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BLAST RESISTANT TRASH RECEPTACLES WITH BLAST LOADING REDIRECTION – COMPARATIVE ANALYSES

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ABSTRACT

Many terrorist attacks in the last decade around the world have exposed the vulnerability of citizens in public places. Public trash receptacles can be easily abused as well-covered places in which Improvised Explosive Devices (IED) can be simply left and then remotely activated. Therefore, blast resistance and possibility of blast loads redirection are very important characteristics of trash receptacles placed in crowded public areas. This paper presents the results of three different trash receptacles: non-blast resistant, blast resistant and blast resistant trash receptacle with blast load redirection. The results have shown that a considerable effect can be achieved by using blast resistant receptacles, thus reducing the possibility of deaths and injuries. A thickness optimization study was additionally performed, based on the size and geometry of the opening by using a finite element model. Based on the results of the study, some valuable recommendations for design of trash receptacles are also given.
Keywords: blast loading, blast response, blast response container, trash receptacle.

1 INTRODUCTION

According to the Department of Homeland Security Science and Technology Center of Excellence [1] nearly 54% of all terrorist attacks in 2014 were done using explosive devices, random citizens or police being a target in around 55% cases. Trash receptacles at shopping centers, metros, city centers, airports, stadiums, streets and etc. can be easily abused by simply dropping the IED. Therefore the replacement of usual receptacles with blast resistant ones at crowded public places can save lives or prevent people's injuries. For that purpose, the blast response examination of trash receptacles is of great importance.

Public trash receptacles are of different designs and sizes. They can be classified as plastic bag, plastic, metal or concrete receptacles based on the material they are made of (Fig. 1). They can also be with or without accompanying housing. Other important classification can be made based on their position relative to the ground, thus grounded (Fig. 1c) or hanged (Fig. 1a). All these classifications greatly influence the blast wave dispersion and possible fragmentation which could prove to be fatal for the people around in case of explosion. Therefore, it is necessary to examine and improve the response of trash receptacles to these high-intensity, short-term loads.

However, preparation and performance of such tests are extremely expensive. It involves a large number of experts from various fields, in some cases even special legal permits and

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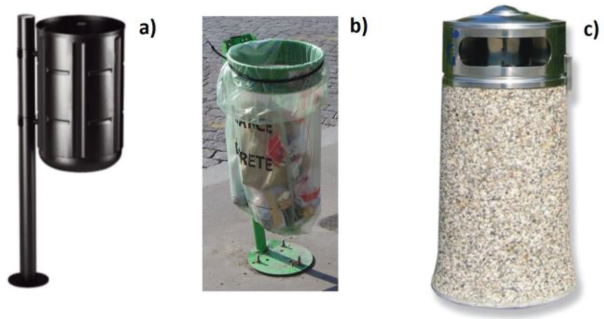

Figure 1: Public trash receptacles.

additional safety requirements are necessary, making numerical analysis the most valuable tool for the examination.

Empirical ConWep method [2], Arbitrary Lagrange Euler (ALE) [3–5] and Smooth Particle Hydrodynamics (SPH) [6–8] are successfully applied methods for blast response examination of military and civilian structures [9–14]. However the literature concerning internal blast response of cylinders is quite rare. Benham and Duffey [15] studied the experimental-theoretical correlation of internal blast response of closed cylindrical vessels, Langdon *et al*. [16] investigated the response of partially confined stainless steel cylinders to internal air-blast loading, Liu *et al*. [17] blast resistance of sandwich-walled hollow cylinders with graded metallic foam cores, and Yousef *et al*. [18] studied blast response of trash receptacles.

In this study, the results of three different hanged metal trash receptacles without housing are presented. For that purpose the explicit code LS-DYNA was used. Although the SPH method has been already used for blast response analyses of military structures [19–21], by our knowledge, it will be used for the first time for blast response examination of trash receptacles. Thickness optimization analyses using the parametric numerical model were also successfully performed using the design optimization and probability analyses software LS-OPT.

2 NUMERICAL MODELS DESCRIPTION

The SPH method has proved to be a reliable and efficient method for modeling blast response of Light Armored Vehicles (LAV) and other structures [19, 21–25]. It is a time efficient method because does not require the surrounding air to be represented in the model. Because the air is not modeled, it is difficult to track the blast wave loading parameters at a certain point in the space. However, the interest of this study is focused only on the response of receptacles to blast loading. Therefore the SPH method was used in a combination with the well-known Finite Element Method (FEM).

