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Verification of Steel Plate as Target for 9-Meter-High Cask Drop Tests

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Abstract: The nuclear fuel cycle encompasses processes from uranium mining to the final disposal or packaging of radioactive waste. For the final packaging, radioactive waste must be transported in specially designed casks. The certification of these casks involves a series of prescribed tests, as outlined by standards and regulations such as CNEN NN 5.05 [1], NUREG-2125 [2], and IAEA SSG-26 [3]. These tests simulate hypothetical accidental transportation conditions, including free drop tests from a height of 9 meters, penetration tests, fire exposure tests, and immersion tests. To satisfy the drop and penetration tests, the cask must be dropped onto a target with a flat, horizontal, and as much as technically feasible, unyielding surface. The standards specify that “the target for drop tests is an essentially unyielding surface,” meaning it is “hard and heavy enough that the package absorbs nearly all of the impact energy, with the target absorbing very little energy.” This unyielding surface is intended to inflict damage on the package equivalent to or greater than what might occur during actual transportation impacts. The use of such a target ensures that analyses and tests can be compared and, if necessary, accurately repeated. This study evaluates the 9-meter drop of a package with a mass equivalent to a 1:4 scale type B(U) transportation cask onto a steel plate fixed to a concrete slab, aiming to qualify the target represented by the steel plate. The numerical simulation was conducted using LS-Prepost® V4.8.29 [4].

Keywords: Transport Cask, Drop test, Numerical simulation, Spent Fuel.

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Verificação de chapa de aço como alvo para teste de queda de casco de uma altura de 9 metros

Resumo: O ciclo do combustível nuclear abrange processos desde a extração de urânio até a disposição final ou embalagem de resíduos radioativos. Para a embalagem final, os resíduos radioativos devem ser transportados em cascos especialmente projetados. A certificação desses cascos envolve uma série de testes postulados, conforme estabelecido por normas e regulamentos como CNEN NN 5.05 [1], NUREG-2125 [2] e IAEA SSG-26 [3]. Esses testes simulam condições hipotéticas de transporte acidental, incluindo testes de queda livre de uma altura de 9 metros, testes de penetração, exposição ao fogo e testes de imersão. Para atender aos testes de queda e penetração, o casco deve cair sobre um alvo com uma superfície plana, horizontal e, tanto quanto tecnicamente possível, indeformável. As normas e regulamentos [1-3] especificam que "o alvo para os ensaios de queda é especificado como uma superfície essencialmente indeformável", ou seja, "o alvo é suficientemente rígido e de grande massa para que a embalagem absorva quase toda a energia de impacto e o alvo absorva muito pouca energia". Além disso, "esta superfície indeformável destina-se a provocar danos na embalagem que sejam equivalentes ou superiores aos previstos para os impactos nas superfícies ou estruturas reais que possam ocorrer durante o transporte". O objetivo da utilização de um alvo é que "também fornece um método para garantir que as análises e os testes possam ser comparados e, se necessário, repetidos com precisão". Este estudo avalia a queda de 9 metros de um bloco com massa equivalente a um casco de transporte tipo B(U) em escala 1:4 sobre uma placa de aço fixada a uma laje de concreto, com o objetivo de qualificar o alvo representado pela placa de aço. A simulação numérica foi conduzida usando o LS-Prepost® V4.8.29 [4].

Palavras-chave: Casco de transporte, Ensaio de impacto, Simulação numérica, Combustível irradiado.

1. INTRODUCTION

The nuclear fuel cycle encompasses all processes from uranium mining to the final disposal of radioactive waste. To transport nuclear fuel from the manufacturing facility or from a nuclear reactor facility to the final destination, a transportation package, i.e., a cask is required. The certification of these casks involves a series of prescribed tests, as outlined in standards such as CNEN NN 5.05 [1], NUREG-2125 [2], and IAEA SSG-26 [3].

These tests include hypothetical accident conditions where the cask must undergo 9-meter free drop tests, penetration tests, fire tests, and immersion tests. To satisfy the drop and penetration tests, the cask must be dropped onto a target that is flat, horizontal, and as unyielding as technically possible.

Regulations specify that "the target for drop tests is defined as an essentially unyielding surface," meaning "the target is hard and heavy enough that the package absorbs nearly all of the impact energy, with the target absorbing very little energy." Additionally, "this unyielding surface is intended to cause damage to the package equivalent to or greater than that anticipated during actual transport." [1, 2]

The purpose of using such a target is to "ensure that analyses and tests can be compared and, if necessary, accurately repeated." This study will evaluate the 9-meter drop of a package with a mass equivalent to a 1:4 scale type B(U) transport cask onto a steel plate fixed to a concrete slab, aiming to qualify the target represented by the steel plate.

