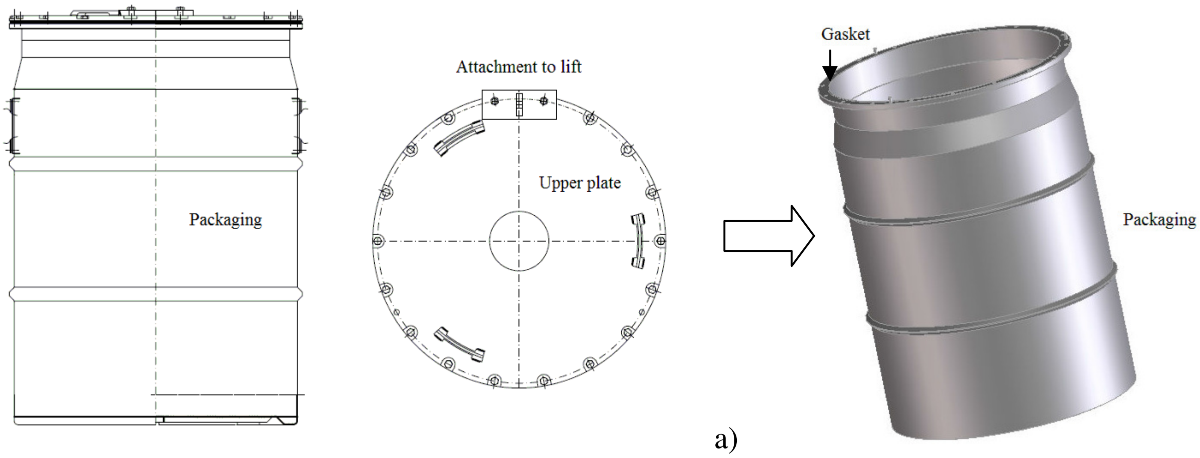
a) water spray test;
b) free drop tests onto a flat and unyielding surface (as indicated in [1]);
c) stacking test;
d) penetration test;
e) thermal tests;
f) water immersion test.

For demonstrating the ability to withstand normal conditions of transport, the prototype of package shall be subjected to b) and c) test, preceded in each case by the water spray test a). Type IP-2 package shall also provide sufficient shielding to ensure that, under routine conditions of transport and with the maximum radioactive contents that the package is designed to contain, the radiation level at any point on its external surface would not exceed, at 3 m from the unshielded material, 10 mSv/h [1].

## PACKAGING SYSTEM: DESCRIPTION OF THE SAMPLE

The package model considered in this study (Figure 1) is a full scale Type IP-2, for solid/solidified waste of 440 $dm^3$ volume [2]. The package is about 0.7 m in diameter and 1.3 m in height. Finally the package is enclosed in a steel overpack to increase overall safety in transport condition.
The overpack of this package has been designed as to prevent the collection and retention of water and also withstand the effects of any acceleration, vibration or vibration resonance that may arise under normal transport conditions, without any deterioration in the effectiveness of the closing devices or in the integrity of the package as a whole.

The materials of the package (made mainly of a steel body containing a concrete mass representing the RWs solidification medium) components were physically and chemically compatible with each other and with the radioactive contents.




a) b)

Figure 1 a, b - Type IP-2 packaging (provided by Sogin).

**DROP TEST: PROCEDURE AND MAIN RESULTS**

The specimen (packaging with simulated inert content + external overpack) has been dropped by 1.2 m onto a flat, horizontal and unyielding surface so as to suffer the maximum damage in respect of the safety features to be tested. Moreover, in order to evaluate the tightness capacity of the containment system, a tracer substance was dispersed in the free volume between the upper plate and the inner cover. A tracer substance, in powder form of about 40 μm grain size (Figure 2), was used to simulate the possible particle of the concrete that might be formed as a consequence of disruption/fragmentation of the inner mass arisen during the impact tests.

Figure 2 - Dispersion of the tracer powder.

