

# Improved criteria for evaluating impact targets in regulative drop tests of dangerous goods packagings

Nikolaos Lengas<sup>1</sup>  | Karsten Müller<sup>1</sup> | Eva Schlick-Hasper<sup>1</sup>  | Marcel Neitsch<sup>1</sup> | Sergej Johann<sup>1</sup> | Manfred W. Zehn<sup>2</sup>

<sup>1</sup>BAM Federal Institute for Materials Research and Testing, Berlin, Germany

<sup>2</sup>Institute of Mechanics, TU Berlin, Berlin, Germany

## Correspondence

Nikolaos Lengas, BAM Federal Institute for Materials Research and Testing, Berlin, Germany.

Email: [nikolaos.lengas@bam.de](mailto:nikolaos.lengas@bam.de)

## Abstract

For dangerous goods packagings, drop testing onto an essential unyielding target can be used to assess the mechanical resistance to impact loads. Adopted regulations like Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)/Regulation concerning the International Carriage of Dangerous Goods by Rail (RID) require that the impact surface provided shall be integral with a mass at least 50 times than that of the heaviest package to be tested. The problem is that many manufacturers do not possess impact targets that satisfy the required 50 times mass ratio for regulative drop tests during series production. The objective of this work is to verify existing and define improved criteria for impact target structures based on systematic investigations. Previous evidence highlights the relevance of other parameters in addition to the mass ratio. Therefore, in this research, a variation of drop test parameters was carried out experimentally. Furthermore, numerical vibration analysis was applied to investigate the deformability of the impact surface. The results conclude that the mass ratio of 1:50 cannot be defined as a decisive criterion. In order to determine the influence of further drop test parameters, the research findings were used to validate a parametric model that assesses impact target deflection. An approximation quality of over 90% was achieved. As a result, new evaluation criteria are proposed. First, a method for identifying critical impact target designs is provided. Second, a new comprehensive formula compares the approximated maximum deflection of a real impact target to the respective theoretical threshold derived from a worst-case assumption. In practice, this leads to great advantages in the evaluation of already installed impact targets for dangerous goods packagings.

## KEYWORDS

corrugated fibreboard box, dangerous goods packagings, drop test, impact target, mechanical response, steel drum, structural dynamics

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## 1 | INTRODUCTION

Design type tests, as defined by the UN Model Regulations 6.1.5<sup>1</sup> and the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) 6.1.5,<sup>2</sup> are used for the approval of dangerous goods packagings. One aspect of design type tests concerns mechanical safety. Due to the possibility of vertical or oblique impact loading in the transportation system, the structural integrity of packages needs to be evaluated. Therefore, transport packages are subjected to free fall drop testing to assess their resistance to mechanical damage. To this end, the impact surface must be considered essentially unyielding. ADR 6.1.5.3<sup>2</sup> refers to ISO 2248,<sup>3</sup> which describes that the impact surface shall be part of an impact target structure with a mass at least 50 times larger than that of the heaviest package to be tested. However, fulfilling this requirement may cause difficulties for many manufacturers of fibreboard packages in Germany since production facilities often do not have appropriately dimensioned impact targets. Thus, regulative drop tests during series production are not possible. Therefore, an investigation of the dependency between impact target characteristics, for example, mass ratio, and the assessment of a packaging's ability to withstand damage is highly relevant for industrial application.

This work aims to provide a detailed analysis of drop test parameters and to improve current criteria for impact target structures comparable to a typical impact pad.<sup>4</sup> Experimental data of recent research<sup>5</sup> indicates that parameters other than the generalized requirement of a mass ratio of 1:50 could have significant influence on the behaviour of the impact surface. For instance, the energy amount in target motion during impact and the mechanical response of the packaging should be considered. Thus, based on systematic investigations and numerical analyses, new criteria for evaluating impact targets are developed. This allows to describe the complex interactions of packaging and target properties during impact. Hence, a framework is established for evaluating the suitability of already installed impact targets in practice. This holds great benefits for manufacturers that would otherwise not be able to conduct regulative drop tests in their own facility.

## 2 | MATERIALS AND METHODS

The test setup<sup>5</sup> consists of three model impact targets with mass ratios of 1:15, 1:30, and 1:50 in relation to 18 kg packages to be tested. Two packaging design types with significantly different mechanical response are investigated, that is, steel drums labelled with code 1A2 and corrugated fibreboard boxes labelled with code 4G according to ADR 6.1.2.7.<sup>2</sup>

Two different methods are used to determine the influence of drop test parameters, such as drop height, mass ratio, eigenfrequency, and damping ratio. The first method is the determination of the 50% failure drop height for combinations of model impact target and packaging design type. The second method concerns the evaluation of the maximum rigid body deflection of underdamped vibrations relating to vertical rigid body motion of impact targets in drop tests.

### 2.1 | Drop test setup

Steel plates of different thicknesses have been used as model impact target to achieve mass ratios of 1:15, 1:30, and 1:50 to packages weighing approx. 18 kg. Their anchoring is simulated using a mounting of five high strength spring elements to control and minimize forces that get transmitted outwards from the system during impact. The model target properties are given in Table 1.<sup>5</sup>

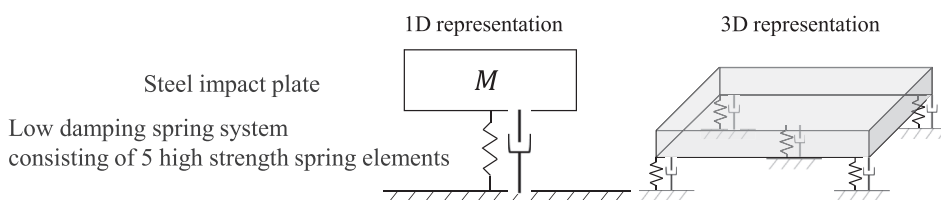
A schematic representation of the model impact target structure is shown in Figure 1.

Each model impact target has been examined and validated in accordance with requirements of regulations<sup>2,3</sup> as well as with previous work.<sup>5</sup> This allows in the investigation to examine the mass ratio as an independent input parameter in the investigations. The experimental setup is depicted in Figure 2 by means of the model impact target consisting of the 280-kg steel plate.

The mechanical response of the impact surface is captured by uniaxial piezoelectric accelerometers. Those sensors feature an amplitude range of  $\pm 50$  g and a frequency range up to 10 000 Hz. The expanded measurement uncertainty lies within a range of

Model impact target	Mass ratio 1:15	Mass ratio 1:30	Mass ratio 1:50
Thickness $z$ (mm)	35	70	120
Impact surface area $A_{\text{impact}}$ (m <sup>2</sup> )	1	1	1
Mass $m_2$ (kg)	280	560	960
Total spring stiffness $k$ (kN/mm)	14.7	13.4	12.1

**TABLE 1** Model impact target properties (mass ratio relates to packages weighing 18 kg).<sup>5</sup>

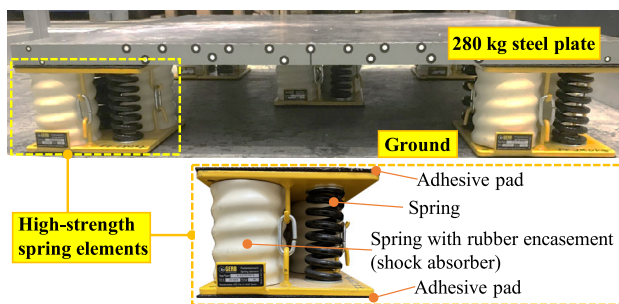


**FIGURE 1** Model impact targets: schematic representation.

approximately  $\pm 2\%$ . The acceleration-time histories are numerically integrated twice to derive the deflection-time histories. The sensors are applied directly on the impact surface by magnetic adhesion. Their positioning is chosen with respect to vibration analysis data, which were determined by spectral analysis of preliminary drop tests as well as by numerical vibration analysis.<sup>5</sup> As illustrated in Figure 3, the impact zone can be localized within a radius of 300 mm from the point of impact (centre of surface with respect to the load line).

This allows to capture minimal amounts of elastic deformation that occurs in form of stress waves propagating through the impact surface supplementary to the dominant vertical rigid body motion of the impact target.

The packages are filled with substitute filling substances that exhibit good flow properties (large damage effect on impact) and



**FIGURE 2** Model impact target consisting of the 280-kg steel plate mounted on high-strength spring elements.

achieve a gross mass of 18 kg whilst satisfying the minimum filling degree of 95% (ADR 6.1.5.2.1<sup>2</sup>). Specifically, glass beads are used for the 1A2 packaging and a polymethylmethacrylate (PMMA) granulate for the 4G packaging, as shown in Figure 4.

