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RESEARCH ARTICLE

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Development of an analysis and testing concept for the evaluation of impact targets in the mechanical safety testing of dangerous goods packagings

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Abstract

The mechanical and geometrical properties of impact targets greatly influence the outcome of a drop test. The International Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) as well as ISO 2248 describe the characteristics of impact targets for drop tests of dangerous goods packagings. According to these regulations, the impact target's surface needs to be unyielding, under testing conditions non-deformable, flat and integral with a mass at least 50 times that of the heaviest packaging to be tested. The problem is that many production facilities, especially manufacturers of corrugated fibreboard boxes, do not have their own testing device with the required 50 times mass ratio of the impact target for a regulation compliant drop test during series production. Furthermore, at UN level, it is considered necessary to revise these requirements. In the present paper, the impact target requirements are examined in detail and compared with those in other technical areas (e.g., impact target for container for the transport of radioactive materials). A research method is being developed to investigate the dependency between the mass ratio of the packaging and the target as well as the damage resistance of a drop tested package in relation to specific design characteristics. The results are of high relevance for industry purposes and intended to ensure a uniform level of safety assessment for the mechanical testing of dangerous goods packagings.

KEYWORDS
corrugated fibreboard boxes, dangerous goods packagings, drop test, impact target, structural dynamics

1 | INTRODUCTION

The suitability of packagings for the transport of dangerous goods is evaluated by means of design type tests, as prescribed by the UN Model Regulations 6.1.5[1] and the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) 6.1.5.[2] Vertical impact tests by dropping of complete, filled transport packagings are conducted to assess the ability of a package to withstand damage in a distribution system where vertical impact is possible. In drop tests, the packaging to be tested gets decelerated due to the impact on an essential unyielding target. Hereby, the impact surface used in regulation compliant drop tests must meet certain criteria which are described in ISO 2248[3] and referred to in ADR 6.1.5.3,[2] respectively.

The impact surface must be flat and massive to be considered as immovable, rigid and non-deformable under test conditions. One of the central requirements of standards[2,3] is that the impact pad must have a mass at least 50 times that of the heaviest packaging to be tested. Further details regarding the influence of dynamic processes occurring on impact are not being considered. The problem is that many production facilities do not possess specific foundations for drop tests with the required 50 times mass ratio, although according to ADR the tests during series production must be carried out at the same level as the design type tests. This topic has also been dealt with several times at UN level. At the 30th Sub-Committee of Experts on the Transport of Dangerous Goods,[4] many delegations pointed out that the physical characteristics of impact targets affect the drop test results significantly. Therefore, it was suggested for standardization. The relevance of this topic was stressed again at the 59th Sub-Committee of Experts on the Transport of Dangerous Goods[5] when the necessity of revision of the requirements for the impact target in ADR 6.1.5.3.4 was discussed.

This paper addresses the development of an analysis and testing concept for the evaluation of targets for the mechanical safety testing of dangerous goods packagings. Thus, the mechanical response in drop tests of different target-packaging constellations will be examined. So far, no sufficient data seem to be available concerning the influence of the mass ratio on the damage resistance of a certain packaging design. Impact targets made of mild steel with different thicknesses and total masses, and consequently mass ratios to the tested packagings, shall be investigated experimentally. This approach enables directly to evaluate the influence of the mass ratio on the damage resistance of a packaging under otherwise identical conditions. Further on, numerical finite-element-method (FEM) computations and analytical models will assist in evaluating impact target characteristics of drop tests with different input parameters (e.g., mass ratio, stiffness and drop height). The aim is to determine how applicable the current specifications in the relevant dangerous goods regulations are[2,3] and whether these assumptions can be refined or further developed by additional technical criteria.

For some fibreboard box manufacturers in Germany non-compliant drop target designs have been identified when collecting statistical data of 21 manufacturer facilities. Therefore, this experimental and analytical research is focused on drop tests with corrugated fibreboard boxes. Due to the different materials and mechanical behaviour, drop tests with steel drums will also be evaluated.

The goal of this paper is to

- analyse the requirements for impact targets in comparable technical applications in consideration with dimensioning and design criteria (Section 2),
- and to propose an analysis and testing concept (Section 3), by means of experimental setup (Section 3.1) as well as numerical FEM models (Section 3.4) for evaluating impact targets in their eligibility to assess the damage resistance of dangerous goods packagings within drop tests (Section 4).

The results are intended to support the revision of the requirements for impact targets in the dangerous goods regulations.

2 | REQUIREMENTS FOR IMPACT TARGETS FOR DROP TESTS OF DANGEROUS GOODS PACKAGINGS

According to international dangerous goods regulations (ADR 6.1.5.3[2]), each packaging design must be tested by means of a free drop onto an unyielding target. As defined in ISO 2248,[3] four requirements need to be fulfilled for every impact surface used in design type drop tests:

1. The impact target's mass must be at least 50 times larger than that of the heaviest package to be tested,
2. the flatness deviation of the impact surface shall not be greater than 2 mm,
3. the target should not be deformed by more than 0.1 mm when a 10-kg static load is applied on an area of 100 mm^2 anywhere on the surface (rigidness), and lastly,
4. the surface area needs to be sufficiently large so that the package falls entirely upon it.

In comparison to the generalized requirement of the 1:50 mass ratio in ISO 2248, there are postulated further evaluation criteria in safety related technical areas. For example, for transport packages of radioactive materials, the international IAEA Specific Safety Standards[6,7] include detailed requirements concerning testing in accordance with hypothetical and most severe accidents as well as the design and properties of impact targets. Herein, the target for drop tests is characterized as essential unyielding and having a rigid impact surface if it causes damage to the package which would be equivalent to, or greater than, that anticipated for impacts on to actual surfaces or structures which might occur during transport (§717.1[7]). Furthermore, the combined mass of a reinforced concrete foundation with a solidly anchored steel impact plate should be at least 10 times that of the specimen for the tests (§717.2[7]). This mass ratio between target and RAM transport packaging is substantially smaller than the value defined for dangerous goods packagings in the ADR.

