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NUMERICAL APPROACH TO DETERMINE A PACKAGE DEPENDENT BAR LENGTH FOR THE IAEA PIN DROP TEST

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ABSTRACT

The Federal Institute for Materials Research and Testing (BAM) is assessing the mechanical and thermal safety performance of packages for the transport of radioactive materials. Drop testing and numerical calculations are usually part of the safety case concepts, where BAM is performing the regulatory tests at their own test facility site. Among other mechanical tests the 1-meter-drop onto a steel puncture bar shall be considered for accident safe packages. According to the IAEA regulations "the bar shall be of solid mild steel of circular section, 15.0 ± 0.5 cm in diameter and 20 cm long, unless a longer bar would cause greater damage…" Particularly with regard to the German transport and storage cask designs, often made from ductile cast iron, an accurate determination of the puncture bar length to guarantee a load impact covering the worst case scenario can be imperative. If the fracture mechanical proof for the cask material shall be provided by a test, small deviations in the concentrated load applied can be decisive for the question if the cask fails or not. The most damaging puncture bar length can be estimated by an iterative procedure in numerical simulations. On the one hand, a sufficient puncture bar length shall guarantee that shock absorbers or other attachments do not prevent or reduce the local load application to the package, on the other hand, a longer and thus less stiff bar causes a smaller maximum impact force. The contrary influence of increasing puncture bar length and increasing effective drop height shall be taken into account if a shock absorber is directly placed in the target area. The paper presents a numerical approach to identify the bar length that causes maximum damage to the package. Using the example of two typical package masses the sensitivity of contact force and puncture bar deformation to the initial length are calculated and assessed with regard to the international IAEA package safety requirements.

INTRODUCTION

According to the international IAEA transport safety regulations [1] accident safe packages for the transport of radioactive material shall withstand impact loads resulting from a 9 m free drop onto an essentially unyielding target in sequence with a 1 m puncture bar drop test in a most damaging attitude. The statements in [1] relevant for this paper are

§727. Mechanical test: "The order in which the specimen is subjected to the drops shall be such that, on completion of the mechanical test, the specimen shall have suffered such damage as will lead to maximum damage in the thermal test that follows:
…
(b) … the specimen shall drop onto a bar rigidly mounted perpendicularly on the target so as to suffer maximum damage. The height of the drop measured from the intended point of impact of the specimen to the upper surface of the bar shall be 1 m. The bar shall be of solid mild steel of circular section, 15.0 ± 0.5 cm in diameter and 20 cm long, unless a longer bar would cause greater damage, in which case a bar of sufficient length to cause maximum damage shall be used…."
The order of the mechanical drop tests is thus not determined in [1] for each case. For specific cask design it shall be derived reasoning from the requirement of maximum damage. The same applies to the length of the puncture bar, for which only the minimum value of 20 cm is specified. The use of a longer bar is not excluded.
Compared with a 9 m drop test onto a flat unyielding surface, the interaction between cask and puncture bar is widely localized. It can be expected for this test that the loading of the cask component, e.g. cask body, will be higher if potential energy released of 1 m drop is absorbed only in the puncture bar and in the local contact zone of the component impacted. Although the stiffness and thus the potential damage in the contact zone is reduced as the length of the bar increases, there is the possibility that other cask areas will come into contact with the unyielding target and participate in the energy absorption if the bar is too short.
In practice, therefore, preliminary considerations are necessary to estimate the most damaging order of the tests as well as the optimal length of the bar. Such preliminary analysis is usually based on simplified calculation models and serve primarily to reduce the number of drop tests or the range of more complex numerical calculations. It is especially important for casks protected by large–volume shock absorbers. In this case the shape of the cask can be significantly changed after 9 m drop, resulting in various geometrical conditions, which shall be considered in deciding on the test order and the puncture bar length. In this paper some methodological aspects of this issue will be discussed.