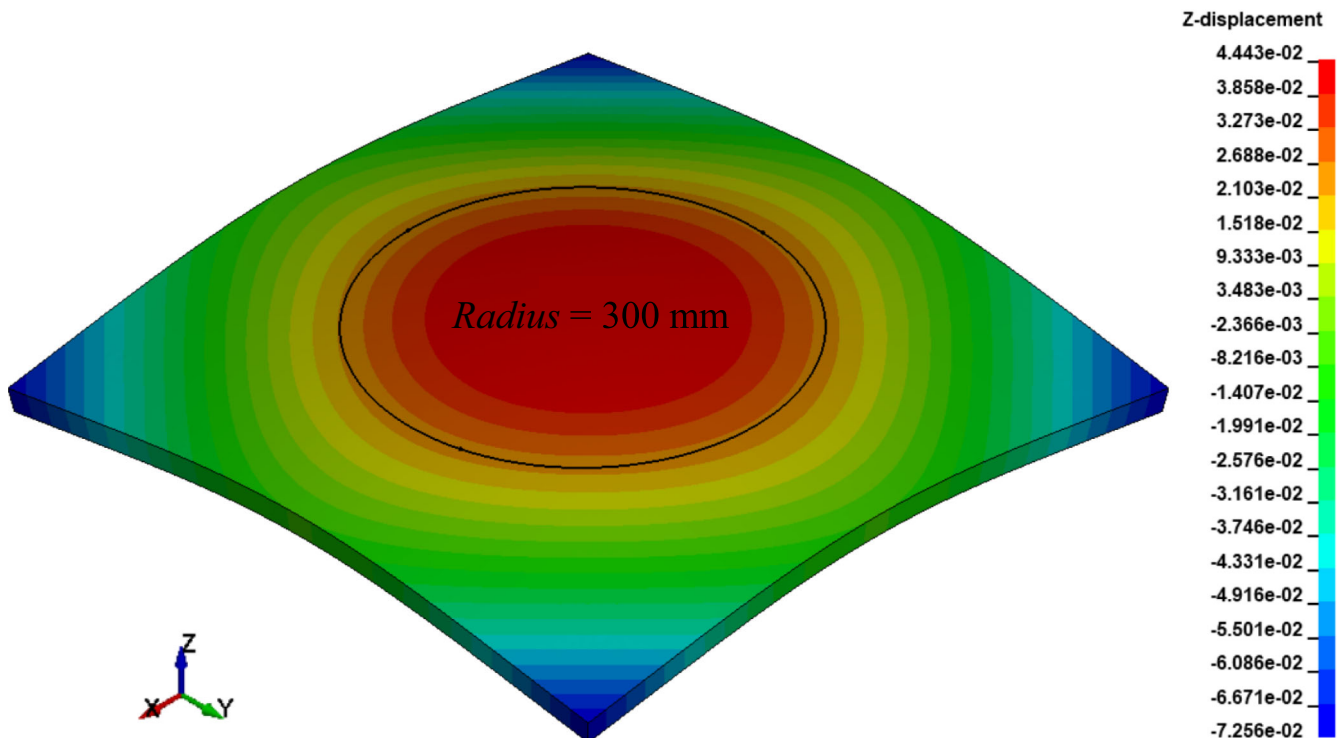
The specifications for the 1A2 and 4G packagings as well as the corresponding filling substances are described in a previous work.<sup>5</sup> Regarding drop test parameters, the point of impact should be chosen to cause the most severe damage for each type of packaging. Thus, the drop positions are defined according to ISO 2206.<sup>6</sup> The steel drum (1A2) shall be dropped with respect to the centre of gravity on the rim of the clamping ring with the fastener having an offset of approximately  $10^\circ$  from the point of impact. The fibreboard box (4G) shall be dropped on the corner of the manufacturer's joint. A representation of both drop positions is depicted in Figure 5.

Furthermore, preliminary drop tests were carried out and recorded with the help of two high-speed cameras by means of digital image correlation (DIC). Thereby, the impact angle was derived and evaluated, as shown in Figure 6, to ensure reproducibility and repeatability of the drop position.

The impact angle tolerances were calculated to be within a range of  $\pm 0.98^\circ$  for the 1A2 and  $\pm 0.59^\circ$  for the 4G packaging.

## 2.2 | Bruce-ton method for determining the 50% failure drop height

An appropriate statistical method for evaluating the mass ratio influence in the drop test is given by the 50% failure drop height according



**FIGURE 3** Impact zone relating to elastic vibration of impact surface (numerical vibration analysis<sup>5</sup>).

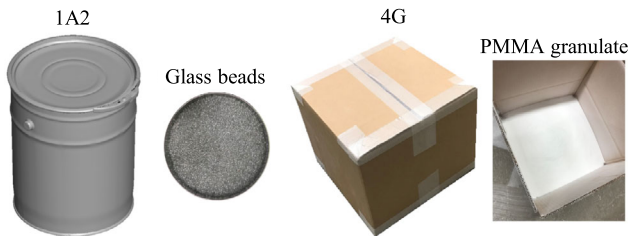
to the Bruceton method.<sup>7</sup> This statistical method allows to calculate the drop height from which a package has a probability of 50% to fail the drop test (evident leakage of contents according to ADR 6.6.5.3.4.5<sup>2</sup>). It aims to determine if there is statistically significant difference in the 50% failure drop height values considering notable change in mass ratio. A test series of 25 total tests is required to

calculate the 50% failure drop height  $H_{50}$  according to Equation (1)<sup>7</sup> for each possible constellation of packaging design type and model impact target.

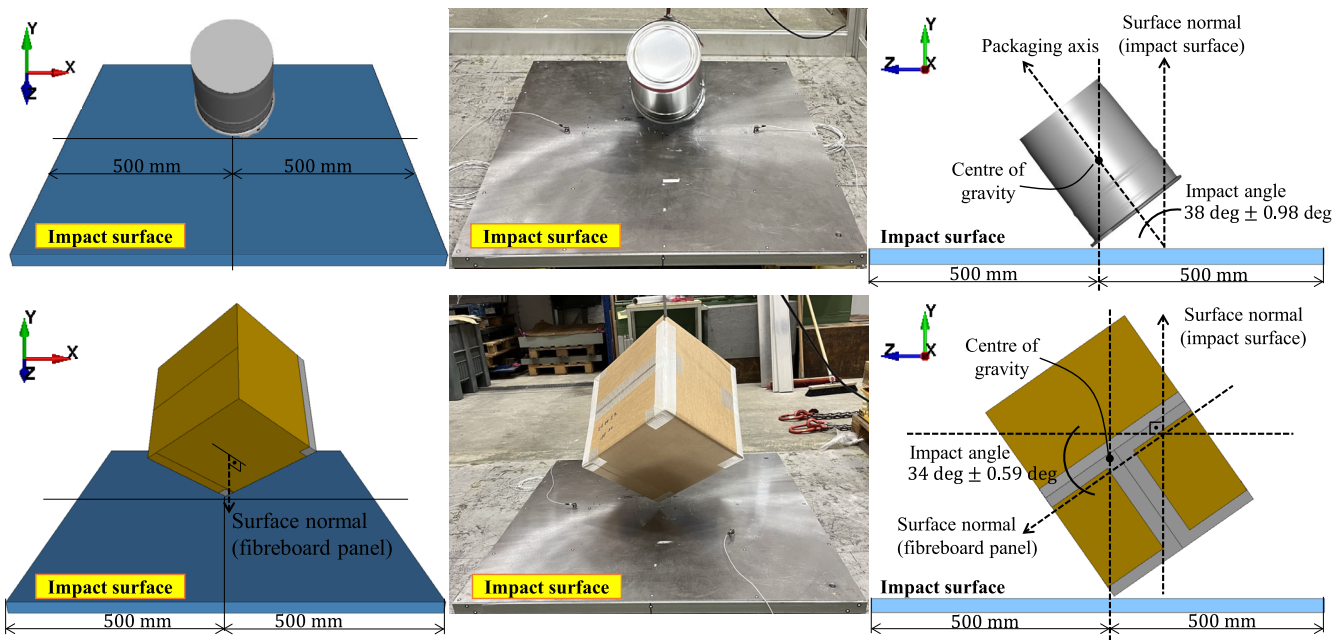
$$H_{50} = c + d \left( \frac{\sum i n_i}{\sum n_i} - 0.5 \right) \quad (1)$$

The incremental jump in drop height denoted with  $d$  depends on the drop test outcome. After a test with packaging failure, the drop height gets incrementally increased for the subsequent test and vice versa. Preliminary tests are necessary to define the values for the lowest drop height  $c$  and the interval  $d$ . The variable  $i$  represents the interval number. Occurrences of failure are given by the variable  $n_i$ . Figure 7 illustrates experimental data by means of the Bruceton method.

