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Study on a new mobile anti-terror barrier

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Abstract

The vehicle-ramming terror attacks in Berlin, Barcelona, London and Nice highlighted our vulnerability: all of us could be wounded or killed during a walk in a crowded place, it is sufficient a car, a van or a truck. The authors of this paper designed a planter full of water and mainly made of steel and cast iron. For this reason, this device serves as both mobile anti-terror barrier and street furniture.
This barrier can stop a 3500 kg vehicle running at 64 km/h and the system itself in less than five meters as demonstrated by the experimental crash test. Starting from these considerations, a simplified mathematical model of the impact was developed and a finite element model was calibrated. The first one points out the main features needed by the obstacle; the second one is a good base for further analyses.

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Keywords: anti-terror barrier, crash, mathematical model, FEM, SPH, experimental test

1. Introduction

The recent terror attacks in Nice, Berlin, Barcelona and London involved trucks or vans slammed into crowds. This aspect has pointed out the necessity of protection for the pedestrians in crowded areas. At the moment, the application of barriers is the most common solution. The current systems can be divided into three categories: fixed, retractable and mobile. Fixed protections have a foundation system and can stop immediately a vehicle. On the other hand, the

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debris could wound the pedestrians. Moreover, these barriers are expensive because of the pose of the foundation and prohibit the passage of the emergency vehicles. Although they require the foundation on the ground, the retractable protection systems (mobile bollards for instance) allow the passage of vehicles when necessary, because they are able to retract inside a compartment in the foundation itself. However, the complexity of the drive system makes them expensive. The mobile protection systems have not any kind of permanent connection to the ground. The most widespread mobile protection systems are jersey barriers and concrete cubes. Their placement gives a false sense of security in the collective imagination because this type of barrier cannot stop a vehicle in an acceptable distance as shown in Baragetti and Arcieri (2019). Nevertheless, today they are commonly used to protect areas because of their low cost and easy availability.

In the last years, a lot of ideas for barriers were born. Some of them are presented in Titmus (2007), Amengual Pericas (2009), Shen et al. (2010), Impero (2013) and Stevanato (2014).

Baragetti and Arcieri (2019) have already designed a new good-looking mobile barrier in collaboration with Besenzoni S.pA. and Besenzoni Defence & Protection S.r.l. This device is mainly made of steel and cast iron, and for this reason it is highly deformable. The final shape of the system is a planter full of water, which can dissipate huge quantities of energy. The barrier is therefore also street furniture.

This work starts from the results of the experimental crash test of a 3500 kg vehicle running at 64 km/h against a single planter-barrier and propose a mathematical model which describes the main features of the anti-terror system. Furthermore, a calibration of the last numerical model presented in Baragetti and Arcieri (2019) is described in order to have a good base for further analyses which could involve for example bigger vehicles.

Nomenclature

A%	elongation
c_0	reference sound speed
e	generic displacement due to F
E	Young's modulus
$E_{barrier}$	energy transferred to the barrier
E_{def}	deformation energy
$E_{friction}$	energy dissipation by friction
E_{kin}	kinetic energy of the van
E_{pot}	potential energy of the van
F	arbitrary force
F_{impact}	force during the impact
g	gravitational acceleration
h	maximum displacement in the vertical direction of the van
k	stiffness of the barrier
M	mass of the van
m	mass of the barrier
t	duration of the impact
v	initial speed of the van
X	slope of the Us-Up curve
YS	yield strength
Γ_0	Gruneisen ratio
δ	deformation of the barrier
Δx	displacement of the barrier
μ	dynamic coefficient of friction barrier-ground
ρ	density
υ	Poisson's ratio

2. Materials and methods

2.1. Description of the barrier

The object of this work is an anti-terror barrier (Fig. 1) which consists of a solid cast iron base, divided into three blocks, perimeter sheet metals in S235JR, a tank and a plastic plate for the flowerpots. The dimensions are 3000mmx860mmx1010mm (radius of curvature: 430 mm). A bag made of polymeric material contains the water, which increases the mass of the barrier once it has been placed. The very reduced strength of the polymeric bag makes the water leak in the event of a collision and transform part of the initial energy of the vehicle in potential and kinetic energy of the water as described in Baragetti and Arcieri (2019). The total mass of the barrier is 3600 kg (1550 kg of water + 2050kg of other components).