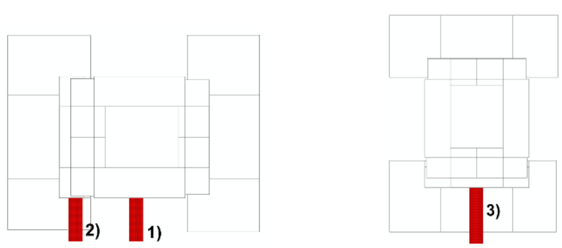

Fig. 1 Possible drop test positions, horizontal (left) and vertical (right) and assigned puncture bar contact positions 1), 2), 3)

Following characteristics and effects of the impact interaction were numerically analyzed and will be presented in this paper:

1. Force and deformation behavior/curves of 1 m drop test with two different masses (20 Mg/150 Mg) onto a puncture bar of initial lengths between 200 mm and 400 mm in increments of 10 mm.
2. The influence of deviations from the optimal puncture bar length on the impact force under consideration of simultaneous target contact of shock absorber.

3. The contrary influence of increasing puncture bar length L_0 on the one hand side and an increasing effective drop height h_{eff} on the other side if the puncture bar hits the cask in an area covered by an impact limiter, Fig. 1, Pos. 2/3.

FINITE ELEMENT MODEL

For the numerical simulation of the puncture bar drop test, a finite element (FE) model was developed using the preprocessor ABAQUS/CAE® [2] by BAM. Taking advantage of the system symmetry, a half-model was generated, Fig. 2 (left).

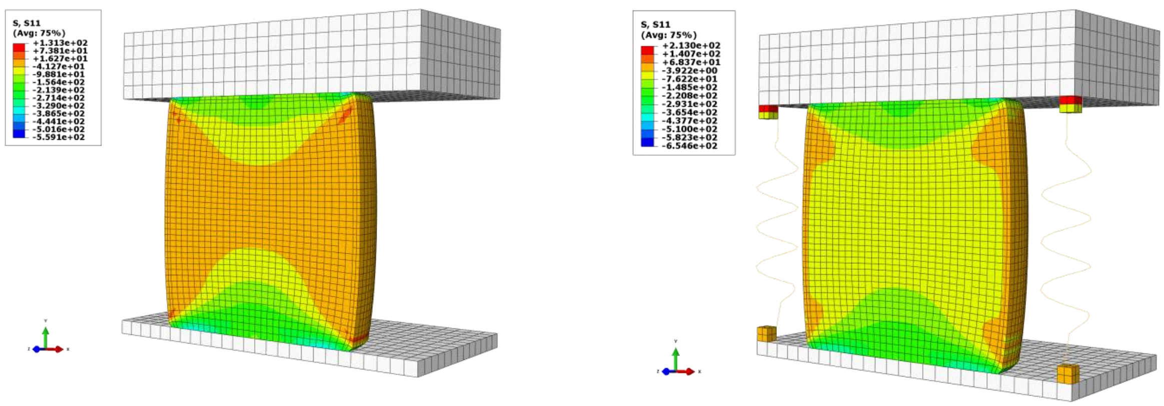

Fig. 2 Finite Element Model (left: basic model; right: simplified shock absorber model)

However, all results presented in the paper, in particular impact forces, refer to the full-model. Following the requirements of [1], a puncture bar diameter of 150 mm was chosen. The puncture bar was modeled by solid first-order hexahedral elements with reduced integration and an average element size of about 5 mm. The elastic material behavior of the puncture bar was characterized by a Young's Modulus E=210000 MPa and a Poisson's Ratio ν=0.3. Both values are typical for a mild steel. The plastic behavior was reproduced by exemplarily chosen strain rate dependent true stress versus logarithmic strain curves. In contrast to the fictitious minimum properties of the puncture bar steel (σ_y=150 MPa), specified in [1], it represents a real and purchasable mild steel. The FE part representing the package was modeled as a rigid body. To avoid problems in the numerical contact behavior caused by an excessive increase of the element density, the assumed package mass is represented by a point mass (20 Mg/150 Mg) attached to the rigid cuboid. At start of the simulation, the drop mass was positioned directly above the upper surface of the puncture bar. The drop height h was considered by initializing of the drop mass with the resulting impact velocity