For the drop testing facility at the Federal Institute for Materials Research and Testing (BAM), the rigidity of the impact target with a combined mass of approximately 15 and 20 times that of the specimen respectively was investigated by drop tests within type design approval.[8] The assessment is based on the evaluation of the kinetic energy conversion at drop impact for various full-scale test containers. The combined absorbed energy amount from target and ground was lower than 2% of the total energy in the system. This means that in the observed drop tests, more than 98% of the energy got converted into deformation energy of the container. In this case, the main criterion for evaluating the impact target as unyielding rests on the absorbed energy amount and not on a specific mass ratio value.

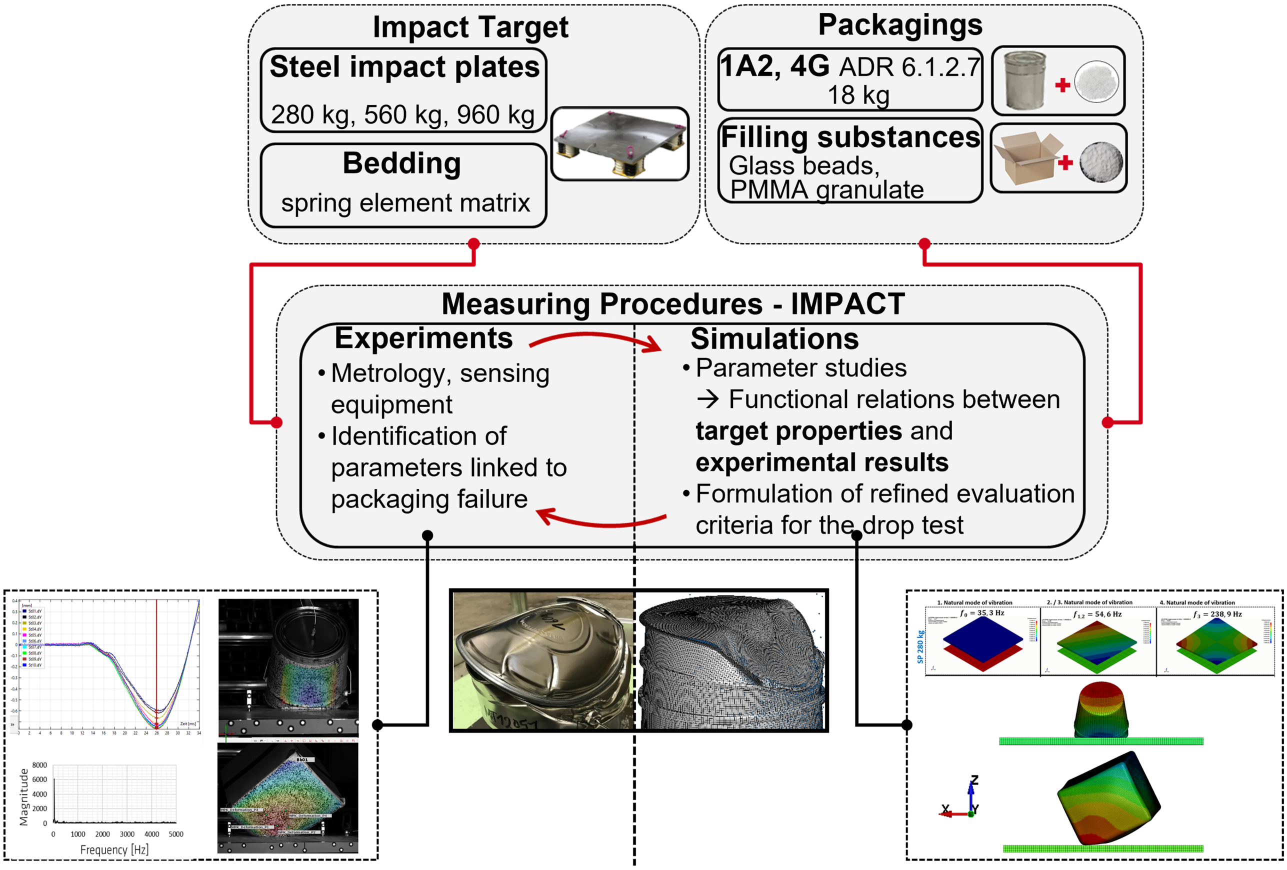

FIGURE 1 Research method—Examination of drop tests for the evaluation of impact targets

Based on further drop test analyses conducted at BAM within design approval procedure of RAM transport packagings, for example, in other studies,[9–13] a drop target can be characterized as essentially unyielding regarding IAEA Safety Regulations[6] if approximately 95% of the kinetic energy in a drop test gets absorbed by the transport packaging and converted into deformation energy.

3 | DEVELOPMENT OF AN ANALYSIS AND TESTING CONCEPT

The analysis and testing concept to be developed shall provide proof for the validity of various and combined characteristics of the target and packaging. To achieve this goal, the drop tests to be conducted are based on three major components, as shown in Figure 1.

The first component is the impact target, consisting of three steel plates with different masses which shall be mechanically decoupled from the ground. The second component is represented by the packagings with a fixed gross mass to satisfy mass ratios of 1:15, 1:30 and 1:50 with regard to the mass of the impact pad. These two components are linked by the impact which is measured and simulated. The drop test foundations are equipped with sensors (accelerometers and optical sensors) which make the data acquisition of the impact kinematics possible and help to identify influencing factors responsible for packaging failure. The FE models of the drop test will be validated by means of experimental results. The validated FE models can then be used for various computational parametric studies to obtain functional relations between target properties and experimental results. This leads to a formulation of new evaluation criteria for the drop test which can be, in turn, investigated and validated experimentally.