The sheet metals (blue and pink in Fig.2a) are 4 mm thick. A plate (10 mm of thickness) is present between the sheet metals and it allows their connection by means of bolts. These plates are notched in order to have a small impact resistance. The red and blue components in the lower part of the barrier aim at puncturing the tires of the vehicle. The base has a series of components (green in Fig.2b) arranged in a radial pattern, six for each support point, which increase friction with the ground. This barrier is therefore able to absorb the kinetic energy of the vehicle and transform it into other forms:

- Plastic deformation (deformation of the sheet metals)
- Viscous dissipation (water)
- Kinetic and potential energy of water
- Energy dissipation by friction between the planter and the ground

All these aspects are indeed needed to stop a vehicle within few meters.

Fig. 1. Anti-terror barrier.

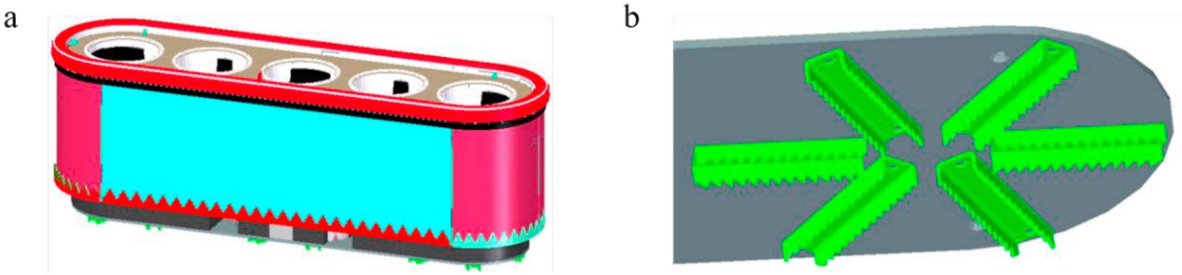

Fig. 2. Anti-terror barrier: (a) CAD; (b) detail of the base.

2.2. Experimental crash test

The performance of the anti-terror barrier in case of an impact with a 3500 kg van running at 64 km/h was evaluated in the crash test described in Baragetti and Arcieri (2019) which was carried out according to PAS (2013) and IWA (2013). The vehicle is an Iveco Daily 35c11 and a ballast was added in order to reach the total mass prescribed by the standards. These standards do not provide acceptable values of displacement for the barrier because they deal with fixed obstacles. Tires, suspensions, wheel alignment and bodywork were compliant to the standards. No repairs, modifications or reinforcements were made because they could alter the general characteristics of the vehicle and invalidate the certification. The van was hauled by ropes and hit the barrier in the perpendicular direction. On the external surface of the vehicle some benchmarks were positioned in order to facilitate the post impact analysis.

In the following lines the dynamics of the impact is described because one of the aims of this paper is to reproduce it. After the first contact between the van and the frontal sheet metal of the barrier, the plastic deformation of the planter and the front of the van began. The water in the barrier opposed the motion of the vehicle by means of its pressure, which was consequence of the deformation of the bag. The water pressure increased until the rupture of the bag in polymeric material occurred, thus allowing the release of pressurized water towards the open end of the planter. As a result of the leakage of the water, the penetration of the van was facilitated and the front tires came into contact with the puncturing system. This device perforated the tires which then gripped the sheet metals and connected the van to the planter. Then the barrier was accelerated in the direction of vehicle travel. However, the van had already lost much of its speed due to the energy dissipation. The action of the overturning moment given by the force of impact made the puncturing device placed in the rear area wedge into the asphalt and raised the van and the barrier itself. Then, the van and the planter fell to the ground. The puncturing device wedged into the asphalt generating mechanical resistance and stopping the vehicle completely.

In conclusion, Aisico (2018) reports that the barrier completely stopped the test vehicle and caused several damages to the cabin and the front axle. The maximum penetration was 2.1 m for IWA standard and 1.3 for PAS standard. The barrier shifted of 3.8 m on right edge and 2.8 m on left edge. The difference in displacement between the two sides can be due the actual impact angle: 90.1°. Because of the huge quantities of energy involved during the crash, it is indeed sufficient a small misalignment to have a different behavior.