$$v_0 = \sqrt{2 * g * h} \qquad (1)$$

where g is the gravity. The contact between the puncture bar and the mass was modeled as a surface-to-surface contact with a penalty contact formulation and a friction coefficient of μ = 0.2 (unlubricated steel/steel). This assumption contradicts the friction coefficient of μ = 0.05, chosen in the numerical calculation, presented in [3], on the basis of comparison of barrel shaping of the bar in the drop test and in the numerical calculation. However, it should be kept in mind that the drop test presented in [3] was carried out at a temperature of -40 °C. This led to an icy/frozen cask surface and to a possible reduction of the friction coefficient. For the comparative considerations in this paper the assumed friction coefficient of μ = 0.20 seems to be reasonable without further investigations. All translational degrees of freedom of the nodes at the lower surface of the bar were completely restrained. A rigid body to represent the target was added at the lower cylinder surface. For comparable results in the following numerical simulations, the buckling of the puncture bar is avoided by the symmetry conditions and an additional horizontal restraining of the nodes along the longitudinal axis of the bar. For the planned investigations considering the simultaneous contact of puncture bar and shock absorber two spring elements were added to represent the shock absorbers stiffness, Fig. 2 (right). Further details will be given in the relevant chapter. All calculations have been done with the dynamic FE code ABAQUS/Explicit® [2].

BASIC INVESTIGATIONS

In the first step a series of basic numerical calculations were performed. It should be mentioned again that the generated FE model simplifies the physical reality of the puncture bar drop test. The deformability of the package and its attachments are neglected and the impact occurs perfectly axial. Buckling cannot happen. Using the example of two different drop masses, 20 Mg and 150 Mg, the behavior of puncture bars of an initial length between 200 mm and 400 mm in increments of 10 mm were investigated where 200 mm stands for the minimum length required by [1]. Fig. 3 (left) shows a series of impact force curves depending on the initial puncture bar length for an exemplarily chosen drop mass of 20 Mg. The maximum impact forces caused by this drop mass are between 9144 kN (200 mm bar) and 7202 kN (400 mm bar).

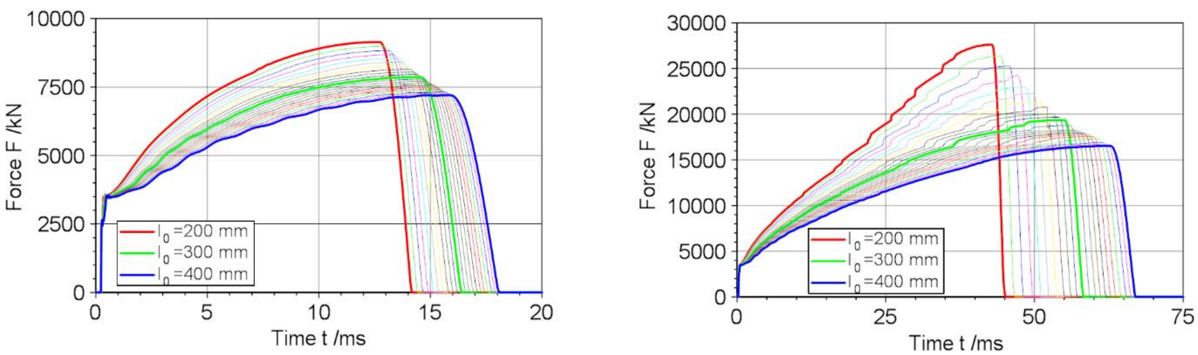

Fig. 3 Curves of impact force depending on initial puncture bar length (left: m=20 Mg; right 50 Mg)

Fig. 3 (right) shows the same analysis for a drop mass of 150 Mg. Maximum impact forces between 27690 kN and 16523 kN were generated in this case. It can be seen that the drop onto longer and hence softer puncture bars causes lower impact forces and higher impact durations. Even Fig. 3 shows the nonlinearity in dependency of the impact force on the initial puncture bar length L_0 but it can be much better visualized by the graphs in Fig. 4. It shows the normalized vertical deformation and the normalized maximum impact forces as a function of the initial puncture bar length in comparison of the two investigated drop masses. It is obvious that the higher mass causes a much higher variation in deformation as well as in impact force in the considered range. That means that the use of puncture bars longer than optimal for the particular case, cause a less decrease of impact force and a less increase of deformation at lower drop masses. The chosen limits of the y-axes make the principal trend for both drop masses more evident. The slope of the decreasing force as well as the slope of the increasing deformation become continuously smaller when the initial puncture bar length increases.

