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Demonstration of structural performance of IP-2 package by simulation and full-scale horizontal free drop test

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ABSTRACT

Packaging systems for the transportation of radioactive wastes have to be designed according to rigorous acceptance criteria and requirements in order to protect people and environment against radiation exposure and contamination risk. The IAEA requirements for type IP2 (Industrial Package Type 2) packages include to carry out free drop tests that represent normal conditions of transport. In such conditions, obviously, the required containment capability of the package has to be ensured.

In this study the mechanical performances of a new Italian packaging system for the transportation of low and intermediate level wastes (LILW) undergoing horizontal free drop test are investigated. Especially, deformations caused in the sealing area of the package, which can affect the capability of the containment system, are evaluated.

The carried out numerical analyses and experimental tests, at the lab. Scalbatraio of the DICI- University of Pisa, are presented and discussed.

Numerical analyses (by qualified MARC® code) have been performed to investigate the stress histories in the bolts, lid, and package body as well as the deformations in the sealing area and the compression conditions of the gasket.

Localised stress appeared at the flange and at the bottom of packaging system. The maximum stresses resulted lower than the stress limits, so the structural integrity of the package was maintained and confirming its tightness. As a consequence of the primary impact a local deformation appeared at the primary lid, no cliff edge or loss of the safety features resulted.

1. Introduction

About 20 million consignments of radioactive waste and material (RWs RAM), stowed in suitable packages, take place around the world each year: ~5% of them is produced by the nuclear facilities, the majority or remaining part is generally produced by the medicine, research, non-destructive testing.

The transportation of RW/RAMs, also over large distance (international transport), requires the adoption of suitable tight containers in order to protect people and environment against radiation exposure and contamination (minimization of the external radiation, because of the ALARA principle).

To ensure the safety, also in routine handling situation, the packaging system must contain the material and prevent any leak, and must guarantee the integrity in normal and accident conditions.

To fulfil all these requirements, set forth by the IAEA in IAEA, (2012) and/or by the National regulations (in Italy IAEA, 2012; UNI 11196 and ISPRA must be considered), the packaging system must be properly designed and qualified by means of experimental tests before to be used for the transport (as schematized in the diagram of Fig. 1): more hazardous is the radioactive material more rigorous are the test procedures and requirements to meet.

Specific requirements are defined by Regulations through a phased approach dependent on the standards of the different package designs and based on the risks arising from the different transport conditions. In fact a package is designed, and thereafter, is qualified taking as design loads those relating to the conditions of transport corresponding to the model to which the package belongs, as shown in Table 1.

Few studies on the investigation and demonstration of packaging system performance are available.

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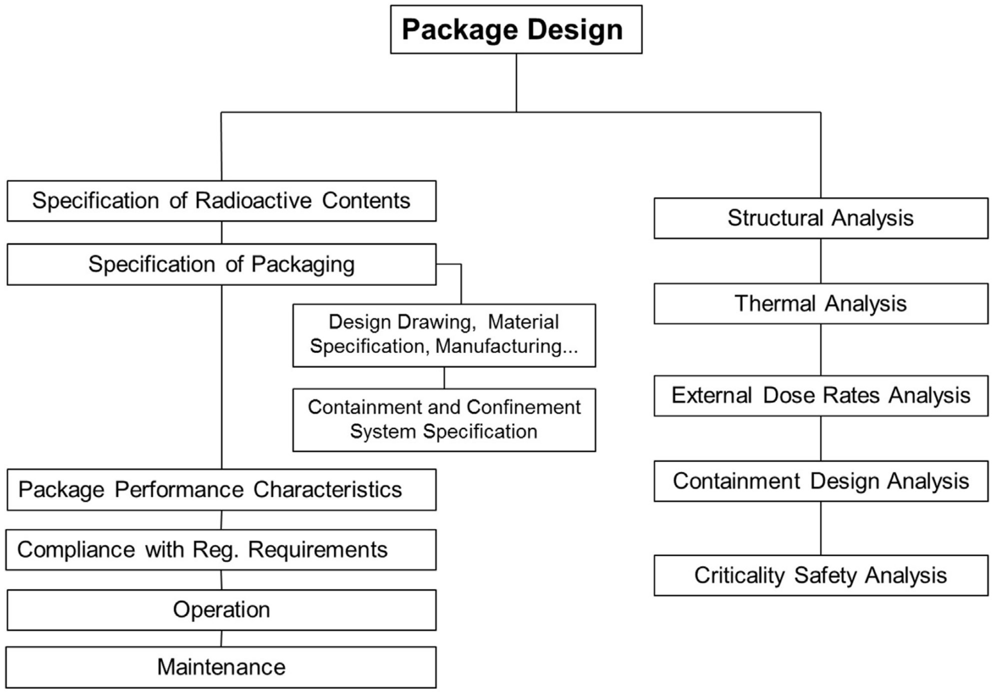

Fig. 1. Procedure to obtain the package qualification.

Lo Frano et al. (2011) and Pugliese et al. (2010) investigated the thermo-mechanical behaviour of a cask undergoing respectively in normal condition of transport (for dry and wet storage condition) and in accidental one (focusing on fire test effects and post-accident cooling phase).

Kim et al. (2010) studied the performance of a IP-2 prismatic package designed to contain up to eight 200-L steel drums so to provide a mid-step in demonstrating the package performance and predict the package behaviour during the drop tests.

Shappert, July (1989) instead provided a technical evaluation of a cask (scale model spent fuel cask and a full-scale canister to be carried inside a spent fuel cask) performance under several normal and accident conditions: they are a combination of theoretical and experimental assumptions used to corroborate or confirm the methodology used.

A demonstration of the structural performance of an IP 2 cylindrical package undergoing vertical drop test (with drop orientation on the bottom of package) is described in Lo Frano et al. (2013). Moreover, in this latter, apart from the exaustive description of test procedure a qualification (and reliability) of the methodology used to investigate numerically the free drop conditions is also given. Sanfiorenzo et al. July (2014) presented and briefly described the effect of an IP2 horizontal drop test for ILLW packaging system.