The numerical study was simulated with LS-Prepost(R) V4.8.29 [4].

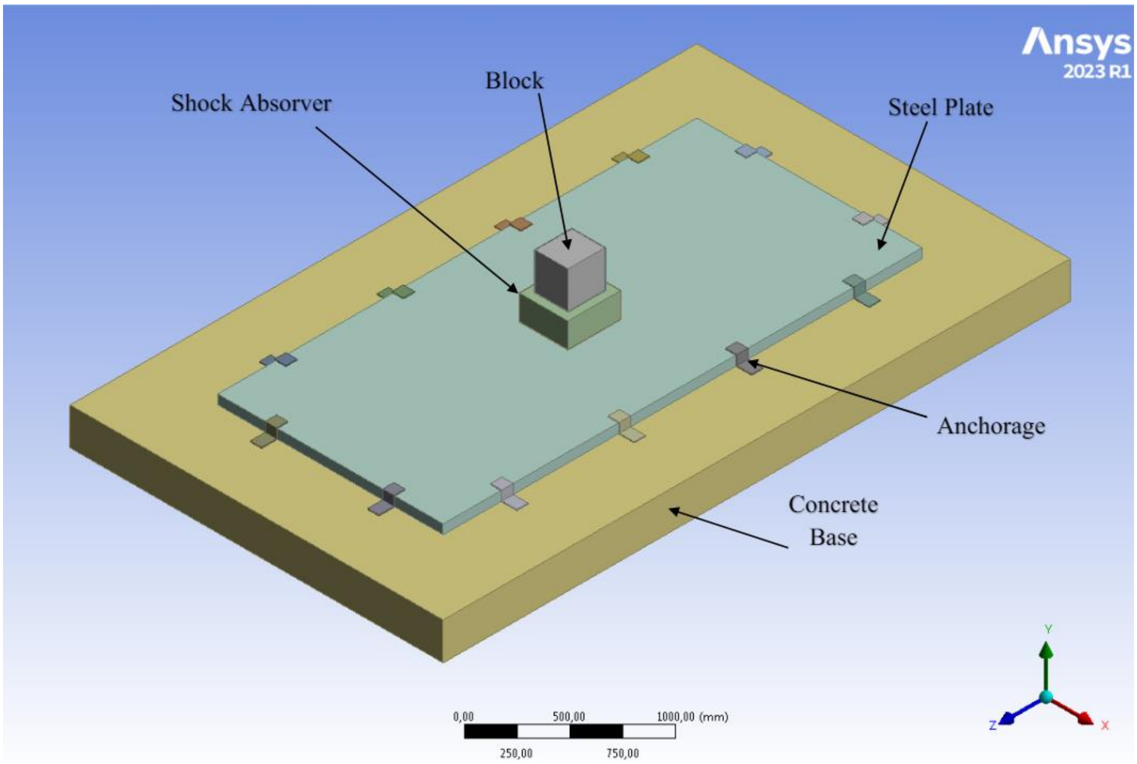
2. MATERIALS AND METHODS

2.1. Physical model

The physical model consists of a rectangular AISI1020 steel block filled with lead and a shock absorber welded to the base of this block, consisting externally of an AISI304 stainless steel box and filled with polyurethane foam. The assembly, constituted by the block and the shock absorber, are referred to hereafter as package.

The drop test target was defined as a 63.5 mm thick steel plate, fixed to a 250 mm thick concrete slab, using twelve anchorage points, as shown in Fig. 1.

Figure 1: Physical model



IAEA SSG-26 [3] recommends that the mass of the steel plate and concrete base should be at least 10 times the mass of the model being tested for tests such as the type B(U) cask, which is the focus of this work. Considering only the steel plate, its mass corresponds to around 2,400kg, which is around 14.5 times greater than the mass of the package analyzed, weighing 165.6 kg.

2.2 Numerical model

Three numerical models were made. The first model, complete, considered the package falling on the steel plate, fixed to the concrete base using twelve anchoring points. The second, yielding target, considered the cask falling on only the steel plate and the third, unyielding target, considered the package falling on a theoretical rigid unyielding plate.

The geometries of the models were created using Ansys R23 Design Modeler [5]. The mesh and numerical simulation were conducted through LS-Prepost(R) V4.8.29 [4]. The mesh for the first model is shown in Figure 2. The second and third utilize the same mesh which are shown in Figure 3. Figure 4 shows a detail of the package mesh.