While the results presented in this chapter give only a first idea of the dependencies between initial puncture bar length, impact force and deformation and so an introduction of the issue, the following chapters deal with some special questions, derived from BAM experience in safety assessment of packages for the transport of radioactive material.

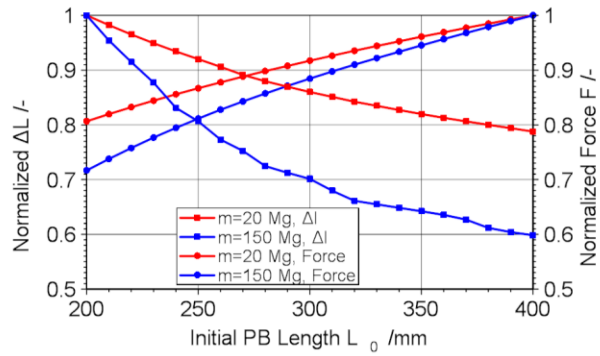

Fig. 4 Curves of normalized vertical deformation and impact force as a function of initial puncture bar length

PUNCTURE BAR LENGTH UNDER CONSIDERATION OF CASK OUTER SHAPE

As already mentioned above, [1] requires "…a bar (shall be) of solid mild steel, of circular section, 15.0 ± 0.5 cm in diameter and 20 cm long, unless a longer bar would cause greater damage, in which case a bar of sufficient length to cause maximum damage shall be used." This could be the case, e.g., if attachments like shock absorbers got in contact with the target and start to absorb energy before the maximum impact force between puncture bar and cask is reached. We assume that the requirement of [1] is fulfilled if the shock absorber or other parts of the package touch the target (but have not already started to absorb energy) just at the instant the maximum deformation and maximum puncture bar impact force have been reached. From this condition the optimal length of the puncture bar can be derived. If the safety assessment concept is solely based on verified numerical calculations, the initial puncture bar length to match this condition can be exactly estimated by an iterative calculation process. If the safety assessment concept includes drop tests and the optimal puncture bar length shall be defined by preliminary considerations, an exact estimation is hardly to get. In the current chapter it shall be discussed if and how variations in the puncture bar length could influence the reliability of drop test results in view of the most damaging test configuration.

If the puncture bar has been chosen too long, the dimension/size of resulting reduction of the maximum impact force can be calculated and assessed. If it has been chosen too short and the shock absorber has already touched the unyielding target before maximum impact force is reached, three cases are possible:

1. If the impact force of the shorter puncture bar reaches the maximum impact force of the optimal puncture bar before the shock absorber starts to absorb drop energy, the drop test can be accepted without further investigations.
2. A longer puncture bar certainly avoids the contact of shock absorber and target. The maximum impact force is always below the maximum impact force of the optimal puncture bar. Depending on the assessment concept and possible safety margins it must be decided, if the underestimation of the induced load can be accepted.
3. If the impact force of the shorter puncture bar does not reach the maximum impact force of the optimal puncture bar before the shock absorber touches the target, the residual drop energy will be absorbed by shock absorber as well. It must be investigated, if the maximum impact force could had been reached despite these unintentional absorbing of energy when bar deformation proceeds.

In a first step, cases 1 and 2 are discussed. It is assumed that the intended point of impact is outside of shock absorbing attachments, Fig. 1, Pos. 1. Therefore, an adaption of the effective drop height (see the next chapter) is not necessary. All simulations were performed using the nominal drop height of 1 m. The drop masses of 20 Mg and 150 Mg, used in the previous chapter, were considered again.