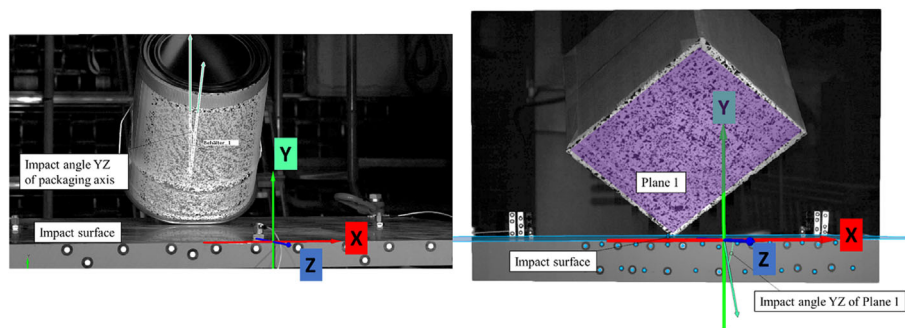
Furthermore, assuming normal distribution, it is possible to calculate the standard deviation for each test series according to Equation (2).



**FIGURE 4** 1A2 and 4G packaging type designs with their respective filling substances.



**FIGURE 5** Drop positions for steel drum and fibreboard box.



**FIGURE 6** Experimental verification of drop position for steel drum and fibreboard box using DIC.

FIGURE 7 Bruceton method.

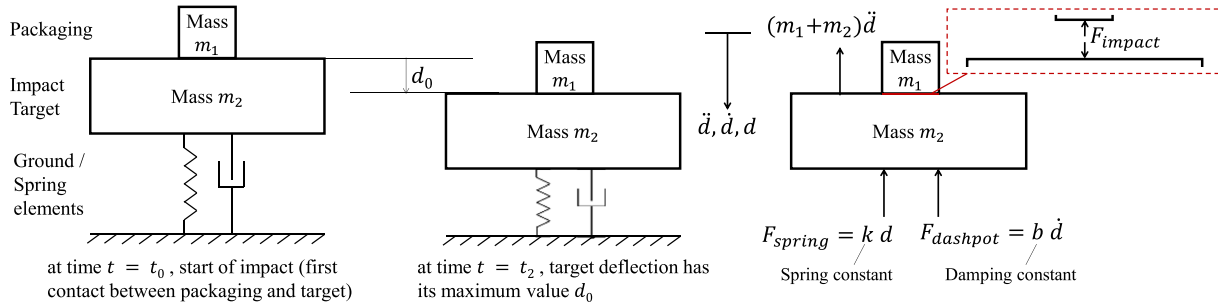
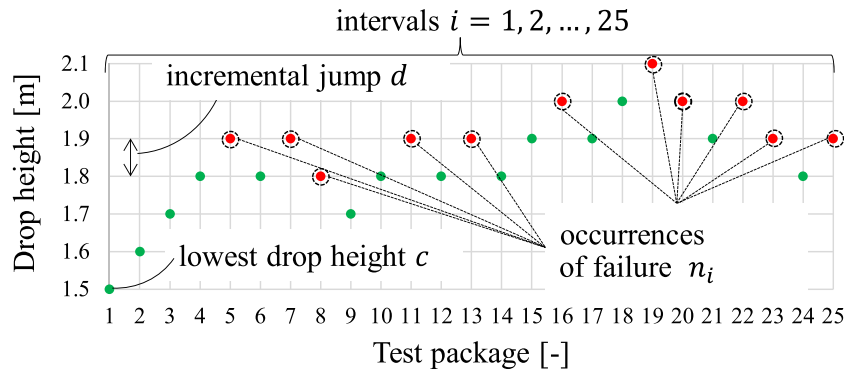


FIGURE 8 Impact dynamics based on analytical impact model.

$$s = 1.62 d \left( \frac{\sum n_i \sum i^2 n_i - (\sum i n_i)^2}{(\sum n_i)^2} + 0.029 \right) \quad (2)$$

velocity  $\dot{d}$  reaches its first maximum value. The time value  $t_2$  is defined as the moment where the rigid body deflection function  $d(t)$  assumes its maximum value  $d_0 = \dot{d}(t_1) / 2\pi f_0 \sqrt{1 - \zeta^2}$ . The eigenfrequency of the system is denoted with  $f_0$ . The vibration decays according to the damping ratio  $\zeta$ . Equation (4) relates eigenfrequency  $f_0$  and damping ratio  $\zeta$  to the spring constant  $k$  and damping constant  $b$ , respectively.<sup>8,9</sup>

### 2.3 | Parametric model based on maximum rigid body deflection

The maximum deflection is evaluated regarding the rigid body motion of impact pads with characteristics of sinusoidal underdamped vibrations. The rigid body deflection as a function of time  $d(t)$  is described by Equation (3).<sup>8</sup>

$$d(t) = d_0 e^{-\zeta 2\pi f_0 t} \sin\left(2\pi f_0 \sqrt{1 - \zeta^2} t\right) = \frac{\dot{d}(t=t_1)}{2\pi f_0 \sqrt{1 - \zeta^2}} e^{-\zeta 2\pi f_0 t} \sin\left(2\pi f_0 \sqrt{1 - \zeta^2} t\right) \quad (3)$$

Equation (3) represents the solution for the differential equation of motion of an underdamped vibration corresponding to an impact pad resting on a spring-dashpot system with one degree of freedom.<sup>8</sup> This is an accurate representation of the impact response for an impact target structure if vertical rigid body motion is dominant and elastic deformation of the impact surface is negligible.<sup>5</sup> A schematic representation of impact dynamics is illustrated in Figure 8.

Initial contact between packaging and impact surface happens at time  $t_0$ . The time value  $t_1$  represents the moment where rigid body

$$2\pi f_0 = \sqrt{\frac{k}{m_1 + m_2}} \quad \text{and} \quad \zeta = \frac{b}{4\pi f_0 (m_1 + m_2)} \quad (4)$$

Thereby, Equation (3) is valid (underdamped vibration), only if the damping ratio  $\zeta$  is greater than or equal to 0 (harmonic oscillation) and less than 1 (critical damping). In practice, this is the case for the damping ratio  $\zeta$  since impact target structures are very stiff systems with low damping properties. Moreover, the initial impact response caused by the interaction between packaging and impact surface influences the value of the vibration eigenfrequency. Depending on the impacting object, the lowest observed frequency of the impact target  $f_0$  may assume different values. This effect is described by the characteristics of the impact force  $F_{\text{impact}}$  and depends on the properties of the packaging, such as deformability and drop position.<sup>10,11</sup> In Figure 9, an example of an impact pad vibration is shown, which corresponds to the rigid body motion assumption described in Equation (3).

Figure 10 depicts representative DIC data of the collision between a fibreboard box and the impact surface. The data evaluation yields information about kinematics of the initial impact



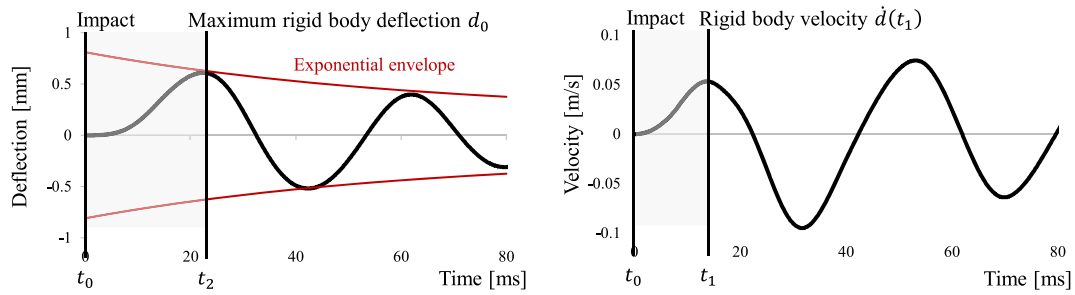


FIGURE 9 Underdamped vibration of impact pad during impact.