This study is therefore aimed to investigate extensively the demonstration of the structural performance of an Italian IP2 package (IAEA, 2012) for low and intermediate level waste, commonly referred to as CC-440. The CC acronym identifies the cylindrical shape of the packaging aimed to stow solid/solidified wastes and 440 indicates the volume of container. In this package, as indicated in Lo Frano et al. (2014), LILWs are uniformly distributed throughout the concrete matrix.

Table 1
Transport conditions for each type of package.

Transport conditions	Package exempt	IP-1	IP-2	IP-3	Type A	Type B	Type C
Regular	X	X	X	X	X	X	X
Normal			X	X	X	X	X
Accident						X	X

Full-scale free drop tests, as foreseen for the normal transport conditions, have been carried out (IAEA, 1983) at the Lab. Scalbatraio of Dept. DICI of the University of Pisa. Particularly, in this study, the horizontal free drop test will be thoroughly discussed.

The experimental results have been used to verify also the reliability of the numerical tools and modelling methodology adopted in the numerical analyses and to confirm the performance of the IP-2. In addition, an advanced analytical simulation for the horizontal free drop, using the finite element (FE) method and specifically MARC® code, has been performed for the design assessment of the developed IP-2, to evaluate its structural performance, and to demonstrate its compliance with the regulatory requirements.

The main results obtained will be described along with the qualification of the numerical code adopted. Finally a critical analysis of the obtained results (experimental vs. numerical) will be also provided.

2. Description of CC-440 packaging system

There are many existing packages available to conduct RAMs/RWs transports, but in some cases the nature of the material to be transported, safety benefits, and/or commercial benefits justify the development of a new package. When such a case exists it is important that the new package has a high degree of flexibility. It needs to be adaptable to any receipt facility and to be able to carry a wide range of types of radioactive material produced though the lifetime of operating facility.

The CC-440 (type IP2) packaging system, a new package designed by Sogin, maximises content and enhances flexibility of use thanks to the possibility of package to be equipped with an internal impeller, to be used during solidification process of liquid wastes, and to a possible double containment boundary (packaging system plus overpack). Loading capability and undemanding handling requirements present a real advantage in comparison to other package options.

The main design characteristics and the geometrical and material properties of a CC-440 packaging system are defined in UNI 11196, which represents the Italian standard to refer to the packaging requirements. As described in Lo Frano et al. (2014), the package consists of a cylindrical body, gasket and closure lid with bolts as visible in Fig. 2.

The primary closure lid is guaranteed by means of M12x18 bolts (UNI EN ISO 4017; UNI EN ISO 3506–1), the sealing through a proper gasket.

The package, about 1 m height and 0.8 m diameter (as seen in Fig. 2), was made of 316 L austenitic steel, according to the UNI EN 10088 rules, that despite the higher cost will assure higher mechanical strength and better corrosion resistance. This austenitic steel offers high ductility, 500 ÷ 700 MPa ultimate tensile strength (with elongation after fracture of about 40%), and a lean chemical composition. It can be also assumed to be adequately tough and not susceptible to brittle fracture for service temperatures down to −40 °C.

The corrosion and the mechanical strength are two important aspects to be considered when dealing with the interim storage and the institutional storage period into the (superficial) repository. The outer package surface was designed so as to be free of protrusions and areas of potential collection and retention of water, and such as to be easily decontaminated.

Moreover the package could be enclosed in a 95 mm thicker steel overpack, in order to increase the overall safety during transport, and facilitate handling operations.

3. Horizontal free drop: test and simulation

The CC-440 mechanical behaviour has been assessed in detail by experimental drop tests of a prototype and by performing numerical simulation. No further IAEA drop tests are expected for that packaging system; there is now a clear understanding of its mechanical behaviour against the IAEA requirements.

In fact, the packaging must resist the effects of accelerations and vibrations without leading to any deterioration in the effectiveness of the closing devices, such as no loosening of nuts, bolts or of any other locking systems, or a loss of integrity.

3.1. Experimental drop test

The experimental campaign have been performed on the unyielding rigid target surface, which is a certified IAEA test section, available at the Lab. Scalbatraio of the DICI-University of Pisa.

The drop height (defined as the height of drop measured from the lowest point of the specimen to the upper surface of the target) was calculated according to (IAEA, 2012) in relation to the package weight: for a 5000 kg CC-440 the drop height resulted 1.2 m as indicated in Table 2.

As also indicated in UNI EN ISO 4017, the carried out drop tests have been:

1) vertical drop on the bottom;
2) horizontal drop with axis parallel to the target surface;
3) vertical drop on the upper of the lid (cover);
4) inclined drop on the upper edge of the lid overpack, with axis through centre of gravity of the package and impact point perpendicular to the target surface.

Herein following a brief description of the horizontal drop test execution of a CC-440 sample with the external overpack (the yellow outer shell) is given. The sample tested consisted of a packaging system with concrete, to simulate the cemented wastes, and the external overpack. Fig. 3 shows the suspension of the sample at 1.2 m (a), with horizontal axis parallel to the target surface, the free drop (b) onto the flat, horizontal and unyielding surface (UNI EN ISO 4017), the first impact (c), the rebounding (d), the secondary impact (e) and the end of test (f).

As indicated in Lo Frano et al. (2014), the sample hits the ground with a very small angle $<0.1^\circ$ of misalignment with respect the target surface determining the rebound and the secondary impact on the opposite edge of the first impact (corresponding to the lid of overpack).

3.1.1. Experimental test: qualification of numerical code

Apart from the qualification of the numerical code (ANSYS© software) given in Lo Frano et al. (2014), herein following is presented the qualification of MSC© FEM code used for the numerical calculation.

During the verification calculations, the ability and reliability of the code in simulating non-linear processes has been verified. These objectives were achieved by comparing the analytical and physical test results, that is, data for the deformation behaviour, strain and accelerations, etc. for both the vertical drop on the bottom and horizontal drop test.