3.1 | Experimental setup for the evaluation of impact targets

For the reproducible examination of interactions between impact target and packaging in regulation compliant drop tests, steel plates with masses of 280, 560 and 960 kg are used. In order to minimize force transmission to the ground during impact, a low damping spring system for low tuning is preferred as a bedding.[14] Thereby, each plate shall be placed on a bedding of five high-strength spring elements and therewith mechanically decoupled from the ground, as depicted in Figure 2. The clear mechanical definition of the bedding properties ensures that defined mass ratios of 1:15, 1:30 and 1:50 to the test object mass (approx. 18 kg) are examined as independent input parameters of the system.

Each set of spring elements is preloaded by a compression of 5 mm to guarantee a static vertical deflection of the respective plate

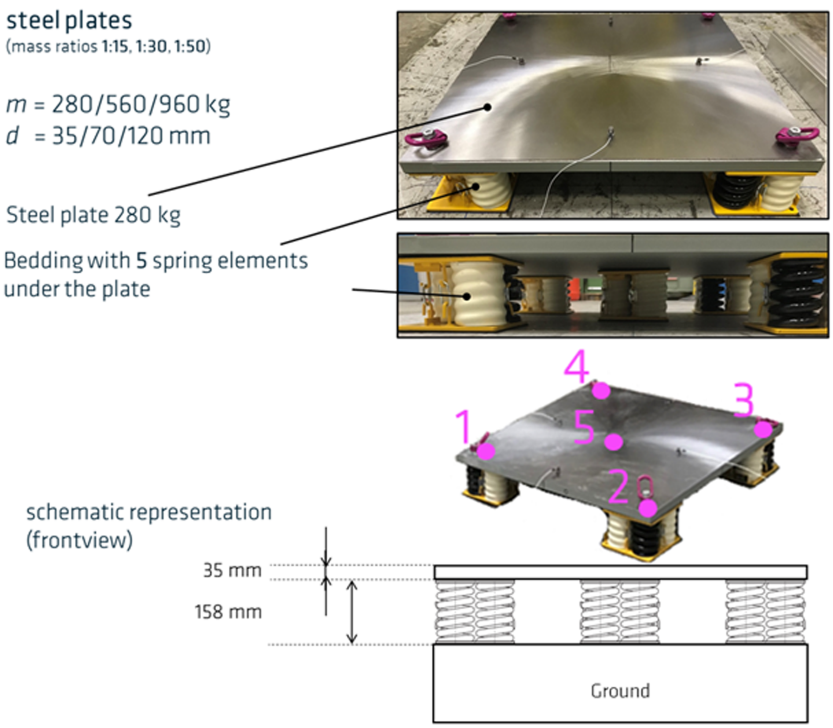

FIGURE 2 Foundation with spring elements

TABLE 1 Impact target technical data

	Steel plate 280 kg	Steel plate 560 kg	Steel plate 960 kg
Mass ratio	1:15	1:30	1:50
Dimensions—steel plate (L × W × H) (mm)	1000 × 1000 × 35	1000 × 1000 × 70	1000 × 1000 × 120
Dimensions—spring element (L × W × H) (mm)	220 × 220 × 158	220 × 220 × 158	220 × 220 × 158
Vertical spring stiffness, k_V (kN mm^{-1})	2.94	2.68	2.42
Static vertical deflection (mm)	~0	~0	~0

close to zero. The geometric and physical properties of each spring element set are shown in Table 1.

In the following, materials, methods and validation of the test setup with respect to the requirements (see Section 2) are presented. A statement regarding the necessity of the mass ratio of 1:50 (requirement 1) or the revised requirement (see Section 4.1) can only be made after evaluating systematic series of drop tests to determine the 50% failure drop height. However, the necessity of revision of the mass ratio requirement is substantiated based on comparative data from design type drop tests onto the proposed model impact targets and an essentially unyielding target (see Section 4.1).

3.2 | Materials and methods

The packaging types are coded according to ADR 6.1.2.7[2] as 1A2 for steel drums with removable heads and 4G for fibreboard boxes. The substitute filling substances used for the drop test should fulfil certain requirements, for instance:

- good flow properties, such as a low angle of repose, ensure a larger damage effect on impact,
- the bulk density of the materials needs to correspond to the available inner volume of each packaging type to achieve the intended gross mass of 18 kg while satisfying a 95% filling degree according to regulations (ADR 6.1.5.2.1[2]),
- the substances should be homogeneous and monodisperse with a spherical grain shape to reach test reproducibility, comparability, and minimization of numerical modelling effort.

Table 2 shows the data for the packagings, and Table 3 shows the corresponding substitute filling substances.

An appropriate statistical testing method to evaluate the influence of the mass ratio on the drop test is provided by the 50% failure drop height. This is given by the height from which a packaging fails with a probability of 50%. The value is determined by the Bruceton method.[16] Menrad[17,18] examines and analyses the 50% failure drop heights of jerrycans with a volume of 22 L made of different materials according to the Bruceton method in guided drop tests on the

TABLE 2 Packaging characteristics

Packaging type	Inner volume (L)	Tare weight (kg)	Dimensions (mm)	
1A2	10	0.84	Nominal thickness	Body: 0.27
				Bottom: 0.26
				Removable head: 0.34
				Clamping ring: 1.00
4G	40.9	0.831	Exterior (L × W × H)	382 × 382 × 330
			Interior (L × W × H)	368 × 368 × 302