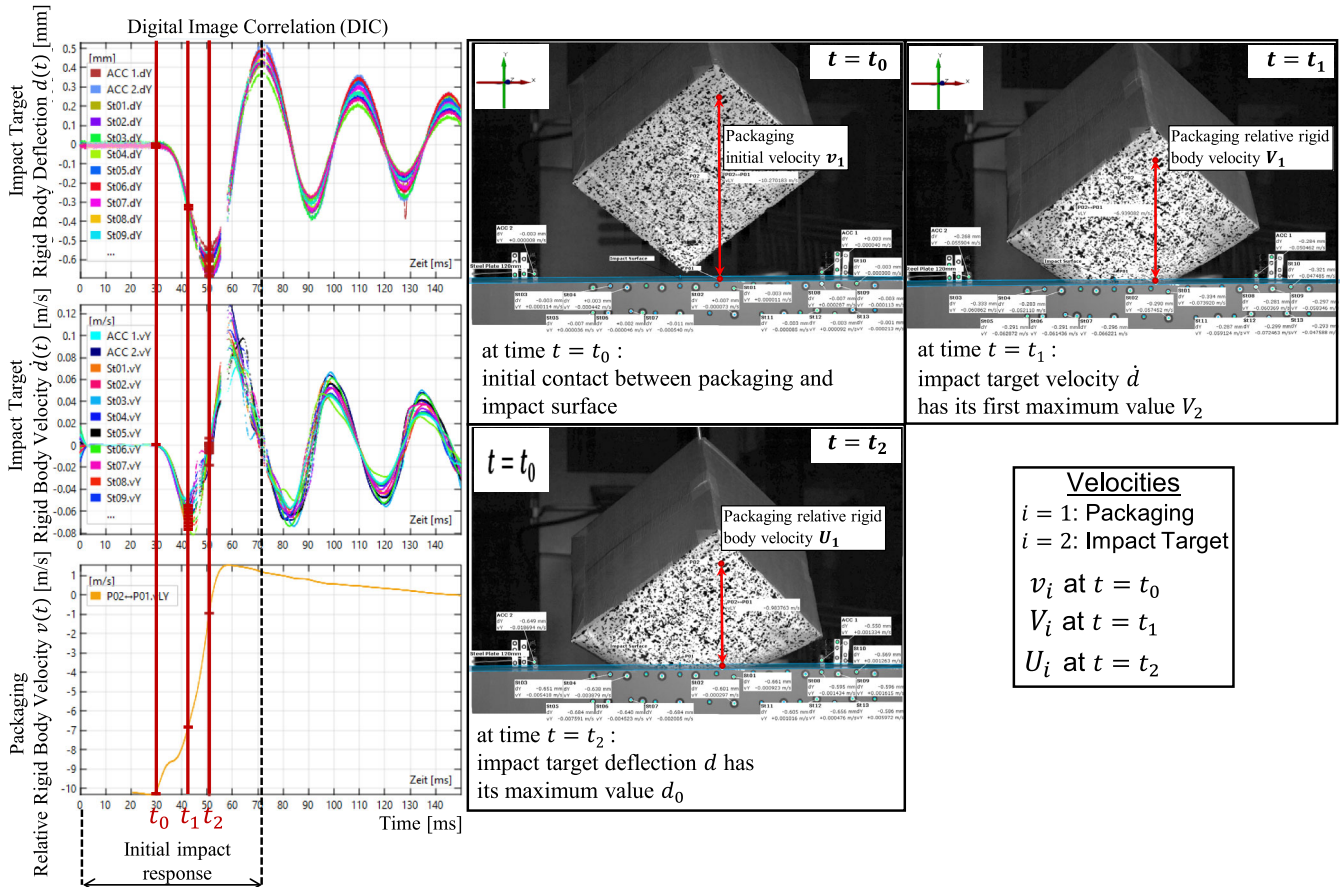


FIGURE 10 DIC data of drop test with fibreboard box onto model impact target with 960-kg steel plate.

response, such as the relative motion between packaging and impact surface as a result of packaging deformation and elastic recoil.

Equations (5)–(8) are used to derive the first maximum velocity value of the impact target  $\dot{d}(t_1)$  considering the law of conservation of momentum<sup>12</sup> at time  $t = t_1$  and  $t = t_2$  (see Equation 5). Thereby,  $m_1$  is the mass of the packaging and  $m_2$  is the mass of the impact target. Velocities  $v_1$  and  $v_2$  are initial velocities of packaging and impact target, respectively. Since the impact target is stationary at  $t = t_0$ , then  $v_2 = \dot{d}(t_0) = 0$  applies. Thus, the total momentum  $p$  is given by the product of packaging mass  $m_1$  and packaging velocity  $v_1$ . The

packaging velocity  $v_1$  is derived directly from the potential energy so that  $v_1 = \sqrt{2gh}$ , where  $g$  is gravitational acceleration and  $h$  is drop height. Furthermore, velocities  $V_1$  at time  $t_1$  and  $U_1$  at time  $t_2$  are the relative rigid body velocities between packaging and impact surface. Velocities  $V_2$  at time  $t_1$  and  $U_2$  at time  $t_2$  are the rigid body velocities of the impact target. The impact target assumes the first maximum velocity value at time  $t_1$ ; thus,  $V_2 = \dot{d}(t_1)$ . In addition, maximum impact target deflection at time  $t_2$  means that  $U_2 = \dot{d}(t_2) = 0$ . Lastly, the terms  $J_{D_1}$ ,  $J_{D_2}$ , and  $\Delta J_D$  relate to the impulse of deformation<sup>11,12</sup> caused by the impact force  $F_{impact}$  in the time periods  $\Delta t_{10} = t_1 - t_0$ ,  $\Delta t_{20} = t_2 - t_0$ , and  $\Delta t_{21} = t_2 - t_1$ , respectively.

$$m_1 V_1 + (m_1 + m_2) V_2 + J_{D_{t_1}} = m_1 U_1 + J_{D_{t_2}} \quad (5)$$

$$\Leftrightarrow V_2 = \frac{m_1}{m_1 + m_2} v_1 \left( \frac{U_1 - V_1}{v_1} + \frac{\Delta J_D}{m_1 v_1} \right) \quad (6)$$

$$\Leftrightarrow V_2 = d(t_1) = \frac{m_1}{m_1 + m_2} \sqrt{2gh} \left( \frac{\Delta J_D}{p} - e \right) = \alpha \left( \frac{\Delta J_D}{p}, e \right) \frac{m_1}{m_1 + m_2} \sqrt{2gh} \quad (7)$$

with

$$\Delta J_D = J_{D_{t_2}} - J_{D_{t_1}} = \int_{t_1}^{t_2} F_{\text{impact}} dt, p = m_1 v_1 \text{ and } e = \frac{V_1 - U_1}{v_1} \quad (8)$$

Thus, velocity  $V_2$  consists of two parts. One part is a velocity term that relates to ideally plastic collision. It is multiplied by the second part, denoted by parameter  $\alpha$ , which depends on packaging deformation, given by the ratio of impulse of deformation to total momentum  $\Delta J_D/p$ , and elastic recoil, given by the coefficient of restitution  $e$ .<sup>13</sup> Parameter  $\alpha$  is a dimensionless parameter that takes values greater than 0 (no collision) and less than 1 (ideally plastic collision). For instance, considering similar drop positions, packaging types like fibreboard boxes would have lower  $\alpha$  values than other types like steel drums since the fibreboard material is highly deformable and thereby absorbs higher amounts of impact energy. Hence, considering Equation (3) and Equations (5)–(8), it is possible to express the maximum rigid body deflection  $d_0$  as a function of drop test parameters.

$$d_0 = \frac{\dot{d}(t_1)}{2\pi f_0 \sqrt{1 - \zeta^2}} = \frac{V_2}{2\pi f_0 \sqrt{1 - \zeta^2}} = \frac{\frac{m_1}{m_1 + m_2} \sqrt{2gh} \left( \frac{\Delta J_D}{p} - e \right)}{2\pi f_0 \sqrt{1 - \zeta^2}} \\ = \frac{\alpha \left( \frac{m_1}{m_1 + m_2} \right) \sqrt{2gh}}{2\pi f_0 \sqrt{1 - \zeta^2}} \quad (9)$$

In addition, substituting the mass ratio  $MR = m_1/m_2$  in Equation (9), a parametric model for the maximum rigid body deflection  $d_0$  is given in Equation (10).

$$d_0(\alpha, h, MR, f_0, \zeta) = \frac{\sqrt{2g}}{2\pi} \alpha \sqrt{h} \frac{1}{f_0 \sqrt{1 - \zeta^2}} \frac{MR}{(MR + 1)} \quad (10)$$

This model reinforces the argument of the importance of further drop test parameters other than the mass ratio between package and impact target. For example, the contact to the ground (stiffness, damping properties) are crucial and should not be neglected. This is also evident in Equation (11) (given by substituting the mass ratio  $MR$  in Equation 4), which relates eigenfrequency  $f_0$  to stiffness  $k$ , mass ratio  $MR$ , and mass of packaging  $m_1$ .