The physical test results were compared with the numerical ones: the strain and acceleration measurements provide the essential components for the verification of the design method. Accelerations were extracted from the FE model at the nodes and elements that were nearest to the sensor locations.

Fig. 4 shows the acceleration calculated in the case of vertical drop on the bottom, as an example, with the time interval of 5 ms. The comparison with the filtered experimental values (by a low-pass filter in order to exclude electrical noise and unnecessary frequency components) in terms of mean values of acceleration resulted quite good because the accelerations oscillate both around a mean value of about 400 g. Nevertheless a punctual comparison resulted quite complex because of the different acceleration time histories. This could be explained with the different acquisition time but especially in the modelling of the “perfect inelastic” vertical drop that cannot represent the small misalignment of the bottom surface occurring during the drop phase.

Fig. 5 shows the total plastic deformation in both vertical and horizontal drop: as it is possible to observe a very good agreement appears between experimental and numerical result; in Fig. 5b the analytical deformation resulted 11.5 × 2.5 cm and about 1 cm deep quite the same of that experimentally measured.

3.2. Horizontal drop test simulation

As noted, mechanical loads on package may produce effects that could impair its containment capability. The main driving forces for potential leaks is the stress in components as well as the relative displacement of key elements of the containment system.

Therefore the FE analysis has to provide the reliable data regarding: 1) the stress in components, and 2) the temporary or permanent deformation of components leading to changes in position and compression of metallic gaskets.

The criteria for the stress assessment are normally defined as allowable maximums on the basis of the material specifications for the components. The corresponding numerical results may not exceed these allowable values.

A first analytical verification of the package against free drop can be done by means of an energy balance. In fact, defining H the

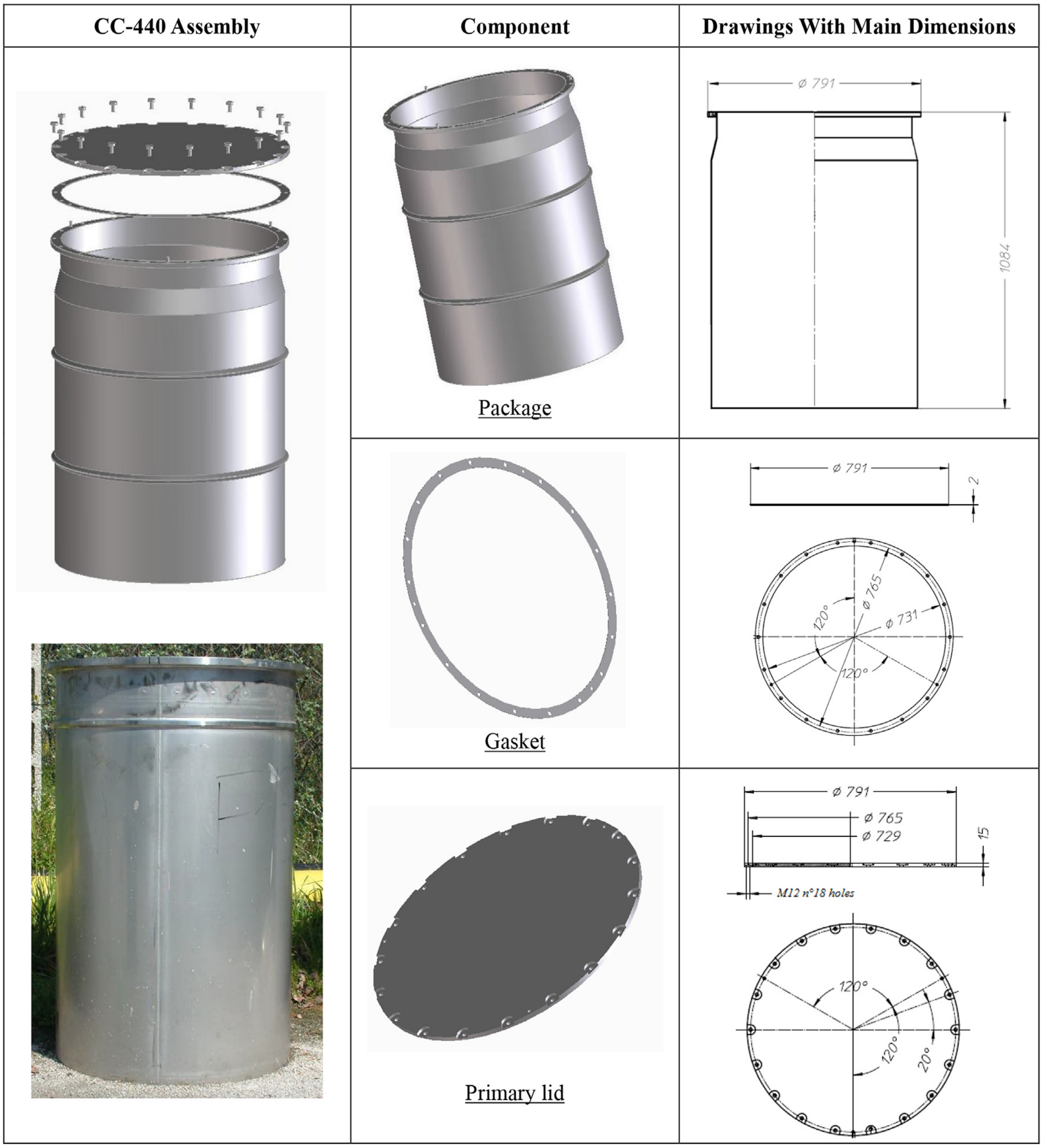

Fig. 2. CC-440 package.

distance between the centre of gravity of the container and the surface of the target, the kinetic energy (E_k) that at the instant of impact is transferred/become deformation energy, is calculated as:

$$M_g H = \frac{1}{2} M_g v_{in}^2 = E_k \tag{1}$$

In addition on the basis of the 1st modal shape of the package

Table 2
Relationship between mass and drop height, according to (IAEA, 2012).