Based on the simulation results presented above, the residual length RL of the puncture bar (with the initial length L_0=300 mm) after drop test was defined as the height of a shock absorber H_{SA}. This definition is arbitrary and serves only to illustrate methodical aspects. That means, the 300 mm puncture bar reaches the maximum impact force in the moment, the shock absorber touches the target but has not already started to absorb energy. Based on our assumptions, it is supposed to be the optimal puncture bar length. The drop mass of 20 Mg led to a final residual length of the puncture bar, which is also equal to the assumed height of the shock absorber, RL (L_0=300 mm)=H_{SA}=264 mm, Fig. 5 (left). The drop mass of 150 Mg caused a residual length of RL (L_0=300 mm)=H_{SA}=152 mm, Fig. 5 (right).

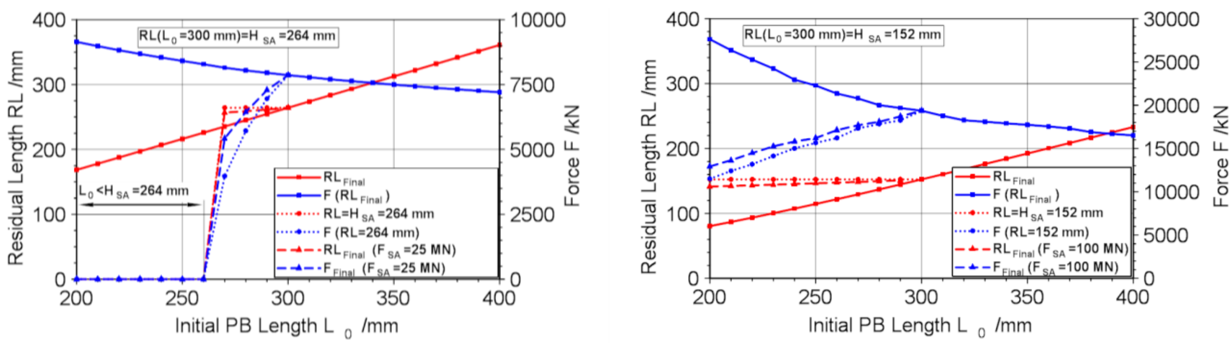

Fig. 5 Influence of imprecisely chosen puncture bar lengths on the impact force (left: 20 Mg; right: 150 Mg)

Starting from the maximum at L_0=300 mm, the curves of relevant impact forces decline in both directions. The supporting points of the solid blue curve on the right of L_0=300 mm represent the maximum forces caused from the maximum deformation of the puncture bar. The shock absorbers have not yet touched the target in these cases. The puncture bar would have been chosen too long. While the drop mass of 20 Mg led to a maximum force of 7863 kN with the optimal 300 mm bar length, the drop test onto a 400 mm length bar led to a maximum force of 7202 kN (-8.4 %), Fig. 5 (left)Fig. 5. The maximum forces of the dashed blue line on the left hand side correspond to the forces acting at the moment when the shock absorber just touches the target. It can be assumed, that the impact force would further increase when the deformation of the bar proceeds although the shock absorber starts to dissipate energy as well, the amount of absorbed energy and so the decay of load increase is hardly to quantify. In the area left of L_0=300 mm, the really expected maximum forces is somewhere between the both blue curves. Starting from a puncture bar length L_0≤264 mm, the indication of forces is not reasonable anymore because the shock absorber would touch the target before the puncture bar gets in contact with the cask.

The drop mass of 150 Mg, Fig. 5 (right), led to a maximum force of 19368 kN if it drops onto the optimal 300 mm length bar. The drop test onto a 400 mm length bar led to a maximum force of 16523 kN (-14.7 %). In contrast to the 20 Mg example, even the 200 mm length bar is long enough to come in contact with the cask before the shock absorber can touch the target. The impact force of 11504 kN means a percentage decrease of 40.6 %.