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m_1} \frac{MR}{MR + 1}} \quad (11)$$

The stiffness coefficient  $k$  in Equation (11) can be interpreted as the contact stiffness<sup>14,15</sup> between impact target and ground in the case of already installed impact target structures (e.g., reinforced concrete foundation with solidly anchored steel plate).<sup>16–18</sup> To investigate such effects, the proposed model impact targets shall be used. Thereby, the mounting of high-strength spring elements is designed to simulate the contact stiffness of a real structure.

## 2.4 | Determination of critical impact target designs

Only impact target structures comparable to the impact pad are described according to Equation (10). Thus, a criterion is necessary to evaluate if vertical rigid body motion is the dominant mode of vibration, that is, if the impact surface can be considered essentially unyielding. It is common to assume that modes of elastic deformation are negligible if their contribution to the total vibration of a body is less than 1%.<sup>19–22</sup> Numerical eigenvalue analysis is used as a tool to extract modes of vibration. Mode participation in the vibration is determined by examining the effective masses compared to the total mass of the system.<sup>20,21</sup> This method can be applied to derive critical impact target designs. In this work, the observed impact target structures are cuboids. Hence, two parameters are defined. Parameter  $\lambda_1$  is defined to express the impact surface  $A_{\text{impact}}$  in relation to the target's thickness  $z$  (see Equation 12). Parameter  $\lambda_2$  is defined as the ratio of the length  $L$  to the width  $W$  of the impact target (with  $L \geq W$ ).

$$A_{\text{impact}} = L \cdot W = (\lambda_1 z)^2 \Leftrightarrow \lambda_1 = \frac{\sqrt{A_{\text{impact}}}}{z} \quad (12)$$

$$\lambda_2 = \frac{L}{W} \quad (13)$$

A variation of  $\lambda_1$  and  $\lambda_2$  was conducted by means of numerical sensitivity analysis with the LS-DYNA simulation software. A steel material with a Young's modulus of 210 GPa and a Poisson's ratio of 0.3 was used for the impact surface. Table 2 shows eigenvalue analysis results. The increasing amount of elastic deformation of the impact surface with increasing  $\lambda_1$  and  $\lambda_2$  values is represented by the respective mode participation in the vibration. Mode participation is given as a percentage of the ratio of effective mass to total mass  $m_{\text{eff}}/m_2$ . Thereby, significant bending modes of vibration are identified for critical designs of impact target structures.

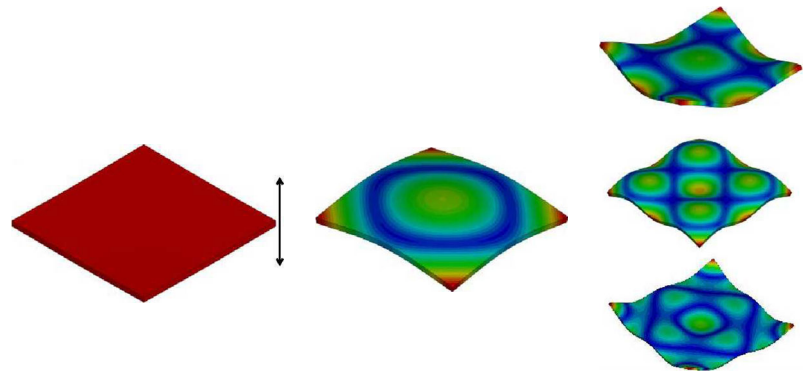
The results of the sensitivity analysis are illustrated in Figure 11. The ratio of the sum of effective masses of elastic deformation modes  $\sum m_{\text{eff}} = m_{\text{eff}_5} + m_{\text{eff}_{10}}$  to the total mass of the target  $m_2$  is plotted against parameter  $\lambda_1$  for different  $\lambda_2$  ratios.

Larger values of the parameter  $\lambda_1$  along the horizontal axis represent proportionately thinner targets and smaller values proportionately thicker targets. Thereby, higher order modes exhibit a higher

TABLE 2 Eigenvalue analysis results.

Impact target properties		Modal effective masses—Participation in the vibration		
		Mode 1 (rigid motion)	Mode 5 (bending)	Higher order modes
Parameters				
$\lambda_1$ [-]	$\lambda_2$ [-]	$\frac{m_{eff1}}{m_2}$ [%]	$\frac{m_{eff5}}{m_2}$ [%]	$\frac{m_{effHO}}{m_2}$ [%]
33	1	99.88	0.11	0.01
40	1	99.65	0.32	0.02
50	1	98.94	0.97	0.09
67	1	96.06	3.27	0.67
33	1.5	99.57	0.36	0.07
40	1.5	98.83	1.03	0.13
50	1.5	96.35	3.27	0.38
67	1.5	85.25	12.76	1.99
33	2.0	98.77	1.18	0.04
40	2.0	96.66	3.27	0.07
50	2.0	90.65	9.18	0.17
67	2.0	74.58	24.53	0.90

Indicative contour plots of resultant relative displacement of the impact surface



participation percentage in the vibration analysis for thinner targets. Larger values of parameter  $\lambda_2$  translate to narrower surfaces and lead to a higher percentage of elastic deformation as well, since larger ratios of length to width lower the flexural strength of a cuboid structure. Thus, elastic deformation increases in a nonlinear matter rapidly with increasing  $\lambda_1$  and  $\lambda_2$  values. Therefore, different designs of impact target structures are investigated in Figure 12. Designs along the dotted red line are considered critical. They correspond to a maximum admissible percentage of elastic deformation of the impact surface equal to 1%.

The accessible plot provided in Figure 12 can be used (e.g., by manufacturers) to decide if the surface of a real installed foundation structure can be considered unyielding for the purpose of drop testing of dangerous goods packagings.

### 3 | RESULTS AND DISCUSSION

Two different drop test series were carried out. In the first one, the 50% failure drop height (see Section 2.2) was determined for both packaging types. In the second drop test series, the parametric model

based on maximum rigid body deflection (see Section 2.3) was evaluated. Thereby, many parameters such as drop height, mass ratio, and target eigenfrequency were varied by means of the three model impact targets and both packaging types.

#### 3.1 | Results—50% failure drop height

The 50% failure drop height  $H_{50}$  was determined according to Equation (1) for the 1A2 and the 4G packaging types onto model impact targets with mass ratios of 1:15 and 1:50, respectively. Hence, a comparison in the  $H_{50}$  values was drawn regarding change in mass ratio. Results in association with drop test presets are illustrated in Table 3.

In Figure 13, there are plots for the purpose of visualization of the results of the respective test series according to the Bruceton method. The calculated values of the 50% failure drop height  $H_{50}$  vary significantly between the two packaging types. Furthermore, they diverge from the regulative drop heights in ADR 6.1.5.3.5<sup>2</sup> since they are meant to determine the energy needed so that the package has a 50% probability to fail. Steel drums fail on average at a drop height of 1.90 m for a mass ratio of 1:15 (Figure 13A) while fibreboard boxes at