Figure 2: Complete model mesh

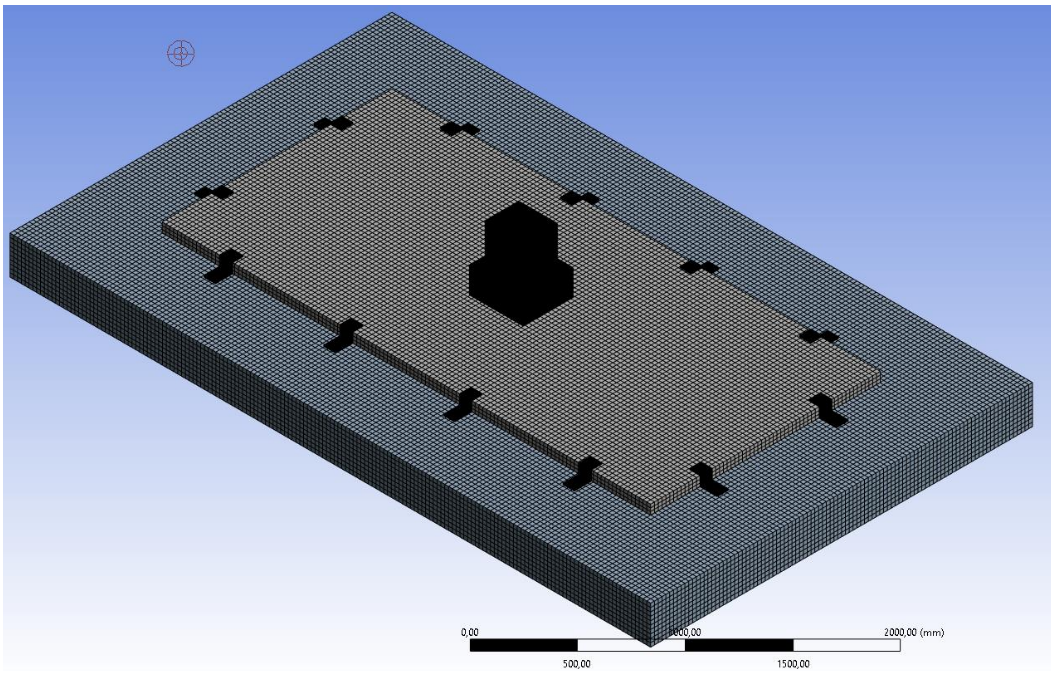


Figure 3: Yielding and unyielding model meshes

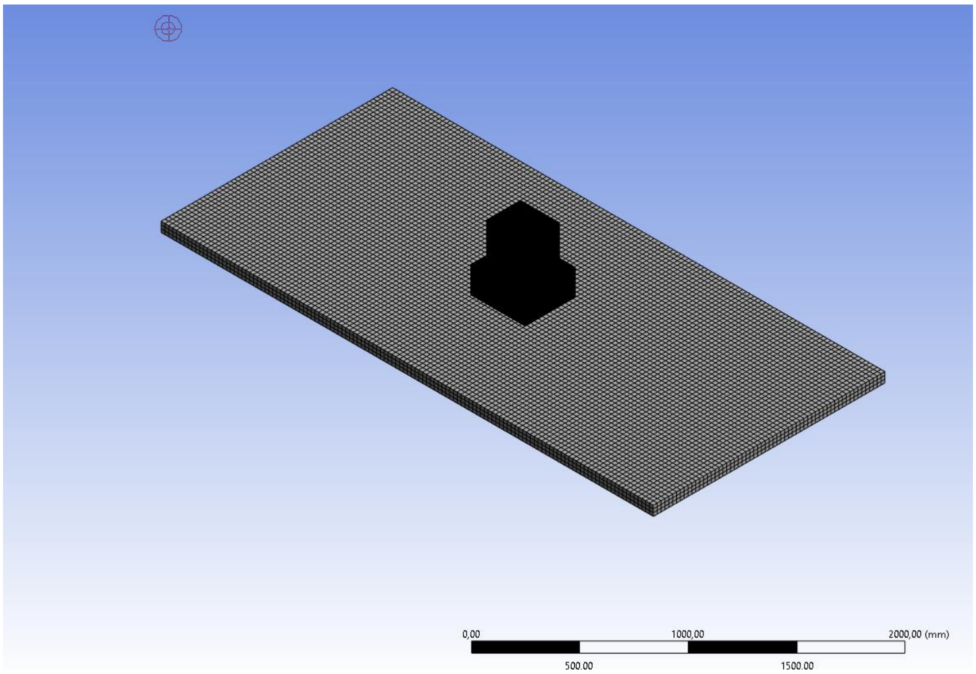
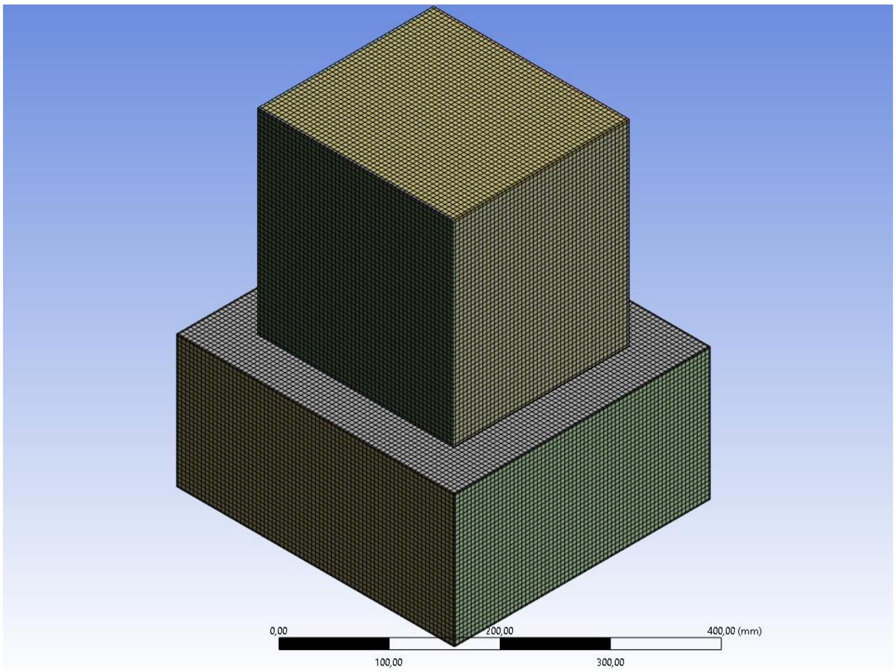


Figure 4: Package model mesh



The complete numerical model consists of 564,237 nodes and 483,925 elements of the SOLID, i.e., an 8-node solid element type. The yielding and unyielding numerical models consist of 327,912 nodes and 313,518 elements of the SOLID element type. As mentioned above, the package weighing 165.6 kg drops from a height of 9 meters onto the steel plate, with a final velocity corresponding to 13.286 m/s.

2.3 Materials, dimensions and properties

The materials, main dimensions (L x W x H - Length x Width x Height) and properties (ϱ - density, E - modulus of elasticity, and ν - Poisson's ratio) are defined in Table 1.

Table 1: Materials, dimensions and Properties

COMPONENT	MATERIAL	L [mm]	W [mm]	H [mm]	ϱ [kg/mm3]	E [MPa]	ν
Block (Plating)	AISI1020 Steel	250	225	251	7.850E-6	2.00E5	0.29
Block (Internal)	Lead	244	219	245	1.135E-5	1.34E4	0.44
Shock Absorber (Plating)	AISI304 Steel	355	327	169	7.950E-6	1.95E5	0.27
Shock Absorber (Foam)	Polyurethane Foam	352	324	166	1.920E-7	6.61E1	0.10
Steel Plate	AISI1020 Steel	3210	1510	63.5	7.850E-6	2.00E5	0.29
Anchorage	AISI1020 Steel	75	75	6.35	7.850E-6	2.00E5	0.29
Concrete Base	Concrete	4200	2500	250	2.390E-6	1.94E4	0.14

2.4 Methodology