TABLE 3 Substitute filling substances

			Angle of repose (°) (DIN ISO 4324[15])	
Substance name	Manufacturer	Bulk density, ρ_b (kg/L)	Mean value	Std. dev.
Diamond pearls (polished and thermal tempered glass beads)	Mühlmeier GmbH & Co. KG, Bärnau, Germany	Specification of manufacturer: 1.49	26.02	0.67
Esplas H130 (polymethyl-methacrylate granulate)	KSL Staubtechnik GmbH, Lauingen, Germany	Specification of manufacturer: 0.49	35.98	0.43

jerrycan side wall. However, this test series was not focussed on the variation of the impact target. In the first interlaboratory comparison of UN-approved dangerous goods packagings, the 50% failure drop height was also used for various packaging design types[19] using the Bruceton method. Fifteen laboratories from 13 countries were involved in the investigations. There were extreme differences in the 50% failure drop height results for identical drop positions which could be attributed to the different impact pads used at each laboratory. A systematic examination of the influence of the impact target on the 50% failure drop height of dangerous goods packagings has not been yet conducted.

3.3 | Instrumentation—Drop test

The mechanical response to impact of the target is captured by means of acceleration measurement. Information regarding rigid body impact acceleration, rigid body impact kinematics of the target during impact (velocity and deflection history), impact duration, vibration frequencies and response spectra is provided in form of continuous acceleration-time histories at the monitored locations of the impact surface. Uniaxial accelerometers with an amplitude range of ±50 and ±10 g, respectively, and a frequency range up to 10 000 Hz are mounted magnetically on the impact surface, so that the measuring direction of each sensor is in line with the motion vector of the target. The expanded measurement uncertainty of the acceleration measurement results is approximately ±2%. The rigid body impact behaviour of the target can be described by its low pass filtered acceleration-time history using an appropriate cut-off frequency at a sampling rate of 10 kHz. The cut-off frequency was set at 3 kHz after transferring and analysing the acceleration-time data from time domain to frequency domain by fast Fourier transformation (FFT).

3.4 | FEM vibration analysis

The numerical simulations are developed and computed using LS DYNA software. By means of preliminary simulative studies, the behaviour of the impact target was examined. The steel plates are modelled as isotropic elastic with a fine homogeneous mesh of solid hexahedral elements. The spring elements are modelled as discrete one-dimensional elements defined by the spring constant in vertical direction, safely assuming that loads in other directions are negligible. A rigid plate modelled with shell elements is used for the ground. The nodes connecting the springs to the impact plate can move in z-direction only while no rotations are allowed. The ground is considered unyielding; hence, all translations and rotations are constrained.

A free vibration eigenvalue analysis of the target structure yields that the first natural mode (vertical rigid body motion) has the main influence on impact kinematics. If the impact does not happen on the centre of the impact surface in accordance with the load line, then the second or third mode (rigid body tilting, possible in two directions) has also a significant influence. A small amount of bending vibration is also present due to the fourth and fifth modes (see Figure 3).

The participation of each mode in the vibration analysis is determined by examining the effective masses of the extracted modes.[20] Rigid body motion modes are responsible for having over 90% participation in excitation in z-direction for all impact targets. The bending modes of vibration, depicted in Figure 3, exhibit a very low percentage of participation respectively. They are the influencing factors in

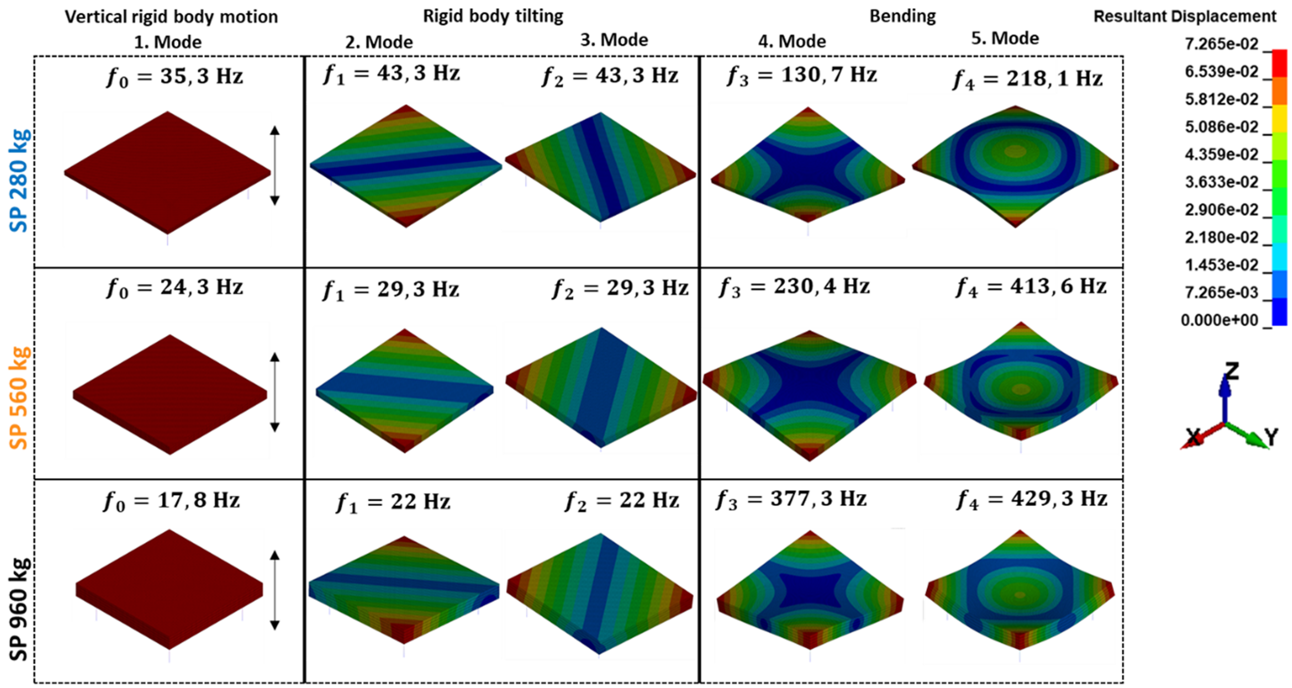

FIGURE 3 FE simulation results for the first five undamped natural modes of vibration of the impact targets