Mass, M (kg)	Free drop height (m)
M < 5000	1.2
5000 ≤ M ≤ 10,000	0.9
10,000 ≤ M ≤ 15,000	0.6
15,000 ≤ M	0.3

and by considering the Hooke's relationship between stress and deformation, the impact force transferred to the package (inelastic impact) is:

$$F_{drop} = \frac{E_k}{\Delta L} \tag{2}$$

Therefore the mean stress caused that may be used to verify the bearing capacity of the package to the impact force is:

$$\sigma_m = \sqrt{\frac{E_k E}{AL}} \tag{3}$$

A more detailed verification must be further done by considering the stress intensity (or equivalent intensity of combined stress like $2\sigma = \tau_{max}$). In doing that the stress obtained from the finite element analysis was compared with the limit one for the

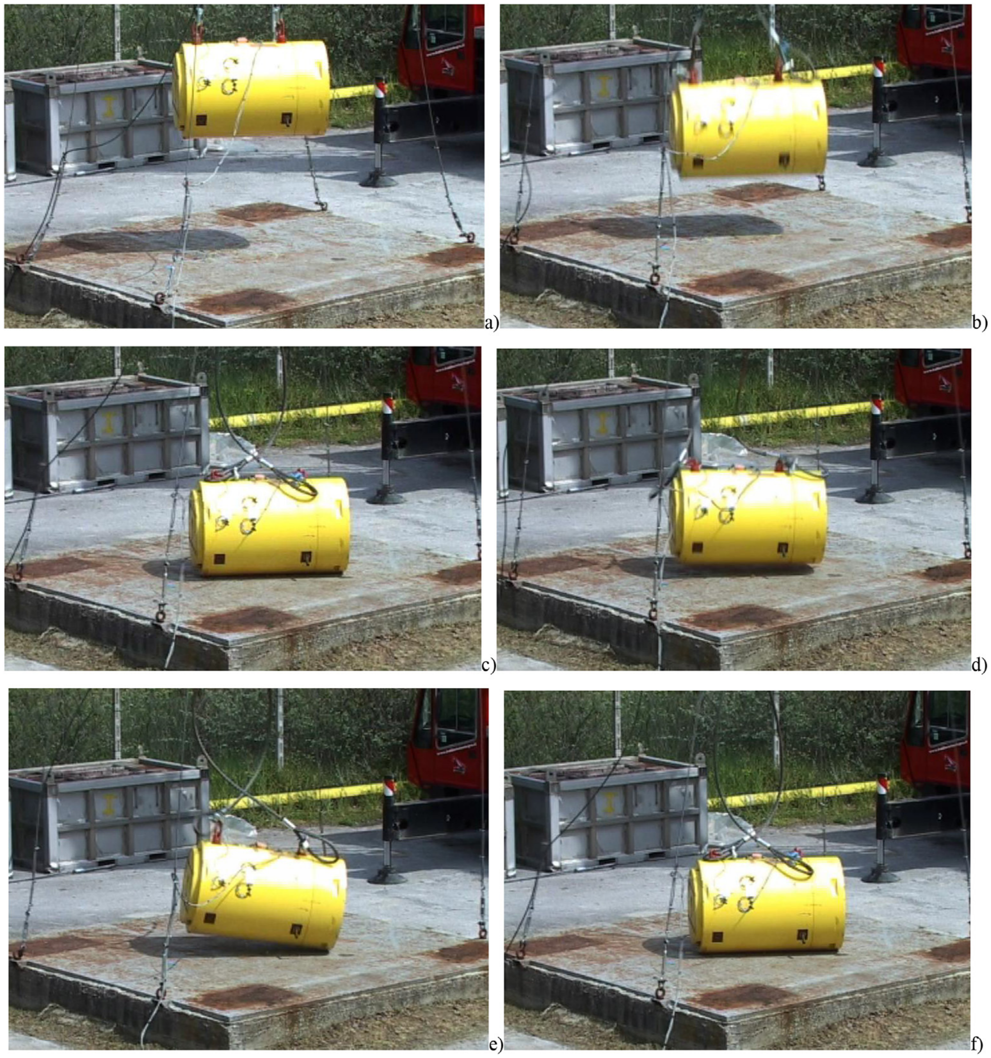

Fig. 3. Sequence of the horizontal drop test execution (Lo Frano et al., 2014).

primary membrane (P_m) or/and localized (P_L) loads according to the ASME Code, Sect. III, Div. 3. part WB (to be referred to for normal conditions of transport).

P_m identifies the average primary stress across the thickness; discontinuities and concentrations in this evaluation are not considered. P_L takes into account instead discontinuities, so it is determined by averaging the stress across the section. Bending stress must consider the sum of P_m and P_L.

For austenitic steel, like that of the CC-440 package (at 20 °C S_m = 275 MPa), the allowable limits of the stress intensities at temperature shall be:

$$P_m < S_m \tag{4}$$

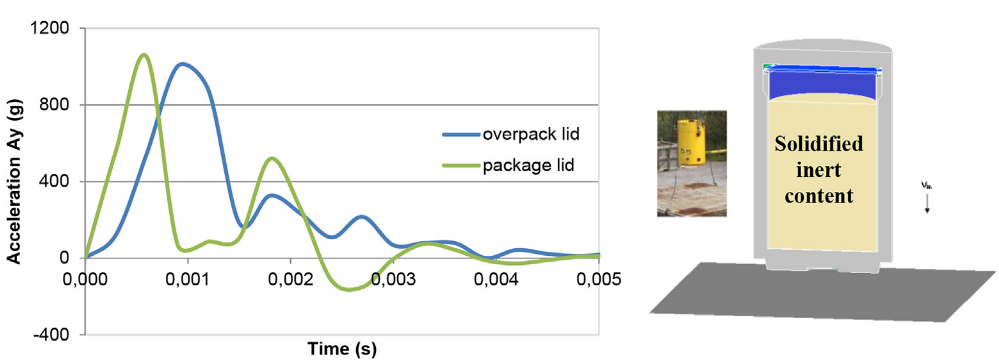

Fig. 4. Analytical acceleration for vertical drop test on the bottom configuration.