Case 3 ideally requires a detailed knowledge of the shock absorber material behavior at all possible load types and a comprehensive finite element material model able to reproduce them in a satisfactory manner. In spite of big efforts, e.g. [4], a suitable finite element model to fulfill all these requirements is not yet available for the wood filled shock absorbers. But, based on BAM's experience in analyzing and assessment of the 9-m-drop tests onto the unyielding target, performed with mounted shock absorbers, an alternative simple approach was developed to estimate the interaction between cask and puncture bar if the shock absorber simultaneously contacts the unyielding target. As mentioned above, the basic FE-model was extended by two pressure springs to represent the stiffness of the shock absorber. In the considered case the puncture bar drop is assumed to be the second test of a sequence. The already performed 9-m-drop has caused a pre-deformation of the shock absorbers. They are usually designed not to exceed an upper limit of final deformation of ca. 60 %. Their stress-strain/deformation curve runs approximately horizontal in this range (plateau). If a vertical drop is considered, position 3) in Fig. 1, and a constant deformation surface of shock absorber can be assumed, a constant reaction force under increasing deformation can be used for the springs. Derived from an established analytical approach developed to estimate the shock absorbers behavior, a constant force of 25 MN was assessed for the 20 Mg cask and a force of 100 MN for the 150 Mg cask.

As expected, the puncture bar is continuously deformed and its impact force increases in spite of the beginning target contact of the shock absorber. As the dashed blue lines in both diagrams in Fig. 5 show, the increase of the puncture bar forces thereafter keeps small due to the comparatively high stiffness of the shock absorber.

In the moment of shock absorber's first contact, a puncture bar force of F(RL=264 mm)=6957 MN was calculated for a puncture bar of 290 mm initial length (dotted blue line) and a cask mass of 20 Mg, Fig. 5 (left). After a further vertical deformation of only 2.8 mm a final impact force of $F_{Final}(F_{SA}=25\text{ MN})=7286$ MN (+4.7 %) is achieved if the simultaneous contact of shock absorber is considered. As already mentioned above, the indication of forces for puncture bar lengths $L_0 \leq 264$ mm is not reasonable in this case because the shock absorber would touch the target before the puncture bar gets in contact with the cask.

The drop mass of 150 Mg leads to a puncture bar force of F(RL=152 mm)=18254 MN in the moment of shock absorber's first contact for the puncture bar of 290 mm initial length (dotted blue line). While puncture bar and shock absorber starts to simultaneously deform, a final impact force of $F_{Final}(F_{SA}=100\text{ MN})=18714$ MN (+2.5 %) is achieved (dashed blue line). In the case of the 200 mm puncture bar, force increases from F(RL=152 mm)=11504 MN to $F_{Final}(F_{SA}=25\text{ MN})=12932$ MN (+12.4 %), while the deformation of the bar increases by 11 mm.

Under the current assumptions it can be stated, that the final impact force of the "exactly" chosen 300 mm puncture bar is not exceeded by the only 10 mm shorter 290 mm puncture bar that causes a beginning energy absorption of the shock absorber. Using the presented example of the 150 Mg cask, the comparison of some selected impact forces in Table 1 shows, that an underestimation of the maximum impact force cannot always be excluded, if the initial length of the puncture bar is chosen slightly longer to avoid a shock absorbers target contact. The initial puncture bar length of 300 mm would cause the maximum force. The residual puncture bar length exactly matches the height of the shock absorber. If a slightly longer initial puncture bar length of 320 mm or more is exemplarily chosen to safely avoid the shock absorbers target contact, an initial puncture bar length of 290 mm would cause a higher impact force of 18714 kN>18264 kN, in spite of the beginning absorption of energy by the deforming shock absorber. Comparing the run of the graphs in both diagrams representing the puncture bar impact forces for initial puncture bar lengths <300 mm, Fig. 5, it can be stated that the risk of underestimation of maximum force by choosing puncture bars much longer than necessary is more pronounced at higher drop masses.