2.1 Geometry and spatial discretization

The openings of trash receptacles are usually large enough to fit a surprisingly large enough charge, capable to destroy even a heavy tank. Considering the density of the TNT explosive given in the Table 1 and the size of the openings shown in Fig. 2, we are coming up to around 10 kg charge masses, comparable to a middle size anti-tank mine. Therefore, the geometry

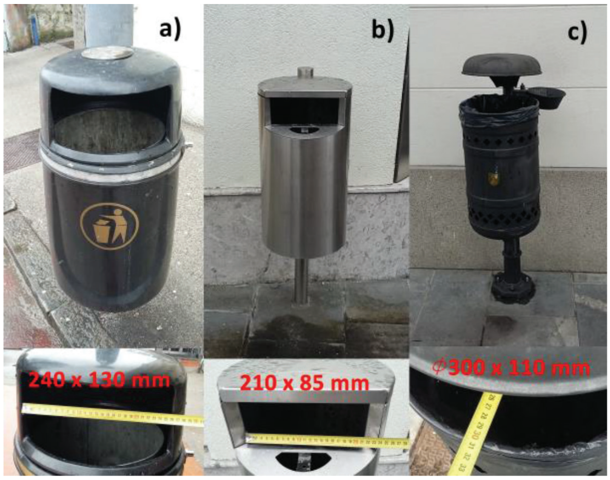

Figure 2: Trash receptacles - openings sizes/dimensions.

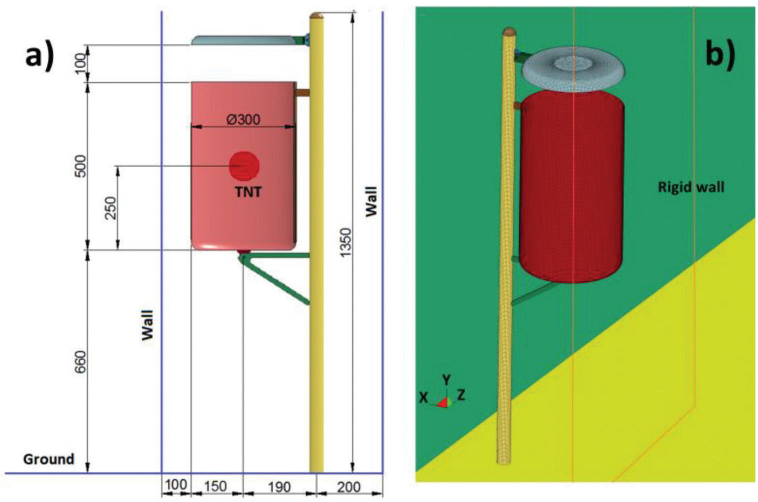

Figure 3: Trash receptacle model: (a) geometry (b) spatial discretization.

with the largest opening shown in Fig. 2c was taken as baseline geometry for this analysis. Its simplified geometry and spatial discretization are presented in Fig. 3 respectively.

Structural trash receptacle was represented with Johnson-Cook material model [26, 27] and 48,500 Lagrangian shell elements with one integration point. Because of that the hourglass energy of the receptacle was carefully controlled to be under 3% of the internal energy. The explosive TNT charge was represented with 14,628 SPH particles in a form of a sphere with diameter 84.2 mm, thus representing a mass of 0.5 kg. In order to simplify the analyses, the all surrounding parts in the numerical model were modelled as rigid. Contacts between different parts in the model were represented with automatic surface to surface or tied surface to surface to better approximate the reality. The contacts between SPH particles and the structural parts were represented with automatic nodes to surface penalty based contact available in LS-DYNA.