2.3. Mathematical model

Fig.3 shows the mathematical model which is simplified and is useful in order to define the main features needed by the barrier. The van is represented as a mass (*M*) with an initial speed v. The van is considered non-deformable because it is difficult to find data about the stiffness of the vehicles. The deformation of the barrier is modelled by a spring with stiffness equal to k. The whole barrier can move on the ground and μ is the dynamic coefficient of friction barrier-ground. The barrier is suitable to be placed on different types of surfaces. For this reason, an average value equal to 0.65 is chosen for μ. Indeed, μ for rubber on wet asphalt (worst case) is between 0.6 and 0.7 as stated in Baldi (2017).

The mathematical model should take into account the energy dissipated by the water in the planter. In first approximation, a constant mass of the barrier can be assumed. In this way, this term is incorporated in the energy dissipation by friction because the mass is higher than the actual value, which is instead variable over time.

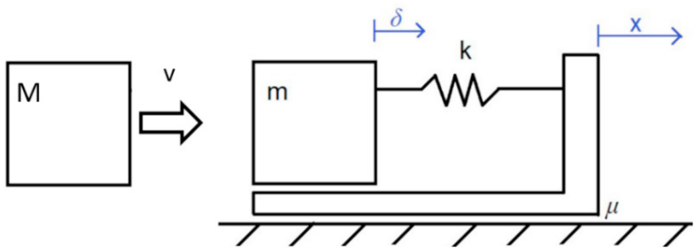

Fig. 3. Mathematical model (*M* and *v* are the mass and the speed of the vehicle, *m* is the mass of the barrier, *k* models the stiffness of the barrier, μ is the dynamic coefficient of friction, δ is the deformation and *x* is the displacement).

The barrier raises the van. For this reason, the kinetic energy of the van can be split into two parts: potential energy of the van and energy transferred to the anti-terror barrier. The first part is then dissipated by the gravitational field while the second one is dissipated by deformation (in first approximation, under the hypothesis of linear elastic behavior) and friction. Therefore, the problem can be modelled as follows:

$$E_{kin} = E_{pot} + E_{barrier} \; \& \; E_{barrier} = E_{def} + E_{friction} \quad (1)$$

This approach considers only the situation before and after the impact, which are the only well-known moments. In case of inelastic collision Eq. 1 becomes:

$$\frac{1}{2}Mv^2 = Mgh + E_{barrier} \; \& \; E_{barrier} = \frac{1}{2}k\delta^2 + \mu(M+m)g\Delta x \quad (2)$$

In case of elastic collision:

$$\frac{1}{2}Mv^2 = Mgh + E_{barrier} \; \& \; E_{barrier} = \frac{1}{2}k\delta^2 + \mu mg\Delta x \quad (3)$$

The stiffness k of the barrier is approximately calculated by a finite element model in Abaqus Standard based on the idea that, under the hypothesis of linear elasticity, the displacement e due to an arbitrary force F is equal to

$$e = \frac{F}{k}. \quad (4)$$

This model contains the barrier. The force F is applied at a reference point which distributes the load on the front face of the obstacle in correspondence of an area representing the van bumper (Fig. 4). A small portion of the base is then fixed to the ground.

In this way, the deformation of the barrier and consequently the stiffness are calculated (k=625000 N/m).
In Eqs. (2) and (3) δ is assumed equal to

$$\delta = \frac{F_{impact}}{k} = \frac{Mv}{t} \quad (5)$$

The duration of the impact is assumed t=0.1 s, as indicated in ACI (2017). Table 1 summarizes the data of the mathematical model.

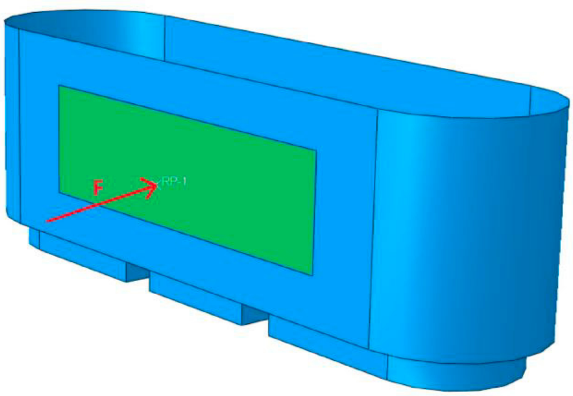

Fig. 4. Model for the calculation of the stiffness of the barrier (F is the applied force).