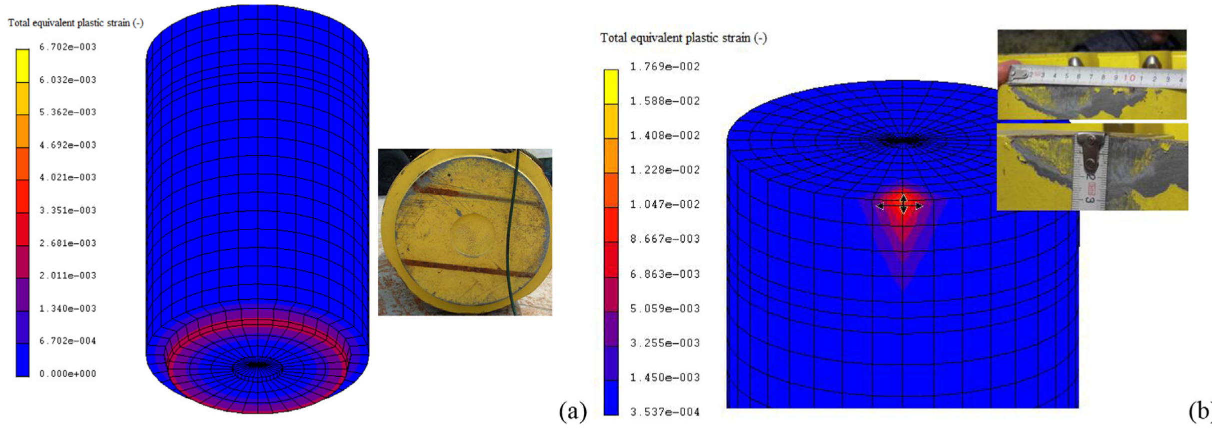

Fig. 5. Plastic deformation vs. experimental evidence for vertical drop on the bottom (a) and for horizontal drop (b).

$$P_L < 1.5\ S_m \tag{5}$$

$$P_m + P_L < 1.5\ S_m \tag{6}$$

“Prying effects”, caused by the rotation of the lid must be considered for bolts ($S_m^b = 640$ Mpa for class 8.8 bolts). Therefore for normal operating condition limits the membrane stress intensity averaged across the bolt cross section, neglecting stress concentrations, shall not exceed two times the stress values, while the average bolt shear stress shall be:

$$S_{bolt} < 0.4 S_y \tag{7}$$

The maximum value of stress intensity, at the periphery of the bolt cross section, resulting from direct tension plus bending and neglecting stress concentrations, shall be:

$$S_{bolt} < 3 S_m^b \tag{8}$$

It is important to note that since the IP-2design requirements have no specific stress limits and that the IAEA regulations prescribe that packages must prevent any loss or dispersion of the radioactive content and the loss of shielding integrity (that could determine a 20% increase in the radiation level), the structural performance of the package was assessed according to the Von-Mises equivalent stress level.

To estimate the potential changes in the working conditions of the gasket, the geometrical configuration of the lid in the seal area, in relation to its assembly state have to be analysed. The main parameters so to monitor are:

- The change of the gasket position in the flange due to lid sliding;
- The gasket decompression caused by the lid/package contact and
- The loss of pre-tension in the lid bolts as a result of their plastic deformation or complete failure.

3.2.1. Main assumption and FE model

For the numerical investigation (Leeet al, 2005; Jaksic and Nilsson, 2009) of the mechanical phenomena in the packaging system a FE model was created; the dimensions and materials adopted are referred to the typical CC-440 system, shown in previous Fig. 2.

Nonlinear numerical calculation provides stress and strain all over the packaging structure.

A detailed model of the IP2 package sample is shown in Fig. 6. It is important to remark that the 3-D full-scale model as the basis configuration for calculation was necessary since a segment model, with symmetry conditions, was not able to correctly represent the nonlinear behaviour of the packaging system during and, especially, after the impact.

IP2 model consists of the overpack, package body, the primary lid with lid bolts of strength class 8.8 and metallic gasket, and the packaging content (inert cement matrix simulating the solidified RAMs). Each component was explicitly modelled in three dimensions.

The mesh was designed to be appropriate for the purpose of the analysis and for the expected behaviour of the package; due to the nature of the problem the mesh is significantly finer, with a more refinement at areas where high stress gradients or large deformation gradients are expected. The overall model is made by more than 80.000 solid elements. The influence of mesh size, although not quoted in this treatment, has been evaluated by doubling and halving the model size: no significant variation was observed.

Regardless of the weld type, all welded connections of the main structural members in the package body were modelled using tied constraints. Each lid bolt has been modelled in its entirety by means of solid elements.

As shown in Fig. 6c the head and the shank were modelled; for simplicity the thread interfaces between the bolts and steel package were modelled with a proper double sided contact condition across the interfaces. In addition bolts pretension load was considered.

To characterize the interaction among the CC-440 components, surface-to-surface contact conditions, available in MSC©MARC code, have been implemented (MARC®, 2010) along with the “deformable body” condition.

All contacts are established in the initial step. DOUBLE-SIDED tool (MARC®, 2010) used for the body contact detection implies a check for the points of bodies in contact; the minimum distance value below which bodies are going in contact was assumed 10^{-5} m.

Moreover the contacts under the bolt head, and between the package and lid are directly enforced in normal direction. A standard friction beneath bolt head and between lid and package (unless otherwise stated) was assumed. Condition for the gasket interface are represented by a connection to the lid by a tied contact and a separable contact with the packaging flange.

In Fig. 7 is represented the target surface, that was simulated like a rigid body accordingly to the IAEA requirements.