The tests performed (as shown in Figure 3) on the same package sample model (complete with the external yellow overpack), have been:

a) vertical drop on the bottom of the overpack with axis perpendicular to the target surface (Test #1);
b) horizontal drop test on the side of the sample with axis parallel to the target surface (Test #2);
c) vertical drop on the upper of the lid (cover), with axis perpendicular to the target surface (Test #3);
d) drop on the upper edge of the lid overpack (inclined impact), with axis through center of gravity of the package and impact point perpendicular to the target surface (Test #4).

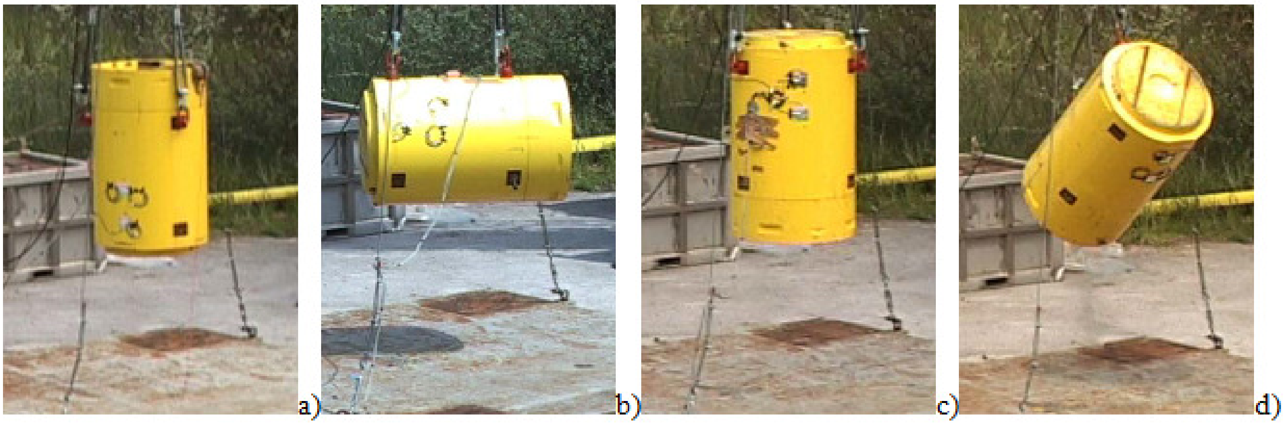



Figure 3 - Drop tests configurations.

The sample was instrumented with piezoelectric accelerometers (Endevco® MA2225 [7], specifically for high amplitude shock motion measurements) and strain gauges connected to an adequate data acquisition system (DAS) as represented in Figure 4.
The accelerometers were mounted on the closure lid, while the strain gauges were positioned at 295 mm (labels B and D) and 545 mm (labels A and C) from the bottom of the overpack (Figure 4).