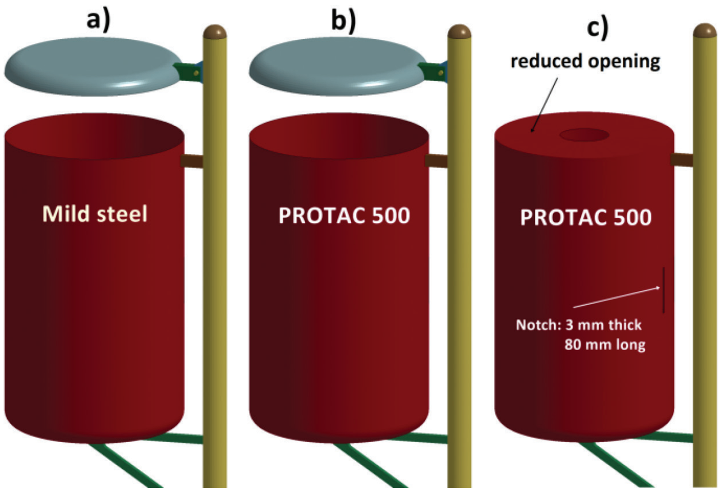

Figure 4: Representation of the numerical models.

Three numerical models shown in Fig. 4 were analyzed in this study: (**a) non-blast resistant model** representing the commonly used trash receptacles made of mild steel, (**b) blast resistant model** in which armored steel PROTAC 500 was used to replace the mild steel and (**c) closed blast resistant trash receptacle with a blast load redirection model** with reduced opening size and two notches on its back side (Fig. 4). It is assumed that the cover plate of the model **c** is strongly attached to the receptacle cylinder. In all three variants the receptacle thickness of 2 mm was chosen. In order to compare the numerical results, rigid wall (0.8 m wide and 2 m high) was placed at a 0.1 m distance from the receptacle, as shown in Fig. 3b. The mesh refinement study was also performed successfully.

2.2 Material models

For the purpose of numerical representation of structural materials, Johnson-Cook (J-C) model was used. The J-C model is based on von Mises plasticity, where the yield stress is scaled depending on the state of equivalent plastic strain, strain rate and temperature:

$$\bar{\sigma} = \left(A + B\left(\bar{\varepsilon}_{pl}\right)^{n}\right)\left(1 + C ln\, \dot{\bar{\varepsilon}}^{*}_{pl}\right)\left(1 - T^{*m}\right), \tag{1}$$

where A, B, n, C and m are material constants, $\bar{\varepsilon}_{pl}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}^{*}_{pl} = \dot{\bar{\varepsilon}}_{p} / \dot{\varepsilon}_{o}$ dimensionless strain rate, where $\dot{\bar{\varepsilon}}_{pl}$ is the equivalent plastic strain rate and is the reference strain rate. Dimensionless temperature is given by $T^*=(T - T_r)/(T_m - T_r)$, where T is the current temperature, T_r is the reference temperature and T_m is the melting temperature of the material.

Similarly the damage model is given by the equation:

$$\bar{\varepsilon}^{f}_{p} = \left(D_1 + D_2 \exp\left(D_3 \sigma^{*}\right)\right)\left(1 + D_4 ln\, \dot{\bar{\varepsilon}}^{*}_{pl}\right)\left(1 + D_5 T^{*}\right), \tag{2}$$

where D_1–D_5 are material constants to be determined from experiments, $\sigma^* = \sigma_H / \bar{\sigma}$ is a stress triaxiality ratio and is hydrostatic pressure.

2.2.1 Mild steel

Different low carbon steels, stainless steels, aluminum alloys and cast irons are common metallic materials used for trash receptacles production. Because they are not commonly used in such harsh environments under severe sort-term loading conditions, material parameters describing their behavior are rarely available in the literature or do not exist. However, for the purpose of the study, higher class low-strength mild steel was chosen for which material parameters regarding the J-C strength and fracture models are available in the literature and are given by Iqbal *et al*. [28].

2.2.2 PROTAC 500

PROTAC 500 is a low carbon high-strength steel which is complexly alloyed with Si (1.01 m. %), Cr (0.69 m. %), Mo (0.33 m. %), and microalloyed with Ti (0.027 m. %) and B (0.002 m. %) [29, 30]. Preliminary ballistic test performed at NATO (North Atlantic Treaty Organization) accredited Beschussamt institute in Ulm, Germany, showed that PROTAC 500 can be successfully used for military and civil applications where high protection is needed [30]. The material parameters used for PROTAC 500 regarding the J-C strength as well as fracture model are given by Trajkovski *et al.* [31], shown in Table 2.