Table 1. Data of the mathematical model from ACI (2017), Aisico (2018) and Baragetti and Arcieri (2019).

Feature	Value
M	3500 kg
v	17.78 m/s
k	625000 N/m
t	0.1 s
g	9.81m/s^2
h	1.5 m
μ	0.65
m	3600 kg

2.4. Numerical model

The numerical model is built in Abaqus Explicit 6.14-5 because explicit calculations are recommended for crash events as stated for example in Borovinsek et al. (2009). The water in the planter is simulated by means of Smooth Particle Hydrodynamics (SPH) which is suitable for this type of models according to Monaghan (2005). Indeed, modelling a fluid could require very dense mesh because the high possible deformations and the consequent distortion of the elements which could generate errors during the calculation. SPH is a lagrangian method which creates a series of particles, points with mass at a defined distance. A physical quantity of a particle is a function of the quantities of the particles near it (kernel approximation). The polymeric bag is not present because its strength is very low.

This model aims at reproducing the behavior of the experimental crash test and it is a modification of the model presented in Baragetti and Arcieri (2019).

The model of the van (Iveco Daily 35c11) is very simplified in order to reduce the computational cost. The van is modeled with shell elements. It is made of two rectangular cuboids representing the body and the front part. The dimensions are presented in Table 2 and comply with the main specifications of the van used in the experimental test as described in Aisico (2018).

Table 2. Data of the van, from Aisico (2018).

Feature	Value	Note
Wheelbase of the vehicle	3750 mm	
Mass	3500 kg	With ballast
Height from the ground	330 mm	Frontal part
Position of the center of gravity in longitudinal direction	1730 mm	From the front axle
Position of the center of gravity in transversal direction	1076 mm	From the ground

The experimental test returned the bursting of the tires. Because this aspect is very important for the correct reproduction of the collision, the deformation of the wheels is modelled.

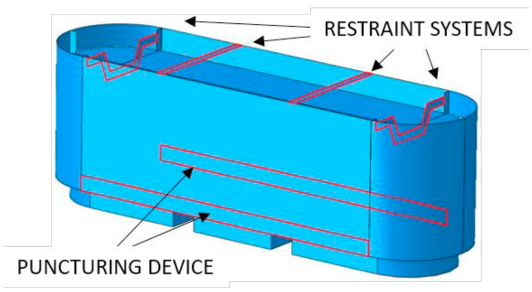

Fig. 5. Model with restraint systems and tires puncturing device.

A series of restraint systems in S235JR (thickness: 5 mm, Fig. 5) in the upper part of the barrier avoids excessive deformation of the vertical sheet metals due to the pressure of the water in the tank. These structures stiffen the anti-terror barrier but their deformability in the event of a collision and therefore the ability to dissipate energy are assured by the notches in the central points. The restraint systems are modelled with shell elements. It is not necessary to weaken the center line because buckling causes the rupture of these components and the finite element model does not take into account it. Also the tires puncturing device (Fig.5) is modelled. It makes the van undriveable and its deformation gives a gripping action on the ground which causes a rapid arrest of the vehicle-planter assembly. Furthermore, the planter rotates and the raises the van because of the penetration of this components in the tires of the vehicle. The tires puncturing device is modelled by a rectangular surface. A fictitious coefficient of friction with the ground equal to 1 is defined. This value is a consequence of different numerical models and provides a behavior of the system similar to the experimental crash test. The coefficient is fictitious because the actual mechanism is not based on friction but on a mechanical resistance to motion given by the constraint between the surface and the ground.

The six components for each support point are not modelled. The 10 mm thick plates are also not modelled. In the correspondent areas, the thickness of the perimeter sheet metal is increased in order to have the same total thickness (4 mm + 10 mm + 4 mm = 9 mm + 9 mm).