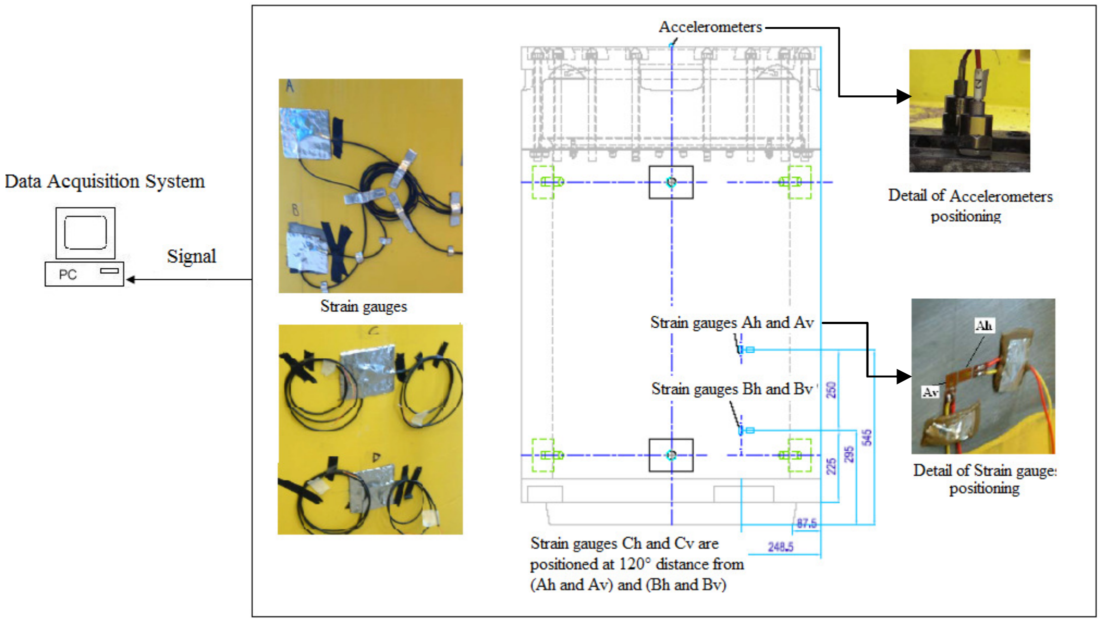



Figure 4- Instrumentation of the packaging system.

Following each drop tests, the package was inspected to check the degree of damage, if any, and verify the fulfillment of the acceptance criteria, based on the capability to prevent loss or dispersal of the radioactive contents and guarantee the shielding integrity.
To comply with the foreseen criteria and to validate the numerical calculation results, measurements, in terms of deformations or dimensional changes and accelerations, were made jointly with the verification of the absence of leakage of the tracer material after the drop tests.

The main results of those tests are:

- the containment system is capable to withstand the impulsive loading due to the impact;
- even in Test #4, although the shallow-angle drop test produced large deformation mainly by buckling outward the cover of the package, the closure lid deformation did not compromise the integrity of sample, which guaranteed the tightness of the tracer powder (see Figure 2);
- the seal of the package, although damaged during the drop test on the edge of the lid (inclined impact) has ensured the tightness of the tracer powder;
- dimensional changes were then used to verify the shielding capability, but this assessment is out of the scope of this paper.

In what follows only the results of the vertical drop test (Test #1) were indicated and thoroughly discussed. The vertical drop test was characterized by a primary impact on the bottom with consequent secondary impact along the generatrix (horizontal side), as indicated in Figure 5.

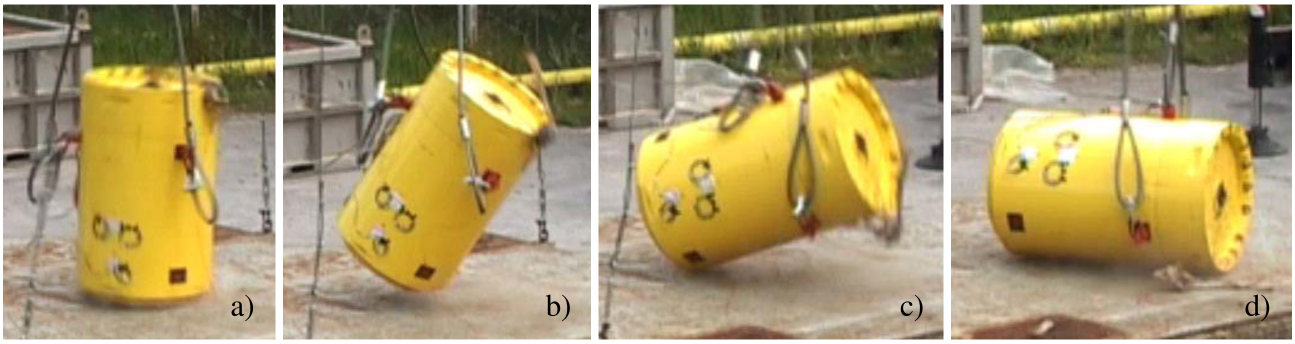



Figure 5 - Execution sequences of the vertical drop test from the first impact (a), rebounding (b) and (c) to the secondary impact (d).

The visual inspection of the impact area of the overpack and package showed no deformation and/or damage (Figure 6).