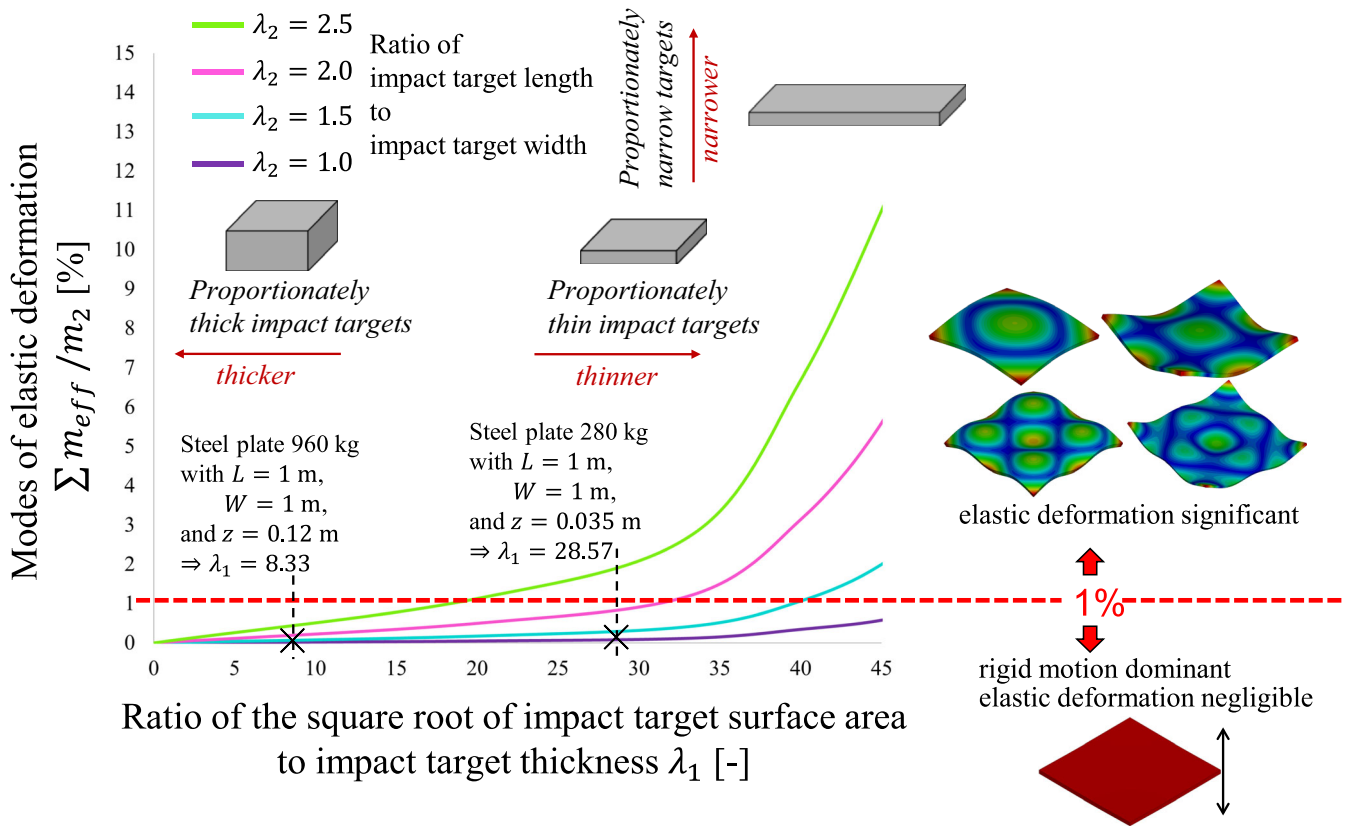


FIGURE 11 Participation percentage of modes of elastic deformation as a function of impact target dimensions.

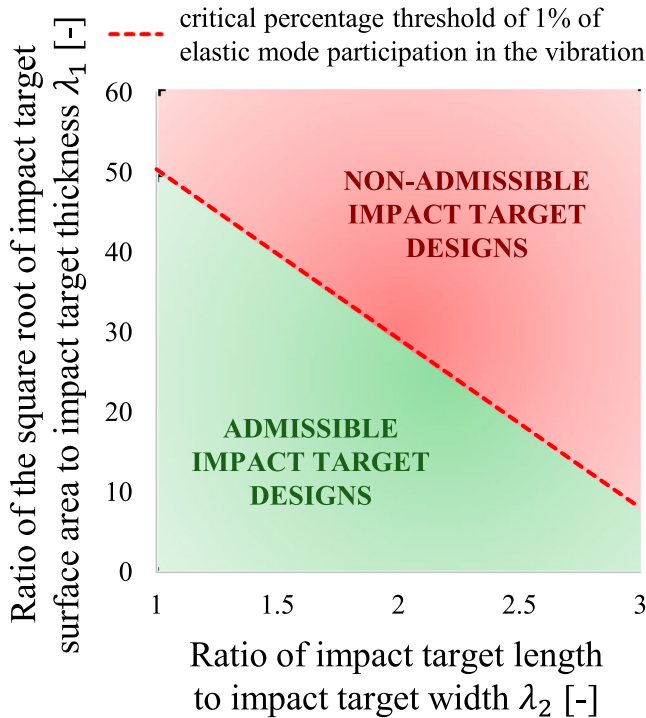


FIGURE 12 Identification of critical impact target designs.

a height of 6.35 m (Figure 13B). This means that less impact energy is needed for a 1A2 packaging to fail the drop test than for a 4G packaging. This result is plausible due to the significant difference of

mechanical response between steel and fibreboard materials. Compared to the steel drum, the fibreboard box can absorb considerably higher amounts of energy in form of deformation before reaching failure; thus, the 50% failure drop height is much larger corresponding to larger potential energy at the moment of impact ( $t = t_0$ ).

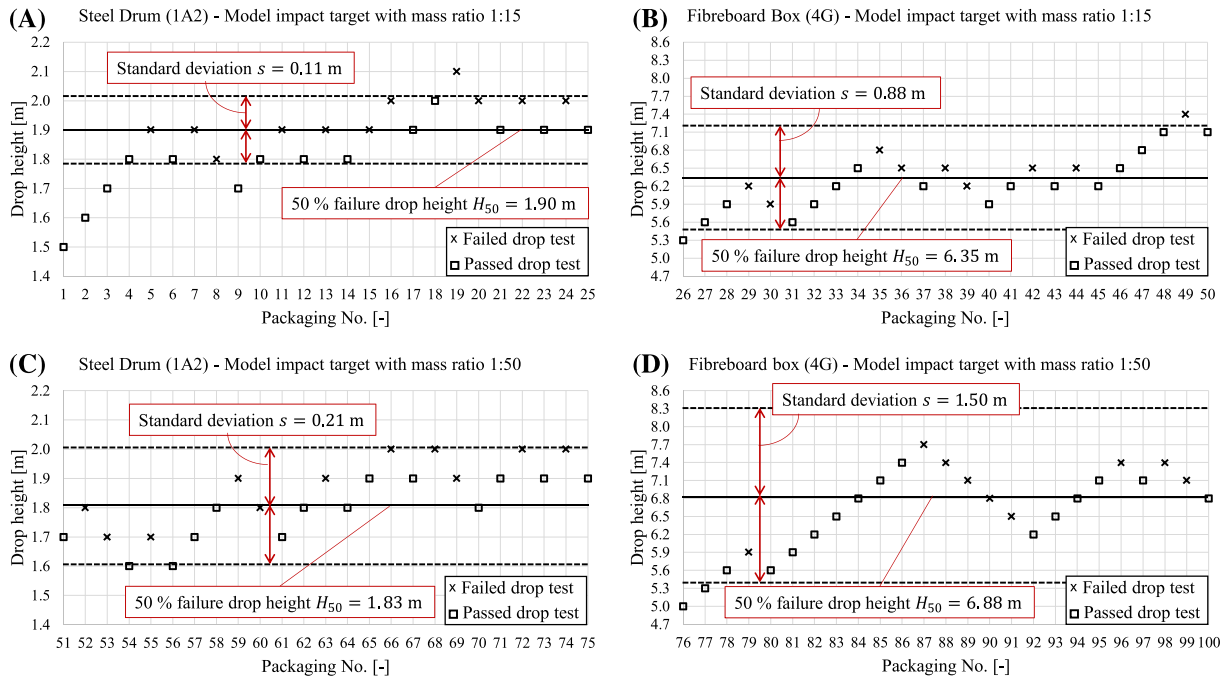
Steel drums exhibit lower variance in 50% failure drop height than fibreboard boxes, as shown in Figure 13. The proportionately larger variance in drop test results of fibreboard boxes (Figure 13B,D) can be attributed to the complex mechanical behaviour of fibreboard materials as well as properties of the Double-T-Seal with the cross-woven fibre-reinforced self-adhesive tape laminate used for sealing the box.

However, the results for  $H_{50}$  and  $s$  are inconclusive for both packaging types regarding the mass ratio influence, as shown in the comparison in Figure 14. Considering a change in mass ratio from 1:50 to 1:15, there is no statistically significant difference since the results overlap for each packaging type.