The material behaviour of packaging was assumed isotropic and

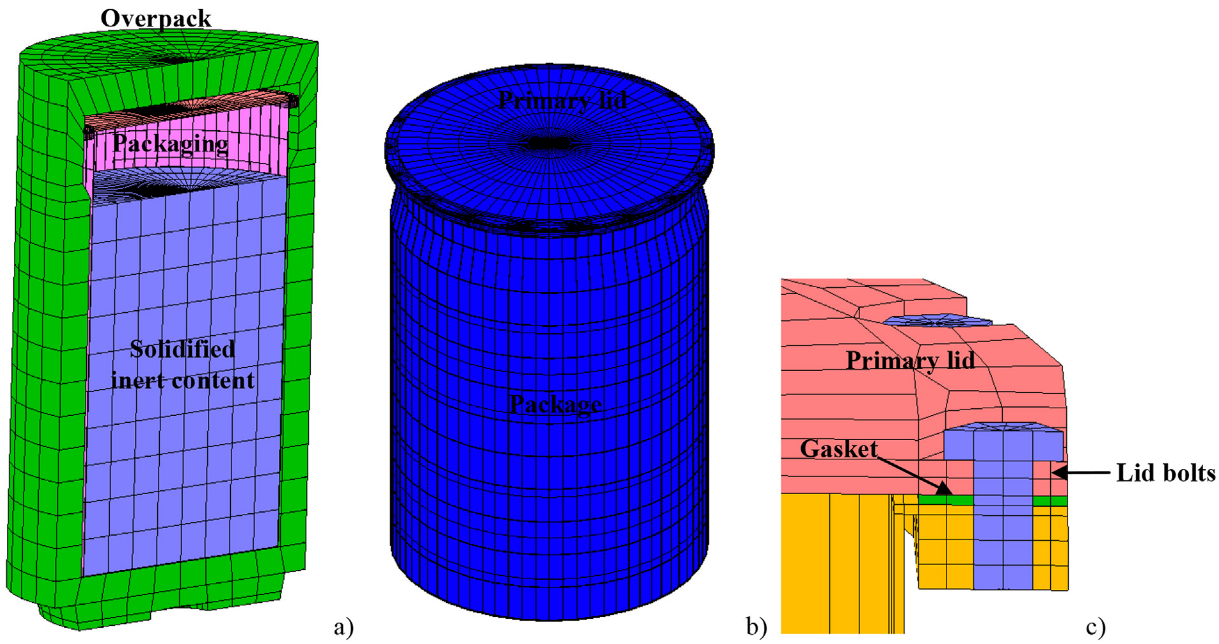

Fig. 6. CC-440 model: overpack (a), packaging system (b), and a detail of the package closure lid with lid bolts (c).

elastic-perfectly plastic, described by the Von Mises criterion; no failure model has been implemented. The stress-strain behaviour of the austenitic steel exhibits a linear elastic behaviour up to the yield stress (>250 MPa at 0.2% strain) and a plateau before strain hardening is encountered.

The concrete mass, representing the solidified RWs, was instead implemented as elastic isotropic material.

The transient dynamic analysis lasted 20 ms with a time step was 10−4 s. Finally, the initial velocity, namely V_{in} in Fig. 7, has been calculated as function of the drop height (equal to 1.2 m). It allows to simulate the physical condition of drop test.

4. Horizontal drop test results

The main numerical results, in terms of deformation, Von Mises stress and accelerations of the CC-440 packaging system, are showed and discussed in what follows.

Fig. 8 illustrates the impact of packaging system without overpack. The dynamic of the horizontal impact foresaw the flange touches initially the target followed subsequently by the rest of the container. The impact determines macroscopic deformations localized at the flange of the package (upper part of the cylindrical shell) and in correspondence of its bottom, as a consequence of the secondary impact.

The plastic deformation caused equivalent has maximum value of $2 \cdot 10^5$ $\mu\varepsilon$ (Fig. 9). Moreover the gasket plasticization appeared at its inner circumference: this was due to the onset of compression stresses generated by the combined action of the inflection of the lid and local deformation of the shell. Furthermore bolts positioned along the impact generatrix suffered some plastic strain, while no sliding of the lid, and no gasket dislocations in the lid flange region were observed.

Gasket was instead suffering a very small deformation (about $3 \cdot 104$ $\mu\varepsilon$) localized in the area surrounding the holed rim of the lid: its effects/consequences may be considered negligible.

The resulting stress appeared in the packaging; stresses resulted also mainly localized along the generatrix of impact, as shown in Fig. 10, and in particular at the flange, gasket and at the cover lid.

Despite a maximum value of about 300 MPa occurring at an early impact time, the stress intensity resulted lower than the limits foreseen for the primary and localised loads (Fig. 9). The same conclusions can be done for a packaging system enclosed in the overpack undergoing horizontal drop: in this case, the maximum stress on the package, as shown in Fig. 11, was about 290 MPa and caused by the first impact (overpack and packaging system came in contact 9 ms after the first impact onto the target surface). As for the bolts concerned, they are subjected to shear stress exceeding locally the allowable limit. The subsequent plastic strain

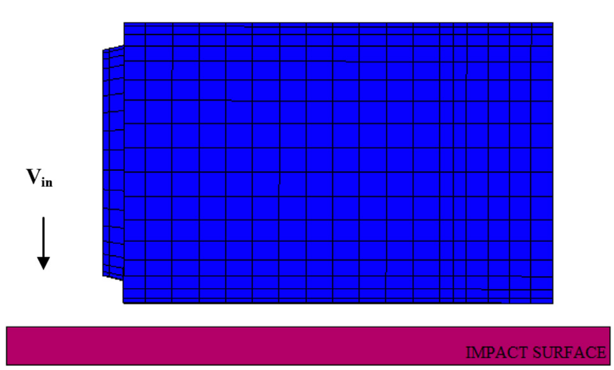

Fig. 7. Horizontal free drop test configuration.