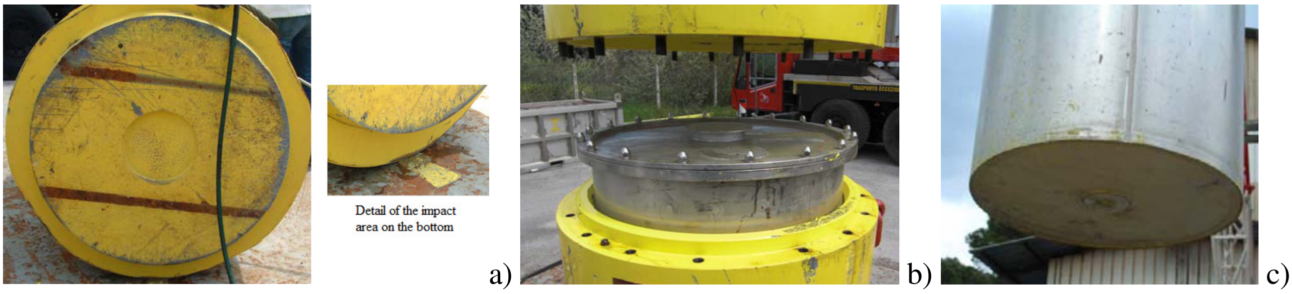



Figure 6 - Post-Test #1 inspection of the bottom of the overpack (a) and of package (b and c).

Figure 7 and Figure 8 show the accelerations and deformations diagrams recorded during the drop test transient. The measured accelerations values (having sampling interval of the order of millisecond) are characterized by high spikes, of 4000-6000 g at high frequency: their physical effect on the large inertia of package is expected to be/is minimal (Figure 7b) as confirmed by filtering the data (at the 1$^{st}$ frequency of packaging system [7]). The filtered accelerations oscillate thus around a mean value of about 300 g.

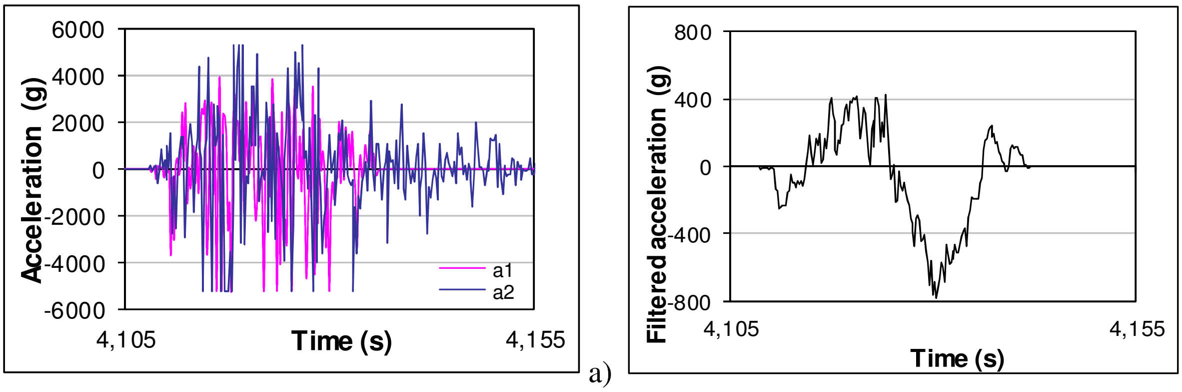



Figure 7 – Unfiltered (a) and filtered (b) accelerations.

The strains measured by strain gauges labeled as A (Figure 8a) and C, positioned at 545 mm from the bottom of the overpack, have maximum values equal to approximately 300 and 150 με, respectively along the vertical and horizontal directions. The strains measured by strain gauges labeled as B (Figure 8b) and D, positioned in the lower part of the overpack, are approximately similar with a maximum value of about 200 με in both horizontal and vertical directions.
In any case the strain values resulted about 1/10 of the deformation that would be required to determine the yielding and plasticization of the overpack.