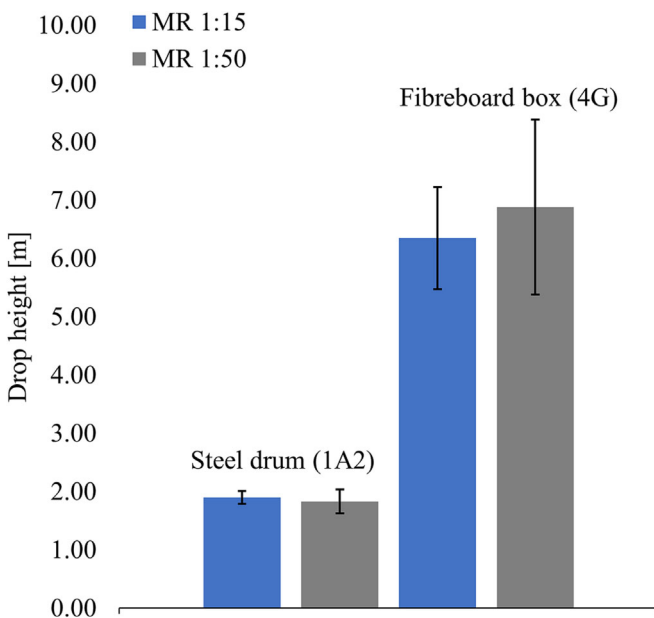
The absence of apparent mass ratio influence in the results can be interpreted by certain aspects of the boundary conditions of this test series. The calculation of parameter  $\lambda_1$  for the investigated model impact targets leads to values of 28.6 (mass ratio 1:15) and 8.3 (mass ratio 1:50). Hence, elastic deformation of the impact surface is negligible in both cases (see Section 2.4). Furthermore, considering Equations (10) and (11), both model impact targets produce a very similar mechanical response since they consist of steel plates that rest on spring elements of comparable stiffness. Thus, it is plausible that the influence of mass ratio would not be reflected in the present 50%

Parameters	Steel drum (1A2)		Fibreboard box (4G)	
Measured gross weight (kg)	18 ± 0.01		18 ± 0.01	
Mass ratio to target	1:15	1:50	1:15	1:50
Lowest drop height $c$ (m)	1.50	1.60	5.30	5.00
Interval $d$ (m)	0.10		0.30	
50% failure drop height $H_{50}$ (m)	1.90	1.83	6.35	6.88
Standard deviation $s$ (m)	0.11	0.21	0.88	1.50

**TABLE 3** Parameters and results of test series for determining the 50% failure drop height.



**FIGURE 13** Plots of test results according to Brucceton method.



**FIGURE 14** Bar charts of 50% failure drop height including standard deviation.

failure drop height results. Therefore, the Brucceton method is not a suitable procedure to investigate the influence of the mass ratio on the failure behaviour of the tested packaging types.

### 3.2 | Validation of parametric model based on maximum rigid body deflection

A variation of packaging and impact target properties in the drop test was carried out by means of steel drums, fibreboard boxes, and the three model impact targets. The maximum rigid body deflection  $d_0$  was evaluated for each drop test of the test series. Thereby, each possible packaging type - model impact target combination was tested for a drop height range of 0.5 m to 5.0 m. The drop height was increased progressively in increments of 0.5 m. The deflection data points were calculated by numerical integration of the acceleration-time histories captured by the IEPE sensors. The eigenfrequencies are determined by Fast-Fourier-Transformation (FFT) analysis of the captured acceleration-time-histories and have also been investigated in previous research.<sup>5</sup> Curve fitting of the exponential envelope (see

Figure 9) was performed to derive the damping ratio  $\zeta$  of each impact target structure. It was determined to be  $\zeta = 0.1 \pm 0.02$  across all model impact targets. In addition, parameter  $\alpha$  was derived for 1A2 and 4G packaging types according to Equation (14).<sup>23</sup>

$$\alpha = \frac{\mathbf{x}^T \cdot \mathbf{d}}{|\mathbf{x}|^2} \quad (14)$$

Thereby, the  $\mathbf{x}$  vector is composed of parameter values specific to each drop test (drop height, mass ratio, eigenfrequency, and damping ratio according to Equation 10) and the  $\mathbf{d}$  vector contains the measured maximum deflection values at time  $t = t_2$ . The detailed expression for calculating  $\alpha$  is given in Equation (15).

$$\alpha = \frac{2\pi}{\sqrt{2g}} \sum_{i=1}^n \left( \frac{\sqrt{h_i}}{f_{0i} \sqrt{1 - \zeta_i^2} (MR_i + 1)} \right)^{-2} \sum_{i=1}^n \left( \left( \frac{\sqrt{h_i}}{f_{0i} \sqrt{1 - \zeta_i^2} (MR_i + 1)} \right) d_{0i} \right) \quad (15)$$

The approximation quality regarding each packaging type was evaluated by means of the coefficient of determination  $R^2$ , as described in Equation (16).<sup>23</sup>

$$R^2 = 1 - \frac{\sum_{i=1}^n (\hat{d}_{0i} - d_{0i})^2}{\sum_{i=1}^n (d_{0i} - \bar{d}_0)^2} \quad (16)$$

The parameters  $\hat{d}_{0i}$  and  $d_{0i}$  represent the predicted deflection value and the measured deflection value for the  $i$ -th drop test, and  $\bar{d}_0$  is the mean deflection value of the total amount  $n$  of observed drop tests. A good approximation quality is given for values of  $R^2$  close to 1. In Table 4, the results for parameter  $\alpha$  as well as for the respective coefficient of determination  $R^2$  are given. A very good approximation quality was achieved. Hence, the approximation of the maximum rigid body deflection of impact target structures comparable to the impact pad according to Equation (10) is validated; that is, this model can be used to define improved criteria for the drop test.

The results show that an impact with the 1A2 packaging causes greater maximum impact target deflection values  $d_0$  by approx. 42% compared to an impact with the 4G packaging with otherwise the same parameters. However, a large change in mass ratio from 1:50 to 1:15 with no further parameter variation results in an increase of 30% in deflection  $d_0$ . This means that the impact target deflection  $d_0$  is

**TABLE 4** Impact target deflection approximation models for 1A2 and 4G packagings.

Packaging type	Impact parameter $\alpha$ (-)	Coefficient of determination $R^2$ (-)
Steel drum (1A2)	0.43	0.97
Fibreboard box (4G)	0.25	0.95

more sensitive to the investigated change of packaging material (considering similar drop positions) than the respective change in mass ratio. The effects of packaging characteristics and mass ratio in the drop test are illustrated in Figure 15 as well.

It is evident that the mass ratio is important but not the only deciding factor for the evaluation of impact target structures. Packaging characteristics such as material properties and drop position are very important as well. Furthermore, the stiffness of the impact target's connection to the ground is essential and should not be neglected considering Equations (10) and (11), that is, significantly higher stiffness of the connection to the ground results in significantly lower deflection values. Consequently, a mass ratio of 1:50 on its own is not a necessary criterion.

## 4 | IMPROVED CRITERIA FOR EVALUATING IMPACT TARGETS

Based on the validated results of this work, two new evaluation criteria are proposed that can be used instead of the generalized 1:50 mass ratio between impact target and heaviest package to be tested.

First, the ratio of impact target length to impact target width must correspond to a ratio of the square root of target surface area to target thickness, which lies below the defined threshold (see Figure 12). This guarantees negligible elastic deformation of the impact surface.

Second, a threshold of maximum admissible rigid body deflection  $d_{0,LIMIT}$  is defined based on the impact energy percentage that gets transmitted to the impact target structure. An analytical threshold  $\delta_{LIMIT} = 1.96\%$  regarding this energy percentage was calculated in Lengas et al.<sup>5</sup>; that is, the energy amount absorbed by the test package must be greater than 98.04%. Here, the parameter  $\delta_{LIMIT}$  is given by the energy ratio between time  $t = t_0$  (moment of impact) and  $t = t_2$  (maximum potential energy of impact target), as described in Equation (17).

$$\delta_{LIMIT} = \frac{E_{t=t_2}}{E_{t=0}} = \frac{0.5k d_{0,LIMIT}^2}{m_1 g h} = 0.0196 \quad (17)$$

A transposition of Equation (17) into Equation (18) yields the maximum admissible rigid body deflection  $d_{0,LIMIT}$  as a function of drop height  $h$ , packaging mass  $m_1$ , and equivalent stiffness coefficient of the target's connection to the ground  $k$ .

$$d_{0,LIMIT} = \sqrt{0.0392 \frac{m_1 g h}{k}} \quad (18)$$

Hence, for a given drop test combination of impact target structure and package, both the actual maximum deflection  $d_0$  (see Equation 10) and the deflection threshold  $d_{0,LIMIT}$  (see Equation 18) can be calculated respectively. Additionally, this allows to define a ratio  $f$  of actual deflection to maximum admissible deflection, which depends on packaging properties, mass ratio, and damping ratio. Ratio function  $f$  can be evaluated for different drop test scenarios according to Equation (19).