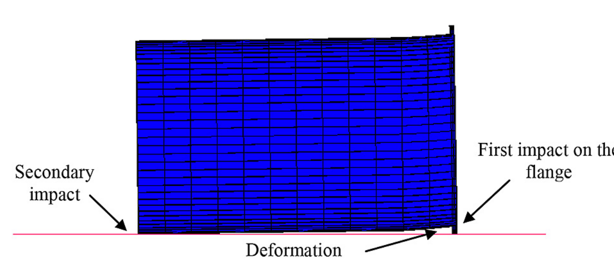

Fig. 8. Impact of packaging system without overpack.

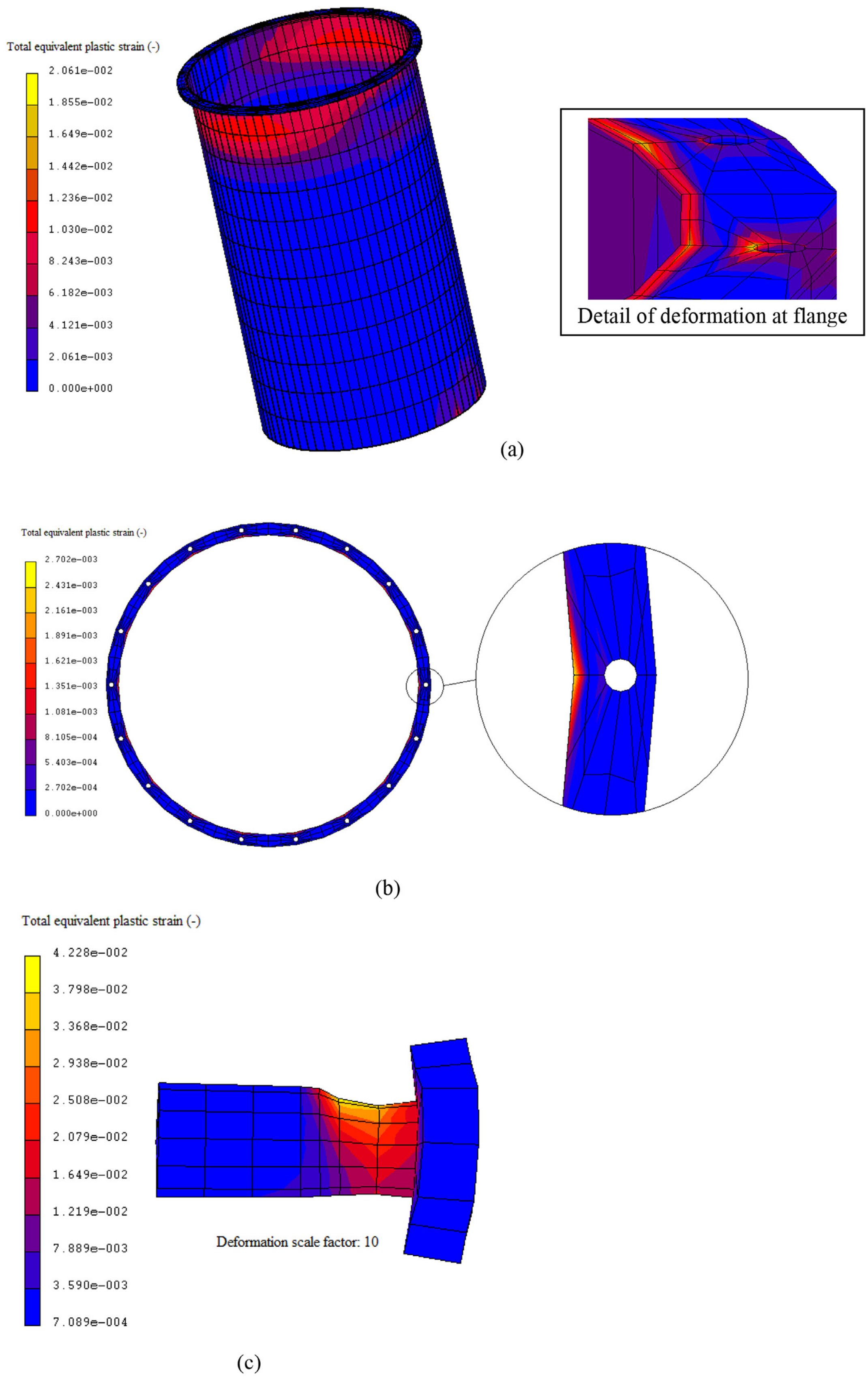

Fig. 9. Plastic strain at the package with a detail of flange (a), at the gasket (b), and bolt (c) localised along impact generatrix.

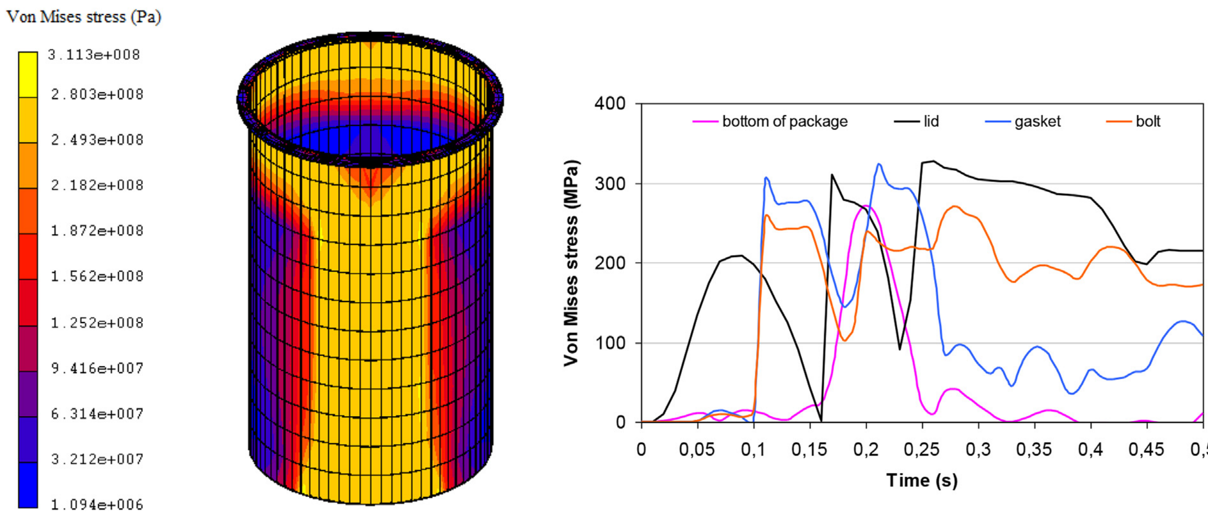

Fig. 10. Von Mises stress in the package shell at first impact (for horizontal drop test without overpack).