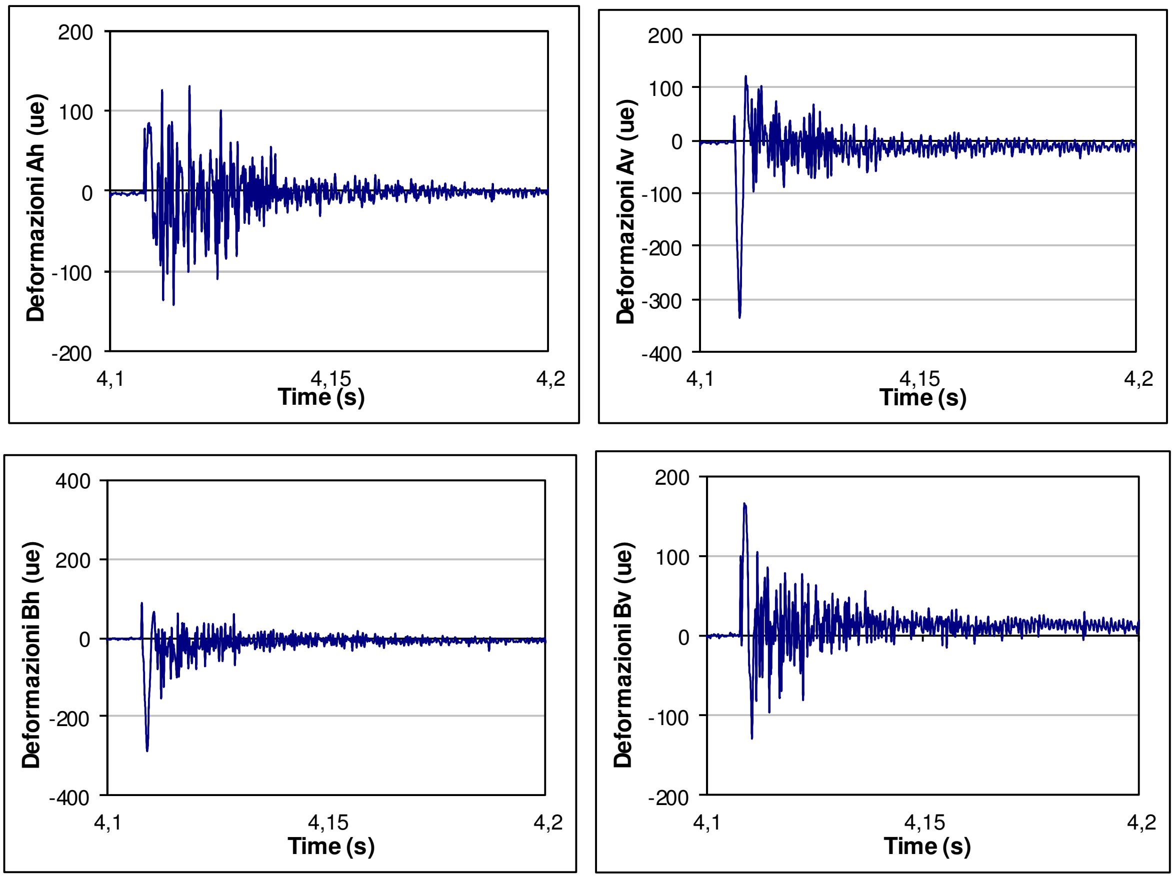



Figure 8 - Deformations recorded at the strain gauge A (a) and B (b) during the vertical drop (Test #1).

## NUMERICAL MODELLING AND VALIDATION

To evaluate the structural response and performance of the considered package under vertical drop, a numerical analysis has been carried out. In this way, it is possible to obtain further information (e. g. accelerations, stresses, etc.) on package components which are not directly instrumented during the tests. To simulate the model behaviour and to determine the progressive damage, during the impact conditions, numerical models (by ANSYS© code [9]) of both the considered packaging system and target surface have been set up and implemented in a rather refined way, taking into account suitable material properties and constitutive laws.

The 3-D FEM model of the considered Type IP-2 packaging system, shown in Figure 9, included more than 60.000 solid element representing the packaging, the solidified waste, the overpack with its bolted closure lid and filtering system. Contact surface element were also adopted to correctly simulate the system non-rigid connection between the various component of the structure.