Table3 summarizes the material properties. The barrier is made of sheet metals in S235JR and a base of cast iron. The energy equation of water is according to Wilkins (1999). S235JR's material properties are assigned to the external surfaces of the van and the rims with a density chosen according to the need to place the center of gravity at the correct position.

The ground is fix and not deformable.

Table 3. Material properties.

Material	ρ (kg/m^3)	E (N/m^2)	ν	YS (N/m^2)	c_0 (m/s)	X	Γ_0
S235JR (elastic-perfectly plastic)	7800	2.06e11	0.30	2.35e8			
Cast iron	7300	1.20e11	0.26	2.50e8			
Water	1000				1450	0	0

The simulation is divided into two steps:

- "Gravity" (20 ms): it activates the interactions between the parts thanks to the gravity load
- "Dyna" (400 ms): it is the step in which the crash occurs.

All the joints are modelled by means of kinematic connections and the interactions of Table 4 are defined.

Table 4. Interactions.

Interaction	μ
Ground – Base of the barrier	0.65
Ground – Vertical sheet metals of the barrier	0.40
Ground – Tires puncturing device	1.00
Ground – Wheels	0.01
Van – Vertical sheet metals of the barrier	0.10
Van – Base of the barrier	0.20
Van – Tires puncturing device	0.10
Wheels – Base of the barrier	0.70
Wheels – Vertical sheet metals of the barrier	0.70
Wheels – Tires puncturing device	0.70
Entire model – Entire model	0.00

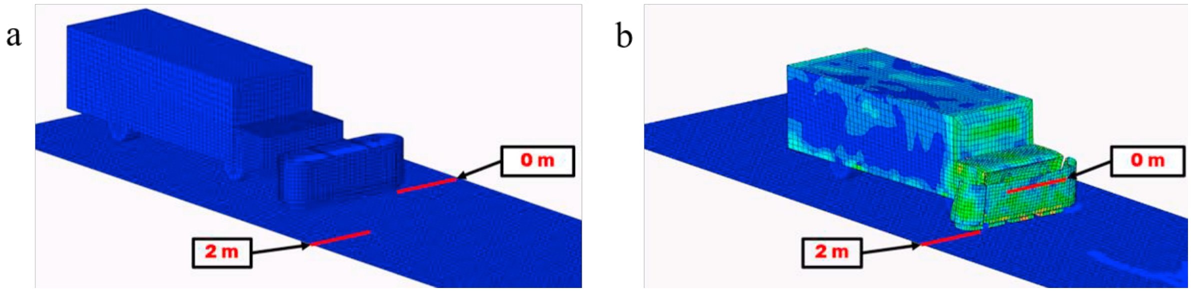

Fig. 6. Numerical model: (a): initial instant; (b) final instant.

The very small value of μ for the interaction "ground-wheels" considers the rolling friction because in the model the wheels cannot rotate.

The mesh of the model is made of S4R and C3D8R elements for surfaces and volumes and it is as symmetrical as possible in order to avoid an asymmetrical behavior of the system. For the interacting parts the mesh is congruent.

3. Results and discussion

The maximum height reached by the center of gravity of the van in the experimental test is h= 1.5 m as reported in Aisico (2018).

According to the mathematical model, a displacement of 4.2 m in case of inelastic collision and 8.3 in case of elastic collision were obtained. For this reason, an inelastic collision is preferable which is the type of collision occurred during the experimental test. Moreover, the displacements of the mathematical model are similar to the result of the experimental crash test even if the model is simplified. Indeed, this model aims at finding the needed features for a powerful mobile anti-terror barrier. First of all, the barrier needs to be very deformable in order to absorb high quantities of energy and stop the van within a few meters. This objective can be obtained using thin sheet metals. Also friction is very important and for this reason high coefficient of friction and high mass are necessary. Since a heavy object is difficult to transport, the high mass of the barrier should be reached in place. Water fills the barrier after its placement simplifying the transportation and transforms the energy during the impact. A heavy base places the center of gravity of the anti-ramming system close to the ground.

Furthermore, according to the numerical simulation, the barrier is stopped in 2 m (Fig. 6) and the dynamics resulted from this approach is similar to the one noticed during the experimental crash test.