Table 1: Selected impact forces (cask mass: m=150 Mg) according to Fig. 5 (right)

Initial PB Length	F (RL_{Final})	F (RL=152 mm)	F_{Final} (F_{SA}=100 MN)
…	…	…	…
320 mm	**18264 kN**	-	-
310 mm	18774 kN	-	-
300 mm	**19369 kN**	**19369 kN**	**19369 kN**
290 mm	-	18254 kN	**18714 kN**
280 mm	-	17826 kN	18090 kN
…	…	…	…

If accompanying finite element simulations are part of the package safety evaluation concept and if the utilization level of the criteria (e.g. stresses, strains) can be described as a continuously rising function of loads, the admissibility could be proved by the demonstration of sufficient safety margins. If a malfunction as the exceeding of the permissible leakage rate could abruptly appear, caused by the displacement of a lid after exceeding of a threshold static friction load, the consequences of a possible underestimation of puncture bar impact force must be critically assessed.

IAEA PUNCTURE BAR DROP TEST AS PART OF A DROP TEST SEQUENCE

"The order in which the specimen is subjected to the drops shall be such that, on completion of the mechanical test, the specimen shall have suffered such damage as will lead to maximum damage in the thermal test that follows…" [1]. Depending on the results of preliminary considerations are usually carried out, the puncture bar test can be performed as first or second part of a two-parts sequence consisting of a 9 m drop test onto the unyielding target and the puncture bar drop test itself. Depending on whether the puncture bar test is performed before or after the 9 m drop, the height of a deformed or undeformed shock absorber shall be considered.

While the previous chapters only addressed the effect of different initial puncture bar lengths, increasing effective drop heights shall be additionally considered now. If the intended point of impact is covered by e.g. an shock absorber, Fig. 1, Pos. 3, and the shock absorber is not explicitly considered in the numerical calculation of the drop test, the effective drop height and so the impact velocity shall be adapted [5]: "The height of the drop measured from the intended point of impact of the specimen to the upper surface of the bar shall be 1 m." [1]

Two sets of numerical simulations were performed to discuss the counteracting influence of increasing puncture bar length and increasing effective drop height. Two masses, 20 Mg and 150 Mg, were considered. Firstly, the calculations were performed assuming a fictitious height of the undeformed shock absorber of $H_{SA,initial}$=500 mm, Fig. 6. The 1 m distance between puncture bar upper surface and lower surface of drop mass was increased by addition of the shock absorber height

$$h_{eff} = h + H_{SA,initial} = 1.00\ \mathrm{m} + 0.50\ \mathrm{m} = 1.50\ \mathrm{m} \qquad (2)$$

In the FE simulation the drop height is considered by a drop mass impact velocity

$$v_0 = \sqrt{2 * 9.81\ \mathrm{m/s^2} * 1.50\ \mathrm{m}} = 5.425\ \mathrm{m/s^2}. \qquad (3)$$

Assuming an shock absorber deformation of 50 % after 9 m drop, the effective drop height is reduced to $H_{SA,initial}$*0.5=$H_{SA,res}$=1.25 m, Fig. 6, for the comparative analysis. Hence, the drop mass was initialized by an impact velocity

$$v_0 = \sqrt{2 * 9.81\ \mathrm{m/s^2} * 1.25\ \mathrm{m}} = 4.952\ \mathrm{m/s^2}. \qquad (4)$$