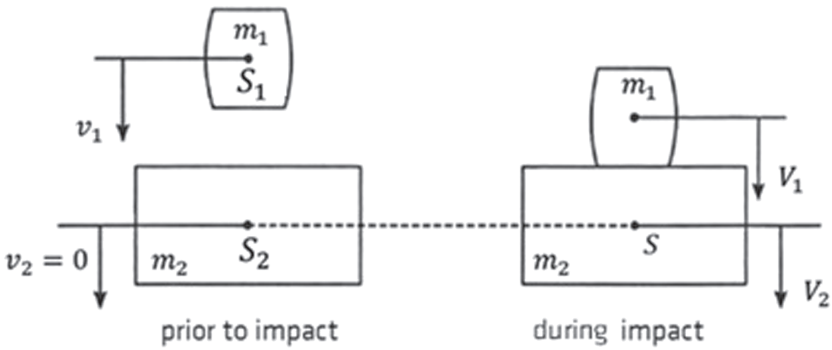

FIGURE 4 Analytical model for an ideally plastic impact behaviour between packaging and target[21,22]

the elastic deformation of the impact surface. Higher frequency modes have a negligible effect. Thus, the amount of target movement due to elastic deformation is significantly smaller than that due to rigid body motion. These results are validated and utilized when evaluating data of experimental drop tests (see Section 4.1).

4 | RESULTS—VALIDATION OF THE EXPERIMENTAL SETUP

The conformity of the experimental setup to regulations and standards[1–3] is examined. Each requirement (see Section 2) is investigated thoroughly regarding the proposed impact targets. Furthermore, results of experimental design type drop tests of packagings onto the model impact targets are presented.

4.1 | Requirement 1—Mass ratio between target and packaging

According to the first requirement presented in ISO 2248, the impact target's mass must be at least 50 times larger than that of the heaviest package to be tested. An alternative evaluation criterion for targets for drop tests regarding the ADR can be formulated, as described in Sperber et al.,[21] where a threshold of kinetic energy that goes into target motion is defined. A simple analytical model with one degree of freedom is used for this purpose, as shown in Figure 4. The target consists of a rigid steel plate, whereas the impact of packaging upon target is considered to behave ideally plastic.

The law of conservation of energy yields a ratio, denoted with δ, which represents the percentage of impact energy that goes into the motion of the impact target (Equation 1).

TABLE 4 Energy amount in target motion δ in experimental regulative drop tests

Target	Mass ratio	Energy amount in target motion, δ (%)	
		Steel drum (1A2)	Fibreboard box (4G)
Steel plate 280 kg with spring elements	1:15	0.553	0.038
Steel plate 560 kg with spring elements	1:30	0.337	0.011
Steel plate 960 kg with spring elements	1:50	0.210	0.007
Reinforced concrete foundation with steel plate (standard)	1:10 000	~0	~0
Impact pad—analytical model according to ISO2248 (limit)	1:50	1.960	

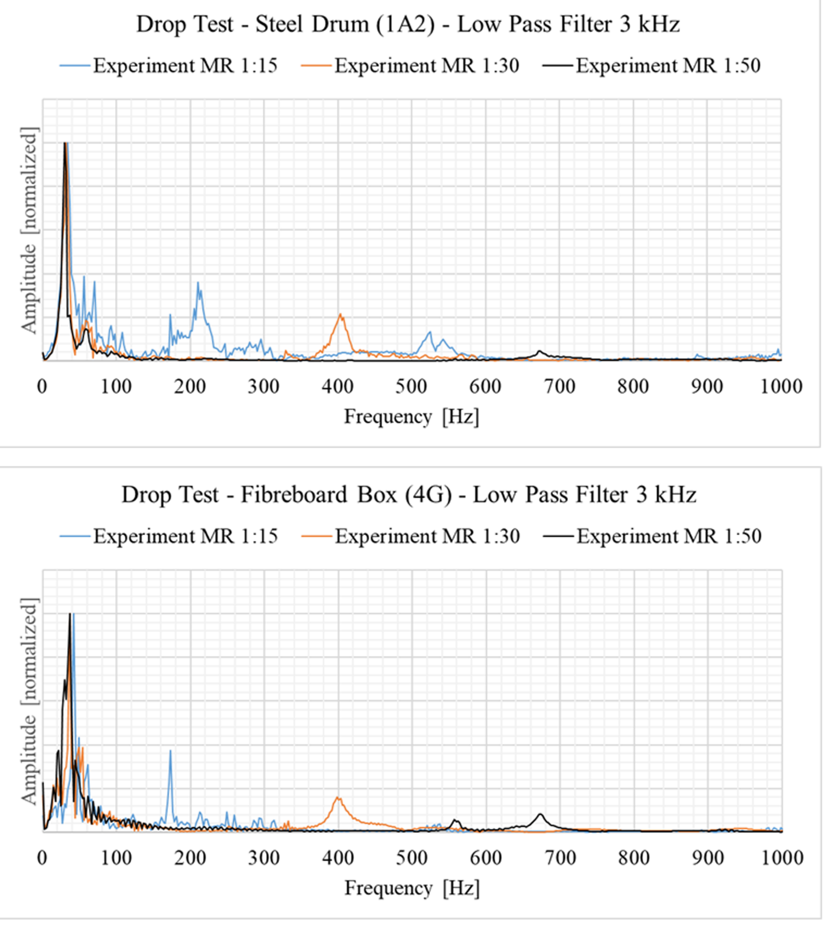

FIGURE 5 Frequency spectra for drop tests with steel drums (up) and fibreboard boxes (down)

$$\delta = \frac{E_{kin,di}}{E_{kin,pi}} = \frac{(m_1 + m_2)V_2^2}{m_1 v_1^2} \quad (1)$$