determined the increase of the tightening (and disassembly) torque for the bolts localized along the impact generatrix and on the opposite side.

Fig. 12 shows the plot of the acceleration versus time for the case of horizontal drop test with overpack.

Firstly as depicted, the acceleration peak corresponding to the first impact progressively propagates inward the packaging components. It reaches the maximum value on the overpack 5000 g in 0.1 ms (equal to one singular integration time step), because of the high stiffness of this component, and then decreases to 800 g or lesser: this rapid variation reflects entirely the impulsive nature of the drop event.

The analytical results confirmed finally the integrity of the closure lid, and the capability of the numerical approach to simulate with a quite good reliability the free drop test condition analysed.

5. Conclusion

In this study has been investigate experimentally and numerically the structural performance of an Italian IP2 package for the transport of LILWs under horizontal (full-scale) free drop test.

The experimental results have been used to verify the reliability of the numerical tools and modelling methodology adopted in the numerical analyses, and to demonstrate the compliance of design criteria with National and International requirements.

The main results indicated no failure or sudden collapse of the packaging system undergoing 1.2 horizontal drop test. In addition a macroscopic deformation was observed at the flange of the package (in agreement with experimental evidence) and at its bottom respectively as a consequence of the first and secondary impact.

The gasket appeared less plasticized at its inner circumference because of compression stress generated by the inflection of the lid and the local deformation of the shell. Furthermore bolts positioned along the impact generatrix suffered some plastic strain, while no sliding of the lid or gasket dislocations in the lid flange region were observed.

Despite the discrepancy that appeared in the punctual comparison of analytical versus experimental accelerations, a quite good agreement is instead obtained by comparing the mean value

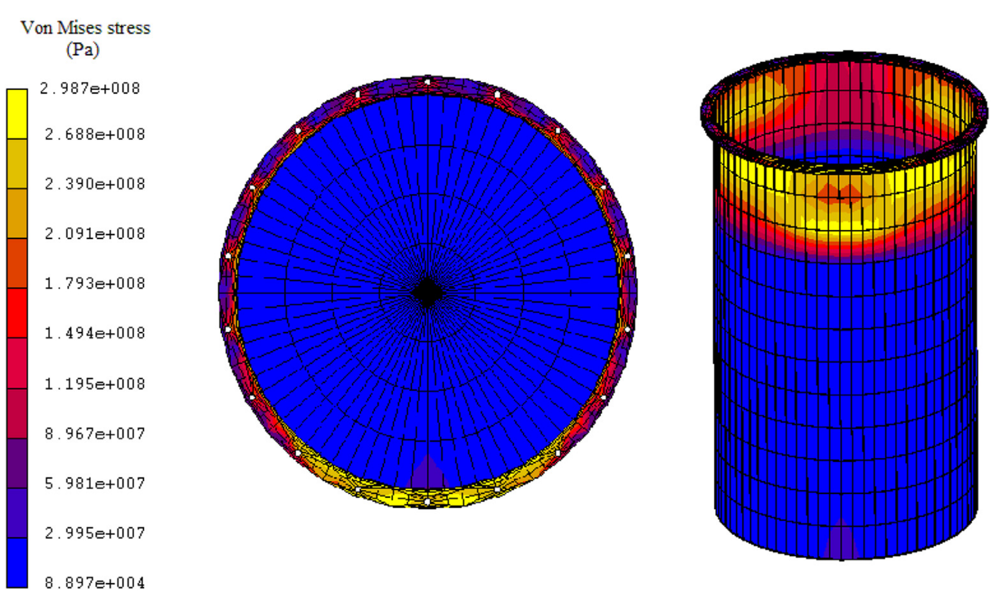

Fig. 11. Von Mises stress in the package shell at first impact (for a horizontal drop test with overpack).

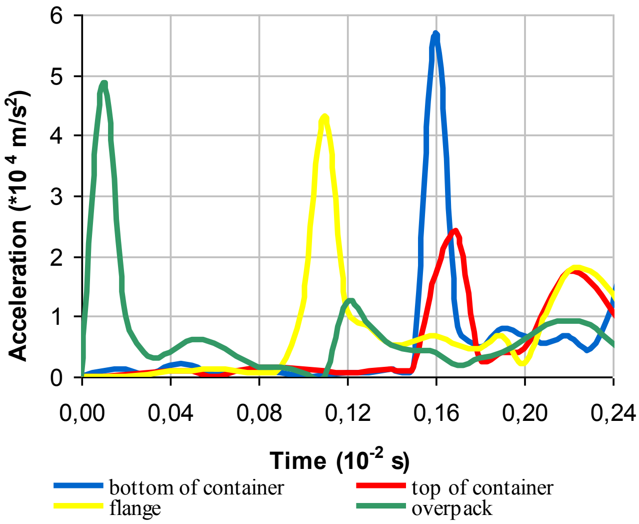

Fig. 12. Accelerations calculated at the CC-440 components.

of accelerations (for both two is around 400 g).

The IP2 package, analysed and tested, demonstrated to withstand horizontal impact loads without cliff edge or loss of the safety features.

Acknowledgement

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