2.2.3 TNT Explosive

The explosive charge in the models was represented with MAT_HIGH_EXPLOSIVE_BURN in combination with Jones-Wilkins-Lee (JWL) equation of state (EOS):

$$p = A\left(1 - \frac{\omega}{R_1 v}\right) exp^{-R_1 v} + B\left(1 - \frac{\omega}{R_2 v}\right) exp^{-R_2 v} + \frac{\omega E}{v}, \tag{3}$$

Table 1: Material properties and JWL parameters of TNT.

ρ (kg/m^3)	D (m/s)	P_{CJ} (GPa)	A (GPa)	B (GPa)	R_1 (–)	R_2 (–)	w (–)	E (J/m^3)
1,590	6,930	21.0	371.2	3.231	4.15	0.95	0.3	$7*10^9$

Table 2: J-C model parameters for PROTAC 500.

J-C strength parameters	*A* (MPa)	*B* (MPa)	*n* (–)	*C* (–)	*m* (–)
	1,380	948	0.2351	0.0035	1.087
J-C fracture parameters	D_1 (–)	D_2 (–)	D_3 (–)	D_4 (–)	D_5 (–)
	0.0001	1.586	−1.718	0.00695	3.247

which calculates the blast pressure as a function of relative volume n=r_0/r, and internal energy E, for an explosive element. In this equation A, B, R_1, R_2, and w are parameters related to the explosive material and can be found in most of the explosive textbooks. They were taken from reference [32] for TNT high explosive and are given in Table 3.

Table 3: J-C model parameters for mild steel.

J-C strength parameters	A (MPa)	B (MPa)	n (–)	C (–)	m (–)
	304.33	422	0.345	0.0156	0.87
J-C fracture parameters	D_1 (–)	D_2 (–)	D_3 (–)	D_4 (–)	D_5 (–)
	0.1152	1.0116	–1.7684	–0.05279	0.5262

2.3 Thickness optimization model

Thickness optimization analysis was performed using the parameterized numerical model **c** by means of LS-OPT, software for structural design optimization and probability analyses. Metamodel-based optimization was performed using single iteration strategy minimizing the weight of the receptacle and resultant force acting on the wall in the numerical model. Default Radial Basis Function Network with space filling was used for determination of the sampling points and LS-PrePost software was used to build the numerical models based on the defined sampling point values. In order to simplify the model, only the plate thickness was considered to be a continuous parameter varied between 0.6 mm and 3 mm while the charge mass and its location remained constants. Ten sampling points were defined instead of minimum default value of five to increase the accuracy of the metamodel.

3 RESULTS

The results comparison of the three models is visually presented in Fig. 5. It is obvious that model (**a**), in which the receptacle is made of mild steel is the weakest solution.

The receptacle has broken into small fragments moving radially with initial velocity of 270 m/s (Fig. 6), while models (b) and (c) showed more improved response to blast loads, almost without fracture. Since no fragmentation occurred in models (b) and (c) the resultant velocities of the nodes were reduced to lower values (Fig. 6), mainly representing the global velocity of the receptacle. In Fig. 7, are presented the resultant forces acting on the rigid wall placed in front of the receptacle (Fig. 3b). Since fragmentation occurred in the model **a**, some of the fragments hit the rigid wall delivering higher peak forces. However, in impulsive loading regime the impulse delivered to the structure is responsible for its response rather than the peak force. Therefore the results for the total impulse acting on the wall for all three models are shown in Fig. 8.

It can be clearly seen in Fig. 8 that model **c** represents improved blast resistant receptacle. Namely, the total impulse maximum value of model **c** is reduced about 93% compared to the basic model and 77% compared to model **b**. This is due to achieved receptacle bending mode and thereby redirecting the blast wave away from the dense pedestrian zone as it is shown on Fig. 9.