The regulations [1-3] define that "The target for drop tests is specified as an essentially unyielding surface", i.e., "The target is hard and heavy enough that the package absorbs nearly all of the impact energy and the target absorbs very little energy". There are two types of energy that are involved in an impact: the kinetic energy of the impacting body(ies), and the internal energy, or absorbed energy, in the package and the target [5]. For impacts onto a yielding target, the kinetic energy of the mass at impact is equal to the total internal energy of the package and the target (Equation 1). For impacts onto an unyielding target, the kinetic energy is equal to the total internal energy of the package (Equation 2), i.e., the internal energy of the target is equal to zero. [6]

$$\frac{1}{2}MV_{yielding}^{2} = E_p + E_t, \qquad \text{Eq. 1}$$

$$\frac{1}{2}MV_{unyielding}^{2} = E_p. \qquad \text{Eq. 2}$$

Where:

M = The mass of the package (cask and shock absorber)

$V_{yielding}$ = The velocity of impact onto a yielding surface

$V_{unyielding}$ = The velocity of impact onto an unyielding surface

E_p = The internal energy of the package

E_t = The internal energy of the target

In this paper, the kinetic and internal energy of the package will be compared in various scenarios, including impacts on both yielding and unyielding targets. This comparison aims to demonstrate that the package absorbs nearly all of the impact energy. Additionally, the strain on a steel plate fixed to a concrete slab will be verified to qualify the target.