The equivalent plastic strain (PEEQ) provides the measure of the permanent deformation of a body. This analysis is carried out to assess whether the sheet metals exceed the elongation $A\%$. In this case the rupture occurs. This value is equal to $A\%$ = 0.26 for S235JR sheet metals with thickness equal to 4 mm according to Matweb (2018). PEEQ exceeds the threshold in the restraint systems (Fig.7). In the figures, the base is gray too because the plastic behavior of the material is not considered. In the experimental test, the frontal sheet metals broke in two zones, in correspondence of the chassis side-members of the vehicle, as shown in Fig. 8. Since these frame elements are not inserted in the finite element model, the results of the simulation do not present these lacerations. For these reasons, the results obtained in terms of PEEQ can be considered reliable.

Finally, a penetration of the van in the front sheet metal of the barrier equal to 300 mm was measured after the experimental test. The numerical model returns a penetration of 279 mm, which is therefore compliant.

As stated before, the numerical model does not take into account the rupture of the components. Moreover, the material laws implemented in the finite element model are not strain-rate dependent, as recommended for crash analyses in Mahadevan (2000). These approximations can be responsible for the differences between the numerical model and the experimental test. For example, if the separation and the rupture of the sheet metals are not modelled, all the sheet metals work together during the impact even if the situation is a bit different.

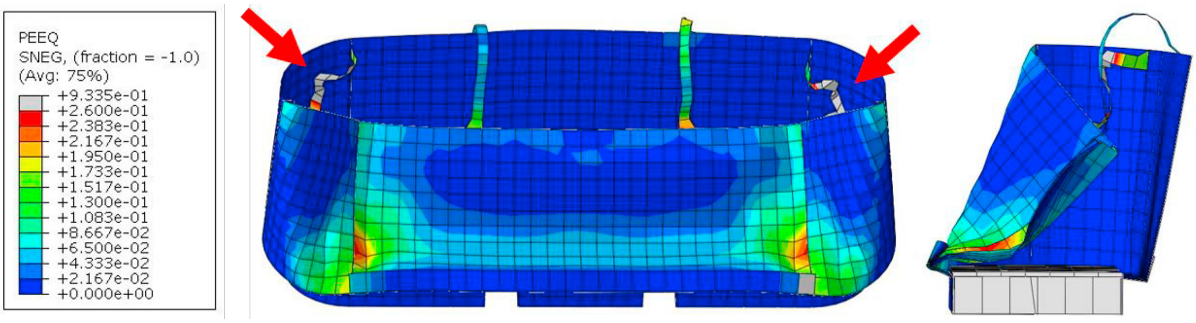

Fig. 7. PEEQ on the assembly and section of the barrier.

Fig. 8. Anti-terror barrier after the experimental test.

This numerical model is also helpful for further simulations, which will involve for instance the impact of bigger vehicles.

4. Conclusions

A new mobile barrier presented in Baragetti and Arcieri (2019) is able to stop a 3500 kg van in a few meters.

The objective of this paper is the creation of a mathematical model and a numerical model of the impact in order to describe the main features of a powerful barrier and to study the impact dynamics. The mathematical model takes into account the potential energy of the van and gives a maximum displacement equal to 4.2 m in case of inelastic collision and 8.3 in case of elastic collision. The displacement resulted in the experimental test is quite similar to the first case even if the mathematical model is simplified.

In the finite element model, the dimensions of the van model are updated to conform the vehicle to the one used in the experimental crash test. Moreover, some missing elements in the barrier model like the restraint systems and the tires puncturing device are added. Thanks to the implementation of all the interactions between the barrier, the van and the ground and the reproduction of the bursting of the front tires, a high level of reliability with respect to what happened during the experimental test is obtained. The stopping distance of the numerical model is 2 m while in the experimental test the maximum displacement was 3.8 m. Also the deformation of the frontal sheet metal is quite similar: about 300 mm in the experimental test vs 279 mm in the numerical model. The differences in the results can be due to the simplifications in the model, which lacks the rupture of the material and the behavior in function of the strain rate.

Therefore, these mathematical and numerical models can be considered a solid base for the possible following analyses (for instance, crashes with bigger vehicles).

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