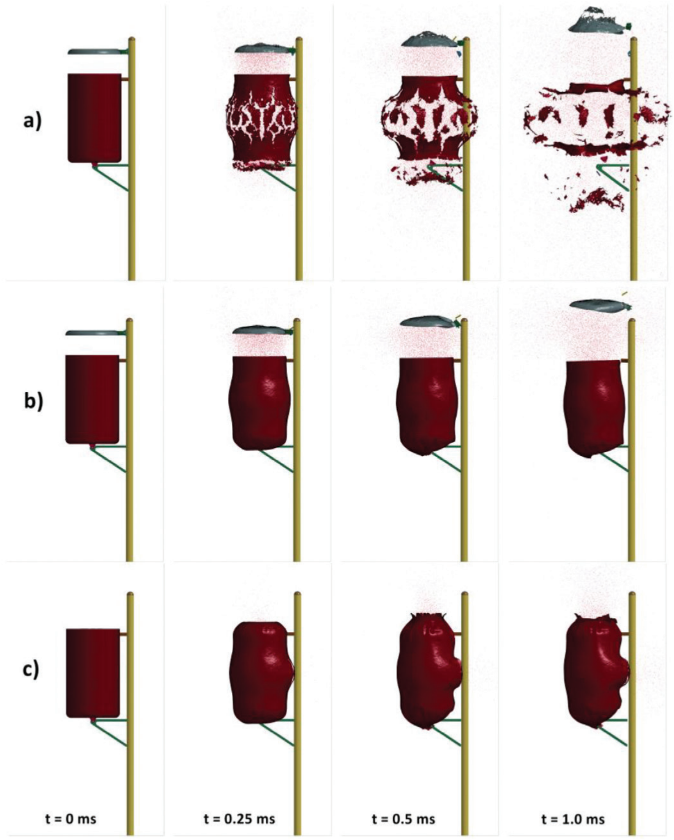

Figure 5: Results comparison – receptacles deformation.

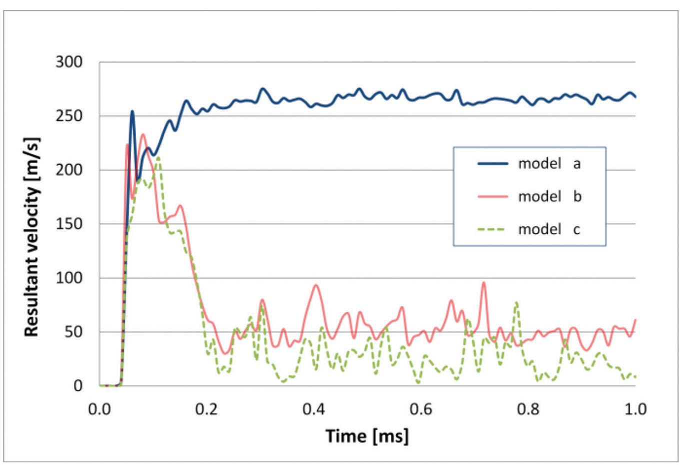

Figure 6: Results comparison – Initial velocity of fragments.

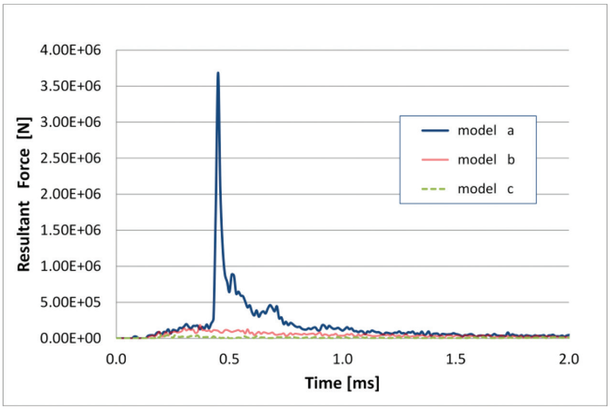

Figure 7: Results comparison – resultant force acting on the rigid wall.

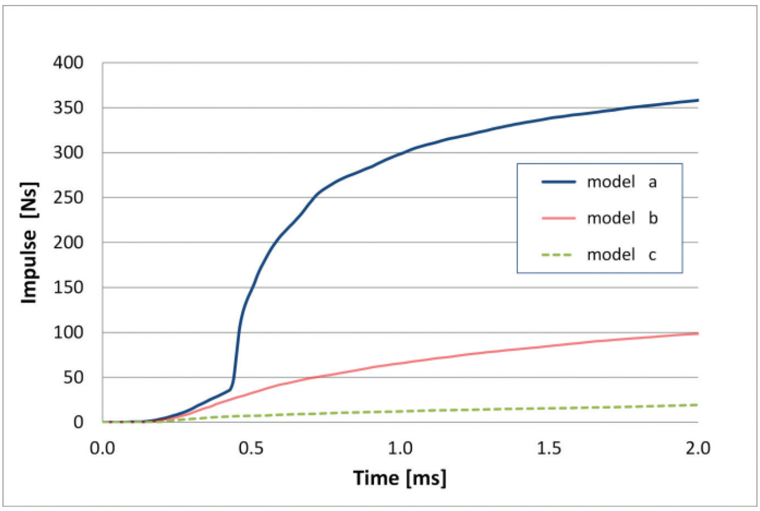

Figure 8: Results comparison – total impulse acting on the rigid wall.