3. RESULTS AND DISCUSSIONS

3.1 Kinetic and internal energy

The theoretical kinetic energy value relative to the package is calculated through the following expression:

$$\frac{1}{2}MV^2 = \frac{1}{2}165{,}6(13{,}286)^2 = 14{,}616\ kJ.$$

Table 2 presents the maximum kinetic and internal energy values reached to each component of the simulated model.

Table 2: Maximum kinetic and internal energy per model

MODEL	KINETIC ENERGY (KJ)			INTERNAL ENERGY (KJ)		
	PACKAGE	PLATE	CONCRETE	PACKAGE	PLATE	CONCRETE
Complete	14.618	0.018	0.0001	12.130	0.042	0.015
Yielding	14.618	0.008	-	11.853	0.034	-
Unyielding	14.618	0	-	11.877	0	-

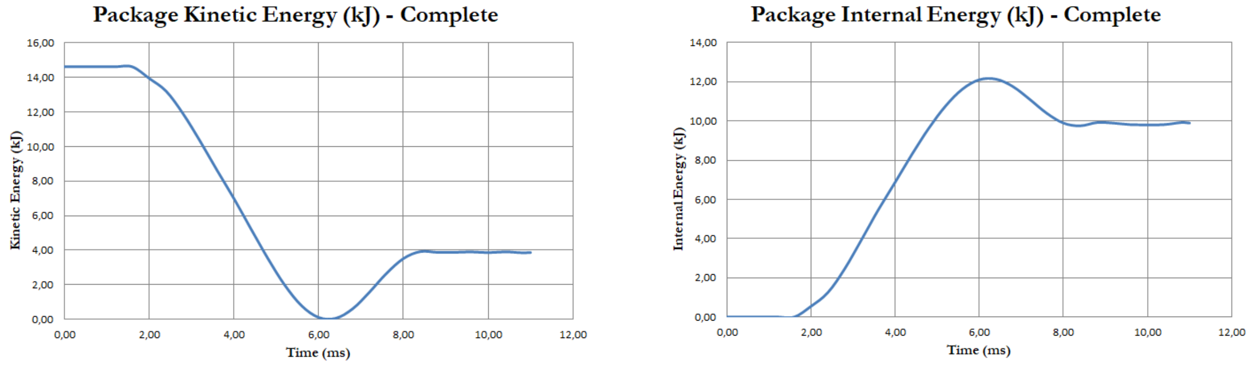
The simulated kinetic energy in the package is about the same as the theoretical kinetic energy. The package absorbs approximately 83% of the impact energy, that is, the target is hard and heavy enough so that the package absorbs nearly all of the impact energy and the target absorbs very little energy, 0.23 - 0.39%. The remaining kinetic energy is due to the elastic reaction of the model that results in a secondary motion. The simulation was interrupted before the second impact as its low energy impact would produce negligible effects.

The difference in internal energy between the unyielding and yielding models in relation to the complete model is approximately 2.5%. The processing time was approximately 32 min for the unyielding model, 36 min for the yielding model, and 52 min for the complete model.

Figures 5, 6 and 7 respectively present the kinetic and internal energy plots versus time elapsed in the simulation of complete, yielding and unyielding models. It is possible to observe the equivalent behavior in the three models.