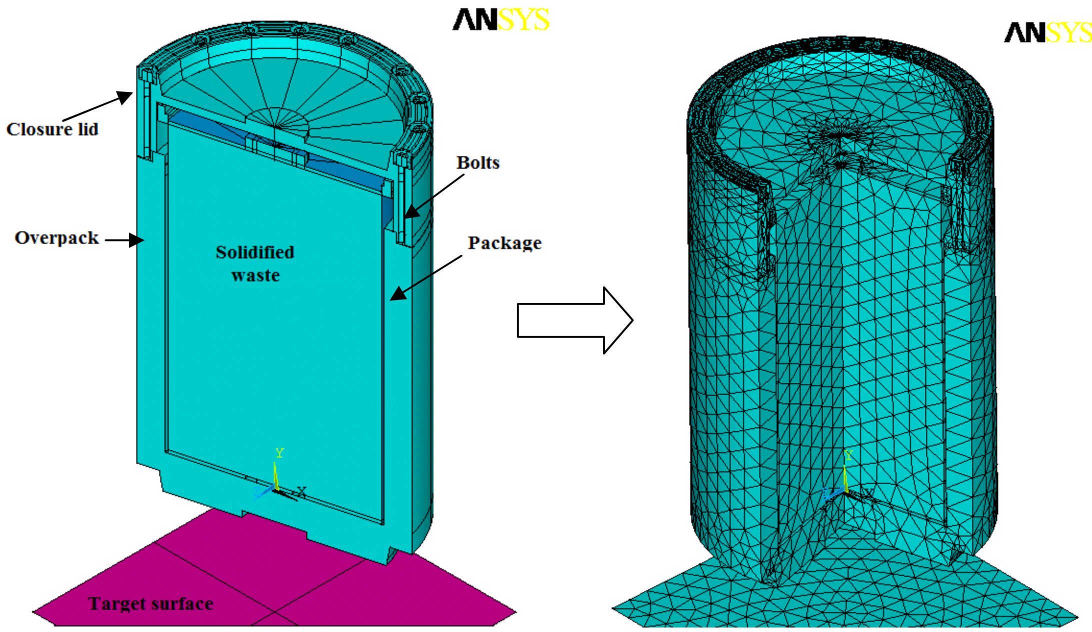



Figure 9 - Overall package and overpack FEM model

The number of the elements was found appropriate (a sensitivity analysis to evaluate the influence of size and type of element was also carried out) to achieve the needed accuracy required by the analyses.

The material behaviour of packaging was assumed elastic-perfectly plastic, described by the Von Mises criterion coupled to kinematic rules, and capable to undergo large deformations; no failure model has been implemented. In addition, to adequately characterize the complex interaction between components, an explicit dynamic analysis, with different surface-to-surface contact types was carried out.

The main numerical results are showed in the following figures.

For the numerical analysis the impact duration was assumed up to 20 ms.

The results show no plastic strains in the overall system for vertical drop conditions. Moreover the strains calculated numerically in the impact area are similar to the ones measured in the tests; the same correspondence was observed as far as the acceleration values are concerned, both from qualitative and quantitative points of view. In fact, the calculated acceleration diagrams (Figure 10) resulted similar to the experimental ones, with the same high spikes (of about 4000-6000g) and mean values (of about 300 g).

Numerical data are so in a quite good agreement with experimental data (variation about 10-15 %): therefore a preliminary validation of code and models may be considered also achieved.