The law of conservation of momentum yields furthermore,

$$V_1 = V_2 = \frac{m_1}{(m_1 + m_2)} v_1 \quad (2)$$

which leads to

$$\delta = \frac{m_1}{(m_1 + m_2)} \quad (3)$$

Equation (3 can be used for different mass ratios in drop tests. For the mass ratios of 1:15, 1:30 and 1:50, the energy amount in motion of the impact target δ is calculated as 6.25%, 3.23% and 1.96%, respectively. Since the first requirement in the regulations[3] refers to a mass ratio of 1:50, a threshold of $\delta_{ISO2248} = 1.96\%$ can be set. This value is compared against the respective experimentally

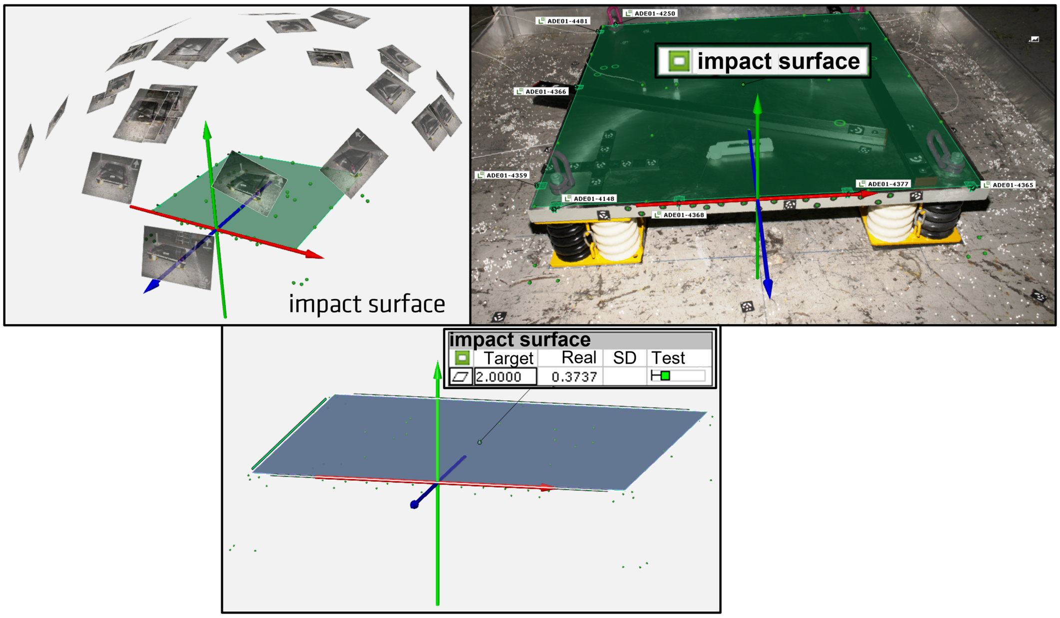

FIGURE 6 Digital reconstruction of the steel plate impact surface (280-kg steel plate)

derived δ for different impact target-packaging drop test constellations. Table 4 shows the results for δ out of eight design type drop tests at a drop height of 1.2 m (ADR 6.1.5.3.5[2]) onto different targets. The experimental values for δ are calculated according to Equation (1), utilizing velocity data by means of numerical integration of the captured acceleration-time histories for each drop test (see Section 3.3). Thereby, the velocity value V_2 is the first maximum value of the velocity-time history during impact. The drop position (ISO 2206[23]) was chosen to be on a corner (top corner/manufacturer's joint) to achieve the highest damage effect. The total mass of each package was 18 kg. All packages passed the drop test successfully. All test parameters for both packaging types except for the mass ratio were kept identical.

The computational vibration analysis with FEM yields that target motion due to elastic deformation is very small compared to that due to rigid body motion (see Section 3.4). This is validated when transferring the measured acceleration-time histories of the drop tests from time domain to frequency domain by means of FFT. Figure 5 depicts acceleration data as a function of frequency. The clear peaks happen at the corresponding frequencies responsible for rigid body motion modes. Smaller peaks due to bending vibration are also present, predominantly in drop tests with mass ratio of 1:15.

Thus, the strain energy of each impact target is very small in proportion to kinetic energy. In all cases presented in Table 4, more than 99% of the impact energy is converted to deformation energy of the packaging. These results support the need for revision of the first requirement. Based on the energy amount in target motion δ values, lower mass ratios than 1:50 fulfil the criteria for assessing damage resistance of dangerous goods packagings.

4.2 | Requirement 2—Flatness of impact surface

According to the second requirement presented in ISO 2248, the flatness deviation of the impact surface shall not be greater than 2 mm. The flatness is measured by means of digital photogrammetry of the impact target structures. By digitally reconstructing the impact surface using 25 predefined points on the structure's geometry, a flatness deviation value can be derived. This method is illustrated by the example of the 280-kg steel plate structure in Figure 6.

The calculated flatness deviation is presented in Table 5 and compared to the 2-mm tolerance. This method was used for every impact target structure consisting of 280, 560 and 960 kg steel plates with the corresponding sets of spring elements.

The second ISO 2248-requirement is hereby verified for the proposed impact target structures.