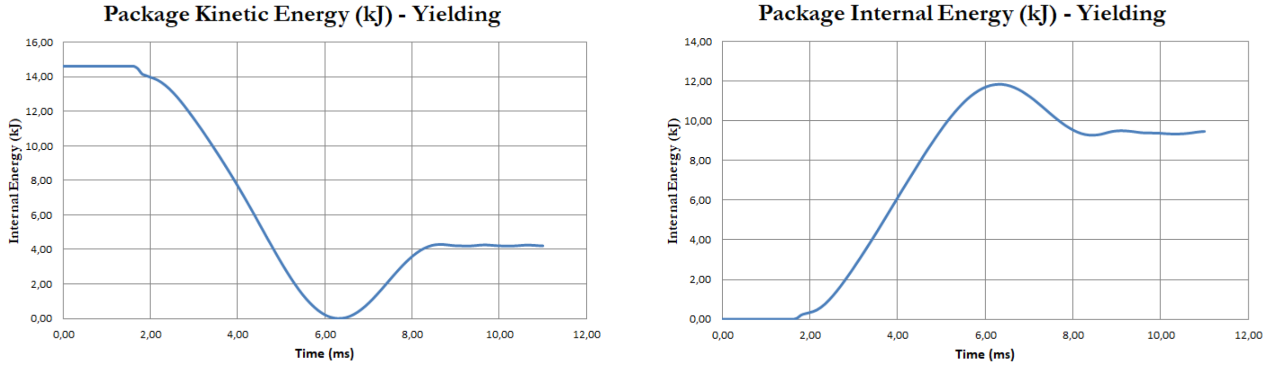
Given the minimal differences in internal energy among the three models and the significantly reduced processing time for the unyielding model, it is deemed the most suitable and therefore, it can be selected as the standard model for further processing. Consequently, the numerical simulation of the complete model could be disregarded for simplicity.

Figure 5: Kinetic and internal energy (complete)


Package Kinetic Energy (kJ) - Complete

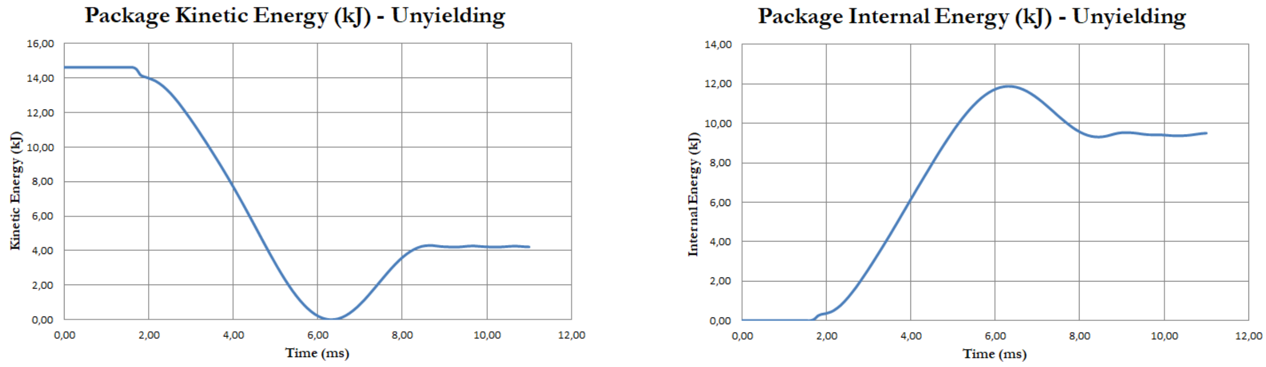
Package Internal Energy (kJ) - Complete

Figure 6: Kinetic and internal energy (yielding target)


Package Kinetic Energy (kJ) - Yielding

Package Internal Energy (kJ) - Yielding

Figure 7: Kinetic and internal energy (unyielding target)


Package Kinetic Energy (kJ) - Unyielding

Package Internal Energy (kJ) - Unyielding

3.2 Strain

Table 3 presents the maximum strain values of each component in the simulated model.

Table 3: Maximum strain per model

MODEL	STRAIN IN THE Y-AXIS		
	PACKAGE	PLATE	CONCRETE
Complete	4.249E-1	3.761E-5	9.708E-3
Yielding	4.446E-1	6.797E-6	-
Unyielding	4.448E-1	-	-

The maximum strains of the package in the three models are very similar, with a difference of 4.6% between the complete and yielding models, and 4.7% between the complete and unyielding models. The strains in both the plate and the concrete slab are minimal, indicating that the target can be considered an essentially unyielding surface within an acceptable uncertainty margin, as supported by references [1-3].

3.3 Stress

Table 4 presents the maximum von-Mises stress values of each component in the simulated model.