In Fig. 10, the output results of the numerical model for each thickness defined with the sampling points are shown. The proposed thickness of 1.7 mm, based on the metamodel optimization which meats the objectives defined in section 2.3 is also shown in the same figure. The accuracy of the metamodel was relatively high, defined with the value of the coefficient of determination of $R^2 = 0.994$ for total impulse prediction.

4 CONCLUSION

In this article, comparative analysis of blast resistance of trash receptacles for crowded public areas was presented. Based on the results of the comparative analyses, metamodel-based optimization was additionally performed and optimal design of the receptacle achieved. The comparison of results showed that blast resistant trash receptacles can greatly reduce the loading parameters in dense pedestrian areas and their usage in crowded public areas can save people's lives or reduce the severity of injuries. The presented bending mode of the receptacle

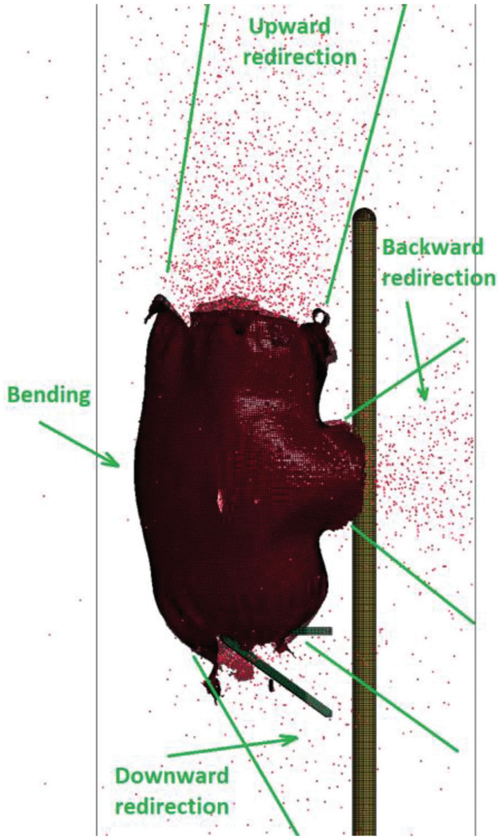

Figure 9: Receptacle bending - redirection of blast wave.

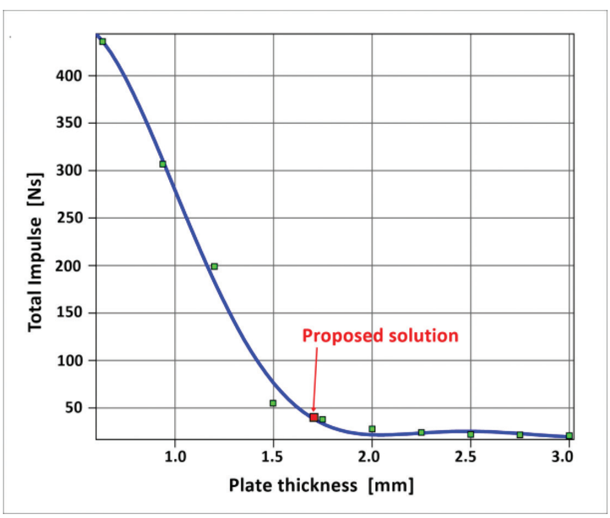

Figure 10: Metamodel results.

just indicates that a lot more can be done to increase the effectiveness of blast wave redirection in trash receptacles. The size of the opening should prevent large volumes to be placed in and its location should be carefully planned to avoid direct blast loading of people. The receptacle holder's locations in combination with the notches geometry and their location have a crucial role in the receptacle deformation mode and therefore should be investigated in future.

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