4.3 | Requirement 3—Rigidness of impact surface

The third ISO 2248-requirement states that the impact surface shall be rigid enough so that it will not be deformed by more than 0.1 mm when a 10-kg static load is applied on an area of 100 mm^2 anywhere on the surface. This provides no information regarding the dynamic properties of the system. However, an equivalent minimum required spring stiffness coefficient $k_{ISO2248}$ can be derived using an analytical model with one degree of freedom in vertical direction of a rigid impact pad resting on a vertical spring. By applying static force equilibrium on the static load referenced in the standard, then Equation (4) yields[21]:

TABLE 5 Validation of the second requirement for the impact target in ISO 2248

	Steel plate 280 kg	Steel plate 560 kg	Steel plate 960 kg
Mass ratio	1:15	1:30	1:50
Flatness actual value (mm)	0.34	0.25	0.22
Flatness tolerance ISO 2248 (mm)	2.00		

TABLE 6 Validation of the third requirement for the impact target in ISO 2248

	Steel plate 280 kg	Steel plate 560 kg	Steel plate 960 kg
Mass ratio	1:15	1:30	1:50
Total spring stiffness, k ($\mathrm{N\,mm^{-1}}$)	14 700	13 400	12 100
Spring stiffness, $k_{ISO2248}$ ($\mathrm{N\,mm^{-1}}$)	1000		

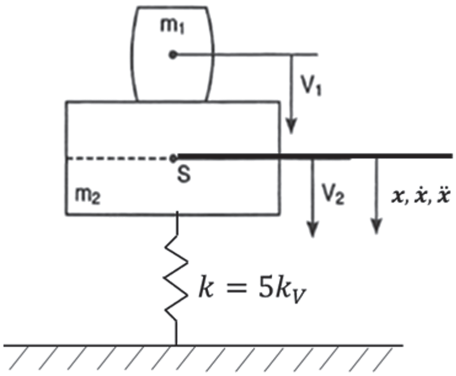

FIGURE 7 Analytical model for the dynamic structural response[21,22]

$$k_{ISO2248} = \frac{m \cdot g}{x_{max}} = \frac{10\,\mathrm{kg} \cdot 9.81\,\mathrm{ms^{-2}}}{0.1\,\mathrm{mm}} = 1000\,\mathrm{N\,mm^{-1}} \tag{4}$$

The same type of calculation can be done for the experimental setup presented in this paper. Since the spring elements are connected in parallel for each structure, the total spring stiffness per steel plate is given by adding the respective spring coefficients of each set of five spring elements. The total spring stiffness must be larger than 1000 N mm^{-1}, which is fulfilled and therewith the third ISO 2248-requirement, see Table 6.

Utilizing the spring stiffness coefficient $k_{ISO2248}$, the third requirement in ISO 2248 can be extended to determine the dynamic properties of the impact target, specifically for calculating the maximal admissible rigid body dynamic vertical deflection values in a drop test. Neglecting damping and assuming the impact of the packaging happens on the centre of the plate, then the first natural mode of vibration (vertical rigid body motion) of the structure is excited. The analytical model, shown in Figure 7, is used to calculate the dynamic vertical deflection of each impact pad for various drop heights.

The impact is assumed to behave as ideally plastic (material) with corresponding velocities $V_1 = V_2$ (see Equation 2) during impact. The ordinary differential equation yields for straight homogeneous motion the following equations.[22]

$$x(t) = X \cdot \sin(\omega_0 t) \tag{5}$$

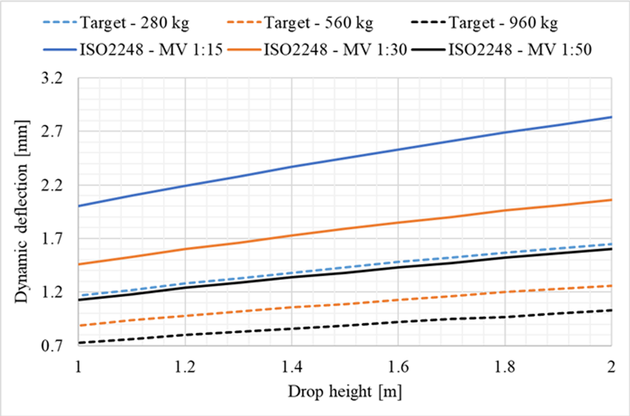

FIGURE 8 Drop height vs dynamic deflection; comparison between experimental setup and ISO 2248

$$\dot{x}(t) = X \cdot \omega_0 \cdot \cos(\omega_0 t) \tag{6}$$

With angular natural frequency ω_0

$$2\pi f_0 = \omega_0 = \sqrt{\frac{5 \cdot k_V}{m_1 + m_2}} \tag{7}$$

The first natural frequency f_0 responsible for the mechanical response of the impact pad in terms of rigid body motion can be determined. According to Equation (7, the values for the natural frequency f_0 are calculated at 35.3, 24.3 and 17.8 s^{-1} for the targets with mass ratios of 1:15, 1:30 and 1:50, respectively. The initial condition yields the maximum dynamic vertical deflection X.

$$\dot{x}(0) = X \cdot \omega_0 = V_2 \tag{8}$$

In Figure 8, the maximum dynamic deflection values at different drop heights are compared between the ISO 2248 and the impact targets of the experimental setup. The values for each impact target structure resting on the proposed bedding of corresponding spring elements are lower than those resting on an equivalent bedding with a stiffness given by the derived spring stiffness coefficient $k_{ISO2248}$. Therefore, the extended dynamic requirement is fulfilled as well.