Table 4: Maximum von-Mises stress per model

MODEL	VON-MISES STRESS (MPA)		
	PACKAGE(*)	PLATE	CONCRETE
Complete	353.6	31.5	6.6
Yielding	350.3	46.6	-
Unyielding	350.3	0	-

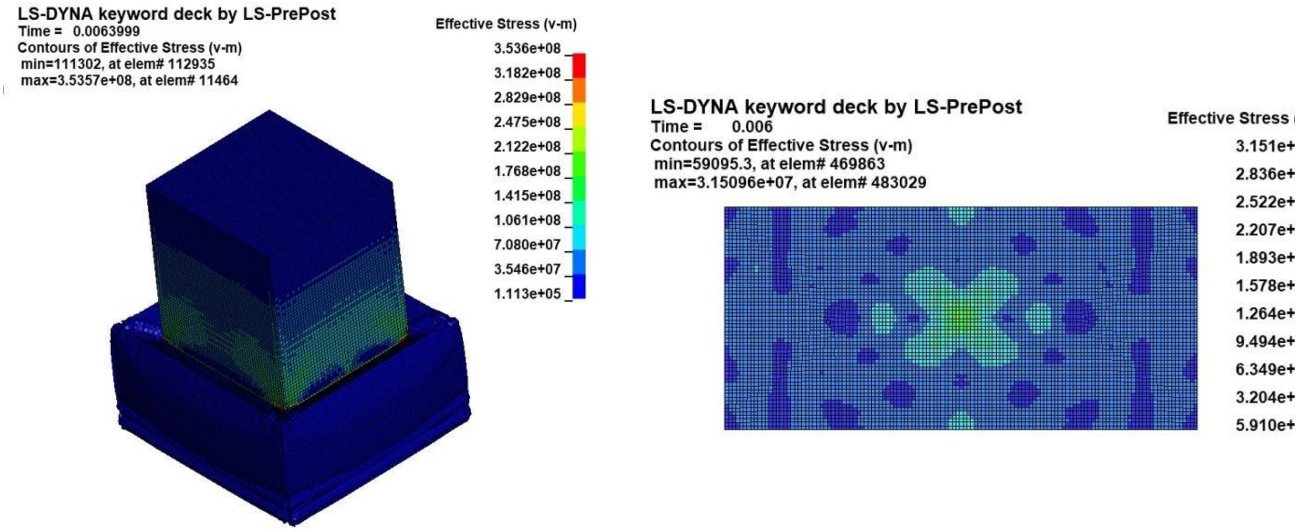
(*) Package without shock absorber plating

The shock absorber plating was excluded from the maximum stress analysis because corner elements concentrate stress, skewing the results, which is known as stress singularity. However, this exclusion does not compromise the accuracy of the comparison, as the primary function of the shock absorber is to protect the attached block through deformation receiving over 99% of the energy.

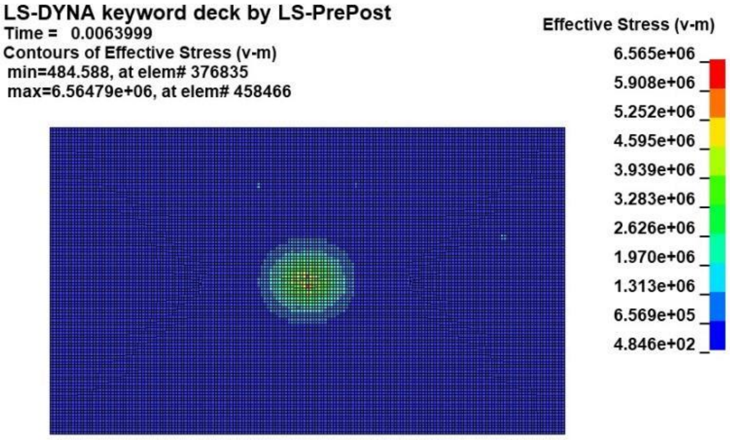
The maximum von-Mises stress on the package in the complete model is 0.07% greater than the unyielding and yielding models which are the same. The maximum von-Mises stresses of the plate and concrete slab are very small, so the target does not suffer major stresses, that is, the plate and the concrete slab can be qualified as a target for packages with equivalent weights to the one studied in this work.

Figures 8, 9 and 10 respectively present the maximum von-Mises stress of complete, yielding and unyielding models.