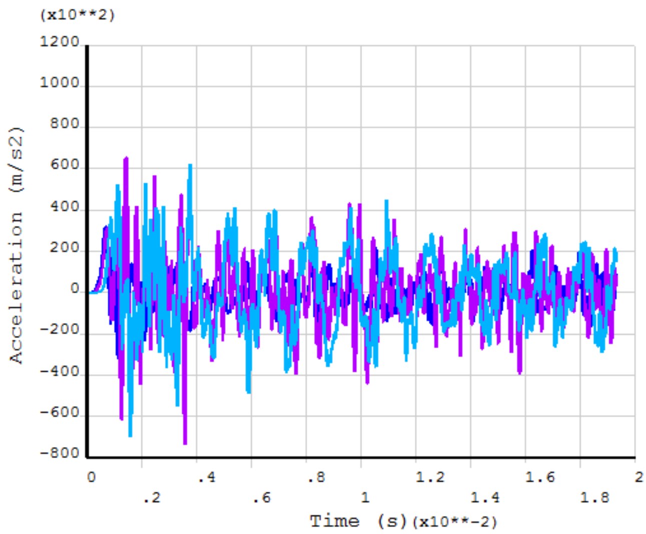
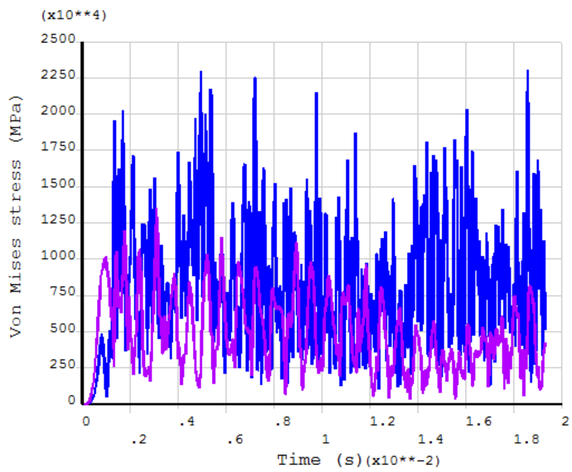
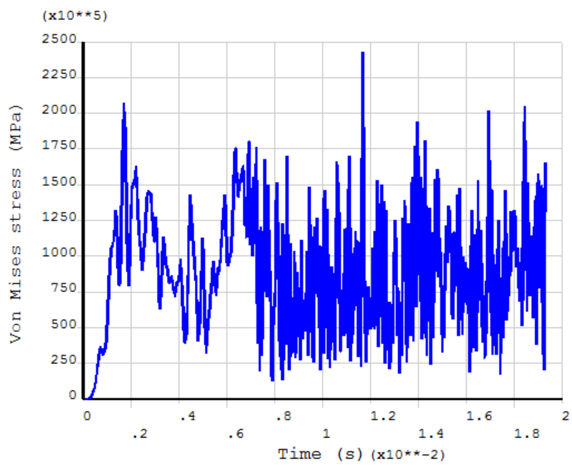



Figure 10 - Accelerations calculated on the closure lid (two nodes representing accelerometers position)

The Von Mises stress distributions especially in correspondence of the closure lid (as it is indicate in blue line in Figure 11a) demonstrated that stress values are below the limit value beyond which large structural damaging/failure effects may come out. This confirms the integrity of the lid and, of course, indirectly confirms its tightness.




a)




b)

Figure 11 - Von Mises stress at the package upper plate and waste (a) and at the overpack (b).

The comparison between the obtained experimental and numerical results highlighted that, although rather sensible local deformations were caused by the inclined longitudinal axis with impact localized on the rim of the closure lid (even if without any loss of structural integrity or lid tightness), the packaging system was capable to withstand the impulsive dynamic loads generated in these drop test conditions, without unacceptable loss of safety features (at least within the sensibility of the chosen leak-tightness checking criteria) and that the numerical approach is able to reproduce with good reliability the test situation.

## CONCLUSION

The present paper summarized the drop test results performed as well as numerically simulated, at the Scalbatraio testing station of the University of Pisa, on a type IP-2 package sample (provided by Sogin), in some standard (drop) conditions according to the relevant IAEA recommendations.

Generally no failure or sudden collapse have been observed during the vertical (on the top or bottom end of system) or horizontal drop tests carried out; only during the inclined axis drop test a localized deformation of the lid rim occurred: however this deformation did not compromise the integrity of sample, which guaranteed the tightness of the tracer powder (at least within the chosen checking method sensibility for the concrete solidified content).

A numerical simulation of the vertical drop test was also carried out in order to evaluate the structural response of the whole packaging system, even far from the areas instrumented during the tests.

The results showed no generalized plastic strains in the overall system, in agreement with what was evidenced during the tests. The acceleration behaviours resulted also similar to the experimental one, with the same high spikes and mean values (of about 300 g).

Moreover the calculated strains, as well as the acceleration values, resulted similar to the test ones. In fact, numerical data are in a quite good agreement with experimental data (variation about 10-15 %), from both a qualitative and a quantitative point of view: this last remark seems to confirm that models and code may be considered preliminarily and roughly validated.

Finally it is possible to say that the package model, analysed and tested, demonstrates to be capable to withstand normal transport conditions as well as meet the safety requirements in terms of performances of containment and radiation protection required by the international and national regulations.

## ACKNOWLEDGEMENT

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