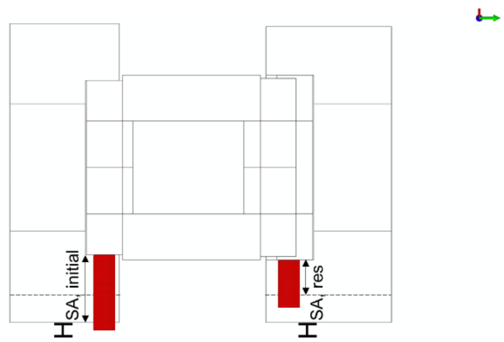

Fig. 6 Puncture bar length depending on shock absorber height

The initial puncture bar length that finally leads to a residual puncture bar length equal to the shock absorber height was chosen by an iterative process (Note: The findings of the previous chapter concerning simultaneous contact of shock absorber and puncture bar are not considered in this case.). The lengths of 560 mm and 290 mm were used with a drop mass of 20 Mg, 780 mm and 450 mm with 150 Mg.
Fig. 7 shows the results of the comparative analyses for both masses. First, it can be concluded, that the puncture bar lengths were correctly chosen in all cases. The residual lengths meet exactly the respective heights of shock absorber. Furthermore, it can be stated, that the higher amount of kinetic energy caused by the increased drop height does not compensate the lower stiffness of the longer puncture bar. In both exemplary cases, the shorter bar and the less drop height generate significantly higher impact forces.

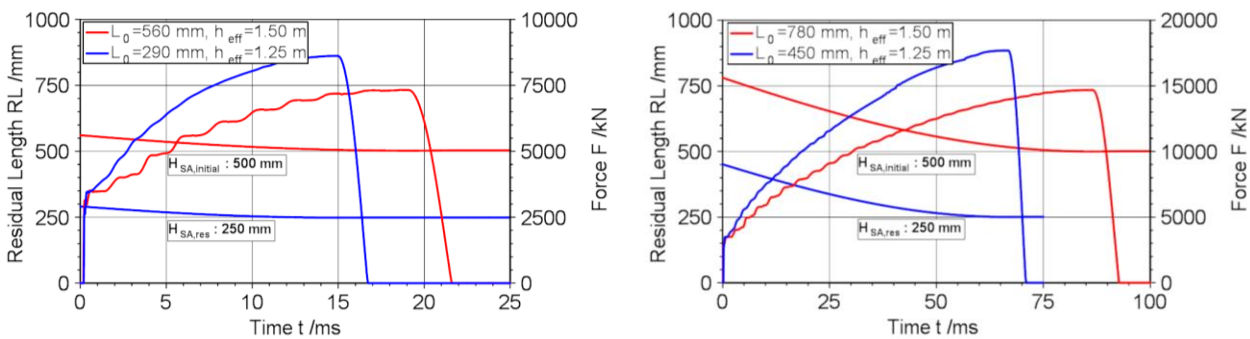

Fig. 7 Impact force under the counteracting influence of initial puncture bar length and effective drop height (left: m=20 Mg; right: m=150 Mg)

CONCLUSION AND OUTLOOK

Accident safe packages for the transport of radioactive material shall withstand mechanical and thermal test scenarios defined in [1]. The mechanical tests consist of a sequence of at least two different drop tests, the 9 m drop onto an essentially unyielding target and a 1 m drop onto a steel puncture bar. While the properties of the unyielding target for 9 m drops are sufficiently described, only the minimum length (≥200 mm) and the exact diameter of the puncture bar are defined. If it caused greater damage, a longer bar shall be used. Therefore, preliminary considerations are necessary to estimate the most damaging order of the tests as well as the optimal length of the bar.

The paper describes and systemizes different problems and questions frequently occurring in package design approval procedures. For this purpose, different numerical simulations using a simplified dynamic ABAQUS®/Explicit analysis were carried out and presented. To give an overview of the dependencies between initial puncture bar length, impact force and deformation, basic investigations using two exemplary drop masses and a series of different puncture bar lengths were performed.

The difficulties are described which could occur if the puncture bars optimal length has to be estimated under the consideration that the shock absorber potentially gets in contact with the target. It is discussed how to handle and assess deviations on the optimal length and so on the maximum impact force. With the aim to estimate the influence of possible contact between shock absorber and target on the puncture bars force, a simple approach is presented to consider the simultaneous contact of puncture bar and shock absorber.

If the intended point of impact is covered by a shock absorber and the shock absorber is not explicitly considered in the numerical simulation due to the lack of reliable FE material models, the nominal drop height of 1 m as well as the puncture bar length shall be increased under consideration of its thickness. Two series of numerical simulations were performed to discuss the counteracting influence of increasing puncture bar length and increasing effective drop height.

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