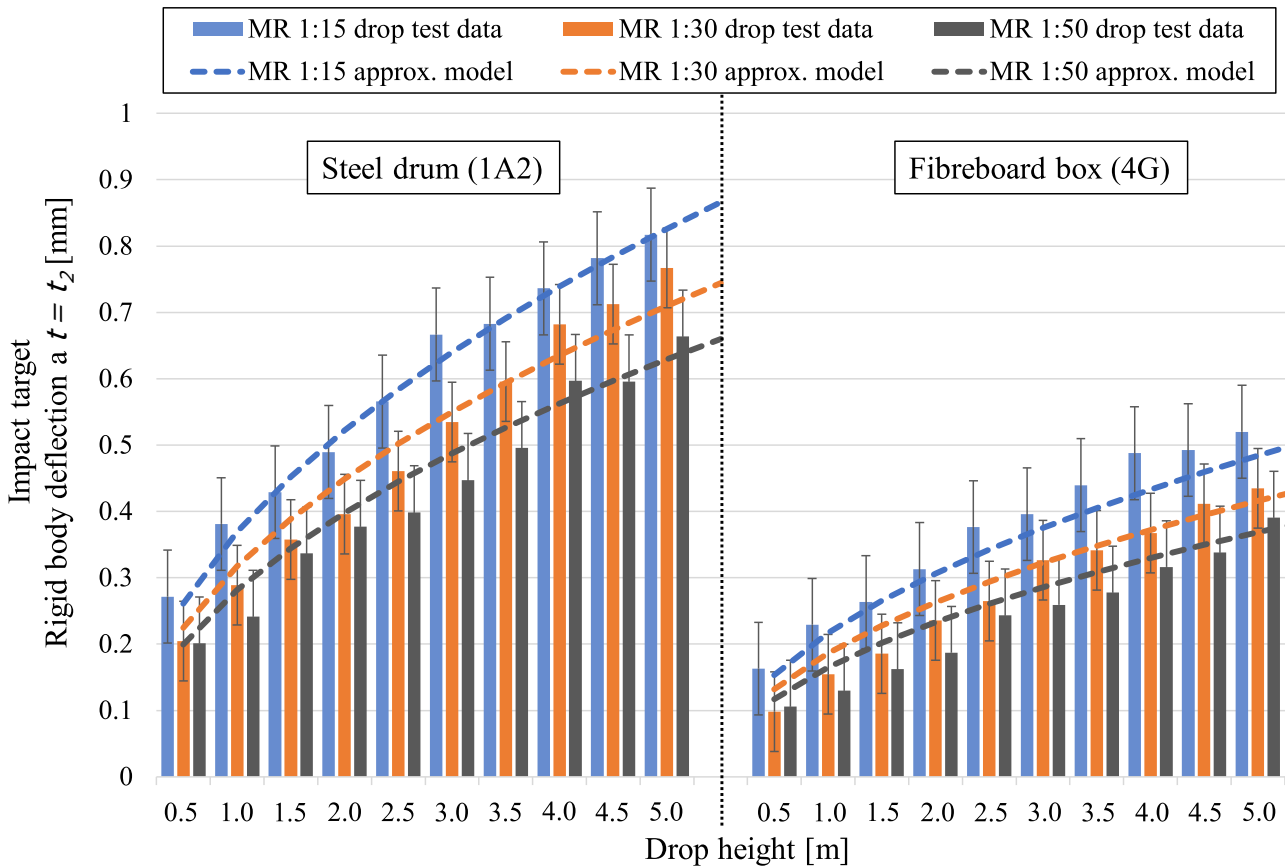


FIGURE 15 Results of drop test series with parameter variation.

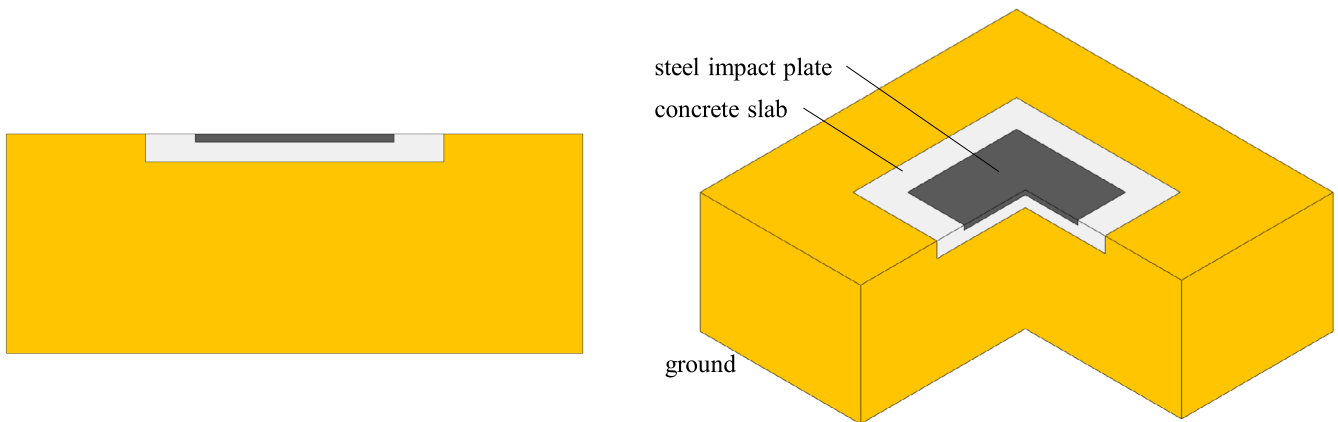


FIGURE 16 Schematic representation of typical installed impact target structure.

$$\frac{d_0}{d_{0,LIMIT}} = f(\alpha, MR, \zeta) = 7.14 \alpha \sqrt{\frac{MR}{(1 - \zeta^2)(MR + 1)}} < 1 \quad (19)$$

A value of  $f$  greater than 1 signifies that the actual deflection value surpasses the defined threshold; that is, the respective impact target would not be suitable to use in regulative drop tests.

#### 4.1 | Example of application in practice

An example of a hypothetical impact target with properties in line with those of a typical already installed impact target structure<sup>4</sup> is considered, as shown in Figure 16. The impact target consists of an installed concrete slab with an anchored impact plate made of mild steel.

**TABLE 5** Impact target and packaging properties in drop test.

Impact target properties	
Length $L$ (m)	2
Width $W$ (m)	1.125
Thickness $z$ (m)	0.15
Mass $m_2$ (kg)	1000
Damping ratio $\zeta$ (–)	0.1
Packaging properties	
Impact characteristics $\alpha$ (–)	0.6
Mass $m_1$ (kg)	100

To illustrate the practical application of the new evaluation criteria, following drop test parameters are chosen and listed in Table 5.

Both new criteria need to be fulfilled for the impact target in Table 5 to be suitable for assessing the respective packaging's resistance to mechanical damage in regulative drop tests.

- Parameters  $\lambda_1$  and  $\lambda_2$  are calculated;  $\lambda_1 = \sqrt{2.25}/0.15 = 10$  and  $\lambda_2 = 2/1.125 = 1.8$ ; thus, the first criterion is fulfilled considering the threshold defined in Figure 12.
- However, the deflection ratio function  $f(\alpha, MR, \zeta)$  yields a value of  $f = 1.3$  according to Equation (11); the second criterion is not satisfied.

The impact target is therefore not admissible for use in regulative drop tests with respect to the observed packaging.

## 5 | CONCLUSION

Two drop test series were carried out with the purpose of improving existing criteria for evaluating impact targets in regulative drop tests of dangerous goods packagings. Within the first series, the 50% failure drop height for steel drum and fibreboard box packagings were determined according to the Bruceton method. The results were statistically inconclusive regarding the influence of mass ratio in the drop test outcome. However, the experimental results were plausible considering the different packaging material properties and the similar mechanical response of the model impact targets. Hence, a variation of packaging type, target eigenfrequency, and mass ratio was carried out in the second drop test series. Based on the findings, two new and improved criteria are proposed for impact target structures comparable to the impact pad. Thereby, a threshold regarding impact target dimensions was determined to guarantee negligible elastic deformation of the impact surface in the drop test. In addition, a rigid body deflection ratio function is defined for the impact target and takes values between 0 and 1. Values larger than 1 are not admissible. They represent an amount of potential energy that exceeds the analytically defined limit of approx. 2%. If both new criteria are satisfied, then the respective impact target structure is suitable for regulative drop testing. This evaluation method encompassing both new criteria

can substitute the current regulation requirement of mass ratio of 1:50 between impact target and package. The results of this work can make a substantial contribution to improve the transferability of experimental and analytical data into practice, that is, in quality control during series production of dangerous goods packagings. Furthermore, this research forms the basis for introducing a standard practice, its technical implementation, and the development of templates for coordination at European and UN level, particularly for proposing changes to ISO 2248.

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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.

## ORCID

Nikolaos Lengas  <https://orcid.org/0000-0003-0989-9502>

Eva Schlick-Hasper  <https://orcid.org/0000-0003-4486-2465>

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