Figure 8: von-Mises stress (complete)

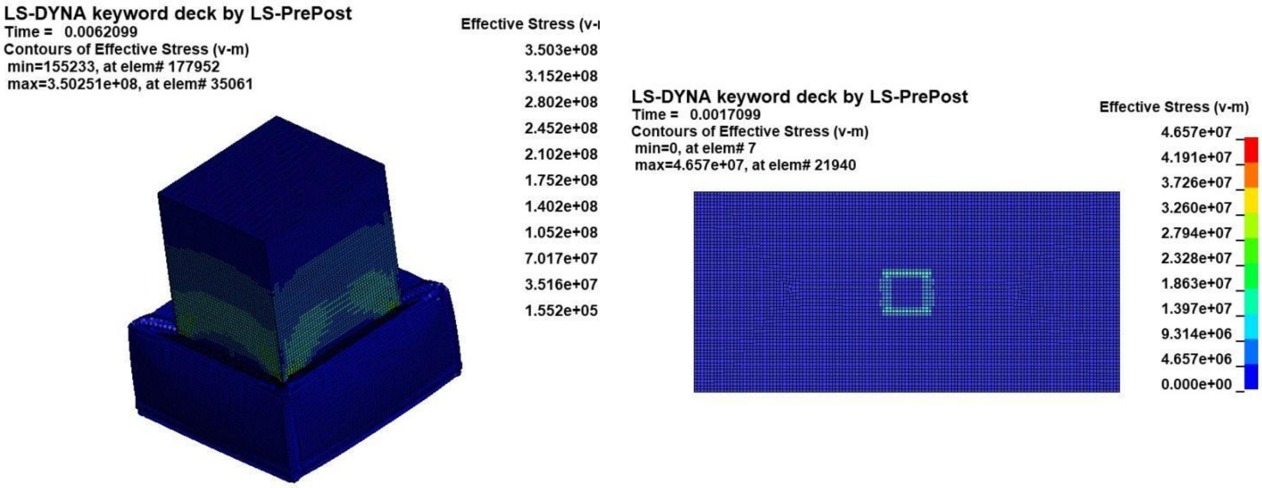


Package(*) Plate



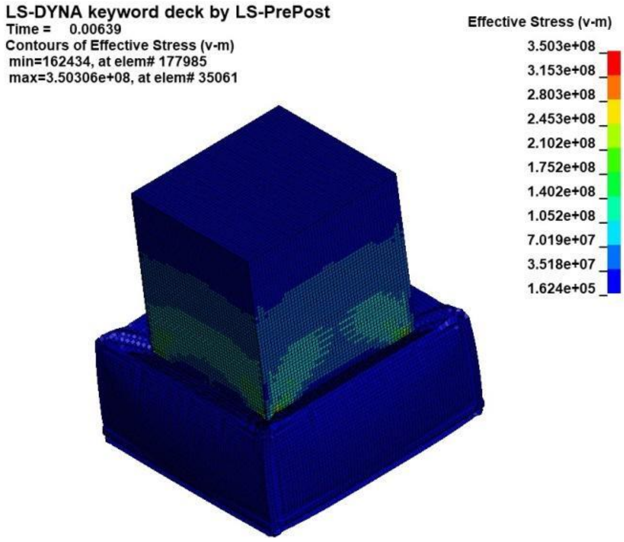
Concrete slab

Figure 9: von-Mises stress (yielding target)



Package(*) Plate

Figure 10: von-Mises stress (unyielding target)



Package(*)

Based on the results obtained, it can be verified that the target, made of the steel plate and the concrete slab, is capable of receiving the drop tests, for a cask of equivalent weight. These results satisfy the requirements of the CNEN NN 5.05 [1] regulatory norm, alongside the NUREG-2125 [2] and IAEA SSG-26 [3] standards, i.e., being made of a flat, horizontal and, as far as technically feasible, unyielding upper surface, and the target absorbing very little energy. Moreover, results indicate that for the simulation of the drop test, the steel plate and the concrete slab could be omitted without compromising the test accuracy and as well as the comparisons with experimental data.

4. CONCLUSIONS

This work analyzes the viability of a target, composed of a 63.5 mm thick steel plate in three simulated models, to receive 9-meter drop tests from a package weighing around 165.6 kg, in compliance with the CNEN NN 5.05 [1] regulatory norm and the NUREG-2125 [2] and IAEA SSG-26 [3] regulations. This study is part of a larger project, which will analyze a radioactive waste transport cask, in a 1:4 scale, with a weight equivalent to the package analyzed. Physical tests will also be carried out to validate the numerical model.

The maximum strains observed in the plate and the concrete slab confirm that "the target for drop tests is specified as an essentially unyielding surface."

The internal energies and maximum von-Mises stresses demonstrate that "the target is hard and heavy enough that the package absorbs nearly all of the impact energy, with the target absorbing very little energy."

Given that the unyielding model provides results for energies, stresses and strains which are very similar to those of the other models, in addition, it has a shorter processing time, it can be used to represent the simulation.

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CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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