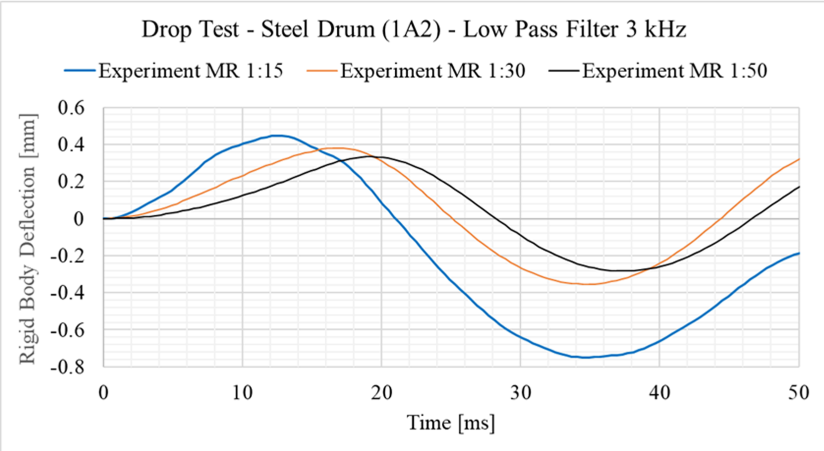

FIGURE 9 Dynamic deflection of impact targets

TABLE 7 Dynamic deflection of test packages in regulative drop tests

Target	Mass ratio	Maximum dynamic deflection (mm)	
		Steel drum (1A2)	Fibreboard box (4G)
Steel plate 280 kg with spring elements	1:15	0.447	0.211
Steel plate 560 kg with spring elements	1:30	0.381	0.158
Steel plate 960 kg with spring elements	1:50	0.330	0.138
Reinforced concrete foundation with steel plate (standard)	1:10,000	0.080	0.001
Impact pad—analytical model according to ISO2248 (drop height of 1.2 m, see Figure 8)	1:50	1.240	

Experimentally, more complex interactions during impact are recorded influencing the mechanical response like material properties or damping which affect the mechanical response. This simplified analytical model does not, for example, consider differences in impact characteristics between different packaging types which are relevant for impact kinematics. Nonetheless, it can be used to define a dynamic deflection limit with which experimental and simulative data can be compared.

Figure 9 depicts typical sinusoidal target deflection characteristics for one period of vibration T (from first moment of contact between steel drum and impact surface). The deflection curves are derived by numerically integrating the acceleration data of drop tests (see Section 4.1) twice.

In Table 7, the maximum dynamic deflections at the first velocity zero crossing between the experimental drop tests and the analytically derived maximum dynamic deflection at a drop height of 1.2 m are compared for the two packaging types.

The impact of the steel drum packaging onto the 280-kg steel plate has the highest dynamic deflection value at 0.447 mm which amounts to 36% of the analytically defined limit for a mass ratio of 1:50. Thus, mass ratios lower than 1:50 fulfil the deflection criteria as well.

5 | CONCLUSION

There is a need to review and adjust the requirements for the impact target for carrying out regulative drop tests of dangerous goods packagings. This results on the one hand from the need for consistent regulations, which has already been discussed at UN level, and on the other hand from the fact that many manufacturing companies, especially those of corrugated fibreboard boxes, do not meet the current requirements during series production. For this reason, the aim of this work is to propose an analysis and testing concept for the evaluation of impact targets in the mechanical safety testing of dangerous goods packagings. The investigations consist of collecting data on relevant drop tests, carrying out experiments under defined drop test conditions as well as performing FE calculations for the simulation of impact loading and mechanical failure.

A comparison with the requirements in other technical areas shows that the mass ratio does not necessarily have to be the essential criterion for impact targets. Results of regulative drop tests of dangerous goods packagings onto model impact targets with mass ratios of 1:15, 1:30 and 1:50 indicate that other parameters than the mass ratio are relevant as well (e.g., percentage of impact energy that goes into motion of impact target).

On that account, the requirement of the 1:50 mass ratio between target and packaging should be verified. The test concept presented here can be the basis for a revision of this requirement, utilizing the validated experimental setup. Therewith, a systematic investigation into the influence of the impact target on the 50% failure drop height of dangerous goods packagings can be conducted. This will make it possible to determine how the mass ratio affects the damage resistance of packagings under otherwise identical constellations. This can contribute to a revision of the dangerous goods regulations.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

NOMENCLATURE

ADR	Agreement concerning the International Carriage of Dangerous Goods by Road
FEM	finite element method
FE	finite element
FFT	fast Fourier transformation
RAM	radioactive materials
$E_{kin,di}$	kinetic energy during impact (Nm)
$E_{kin,pi}$	kinetic energy prior to impact (Nm)
f_0	first natural frequency of impact target (s^{-1})
g	acceleration due to gravity (ms^{-2})
k_V	vertical spring stiffness coefficient of a spring element ($kN\ mm^{-1}$)
k	vertical spring stiffness coefficient of a spring element set ($kN\ mm^{-1}$)
$k_{ISO2248}$	equivalent minimum required spring stiffness coefficient ($kN\ mm^{-1}$)
m	mass of rigid impact pad (kg)
m_1	packaging mass (kg)
m_2	target mass (kg)
T	period of vibration (s)
$u(t)$	rigid body deflection of packaging function (mm)
v_1	packaging velocity prior to impact (ms^{-1})
V_1	packaging velocity after impact (ms^{-1})
v_2	target velocity prior to impact (ms^{-1})
V_2	target velocity after impact (ms^{-1})
$x(t)$	vertical deflection function (m)
$\dot{x}(t)$	vertical deflection velocity function (ms^{-1})
$\ddot{x}(t)$	vertical deflection acceleration function (ms^{-2})
x_{max}	maximum spring deflection (mm)
X	maximum dynamic vertical deflection (mm)
δ	percentage of impact energy that goes into motion of impact target (%)
ρ_b	bulk density ($kg\ L^{-1}$)
ω_0	angular natural frequency (s^{-1})

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