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Finite element modelling of a truck crashing into a new form of mobile vehicle blocker

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Abstract. In the last years, a new form of terrorist attack has sowed panic in western countries: vehicles have been run into crowded places injuring and killing many people. The first solution to preventing the vehicle ramming attack has been the placement of concrete barriers around areas that are potential terrorist targets. The performance of these systems is questionable and the design of new, effective and good-looking protection devices is a hot topic. The authors have already presented a new certified mobile barrier, which is able to stop a 3500 kg vehicle run at 64 km/h in a few meters thank to its high deformability and the adoption of water as a filler. The water flows out and removes an appreciable amount of the impact energy. In this paper, the crashes of a 7500 kg truck running at 64 km/h against a concrete block and a single barrier designed by the authors are analysed with the help of finite element (FE) calculations in Abaqus Explicit. The water in the barrier is modelled using Smooth Particle Hydrodynamics (SPH). Due to the complexity of the truck modelling, a very simplified geometry is adopted, which is a consequence of the different versions tested. According to the results, compared to the concrete blocks, the designed barrier is overall more effective, even in a single configuration.

1. Introduction

Recently, terrorists have injured and killed some European civilians by driving heavy vehicles at high speed. At the beginning, the municipalities commonly faced the problem by enclosing crowded places, which represent a sensitive target for this form of attack, with concrete blocks. In general, the protection systems can be fixed, retractable and mobile. The first ones are very effective but also expensive because of their foundation system. They can also be a danger themselves because some of the fragments generated as a result of the impact can hit people. Furthermore, fixed systems prevent rescue vehicles from entering the protected area causing difficulties and delays. Retractable systems such as mobile bollards solve this problem even though they have foundations but are still expensive due to the presence of the mechanism which produces their movement. Concrete blocks, e.g. the jersey barriers and the cubes which appear in our cities, are mobile blockers. They are not fixed to the ground and for this reason they are low-priced. Considering the concrete blocks, friction is the main responsible for the dissipation of the energy possessed by the impacting vehicle and for this reason these types of systems are not very effective, as shown in [1]. Furthermore, it should be stressed that the primary purpose of the jersey barriers is actually to prevent the vehicles from invading the opposite lane. These barriers are therefore effective in the case of oblique impacts [2].

Design of protection systems has been a hot research topic in recent years, as demonstrated by the considerable amount of solutions studied, some of which are patented. For example, the kinetic energy

of an impacting object can be partially converted in plastic energy [3]. An energy absorption system can be find in [4] and in [5]. The latter solution is good looking and can be adopted as street furniture. In order to stop an object, a crash cushion can be adopted which collapses when the system undergoes a high axial force [6]. Another device presents two end posts and intermediate posts firmly fixed to the ground [7]. The system presented in [8] acts as a leverage and raises the impacting vehicle with consequent change of vehicle momentum direction.

The authors have already designed a new mobile barrier capable of stopping a 3500 kg vehicle that runs at 64 km/h in less than five meters [1]. As a result, the barrier is certified. The design process was conducted through mathematical and numerical models and experimental tests. The calibration of the FE model is described in [9-10] while the reasons why some materials have been chosen for the blocker are explained in [11] using the simplified model of a pendulum hitting various obstacles.

The Abaqus/Explicit simulations described in this paper examine the performance of the vehicle blocker presented in [1] in the event of a normal central impact of a 7500 kg truck driven at 64 km/h. Modelling a truck is a very difficult matter and therefore a simplified vehicle geometry is proposed in this work. The results show an overall better performance of the metal barrier with respect to the concrete blocker.
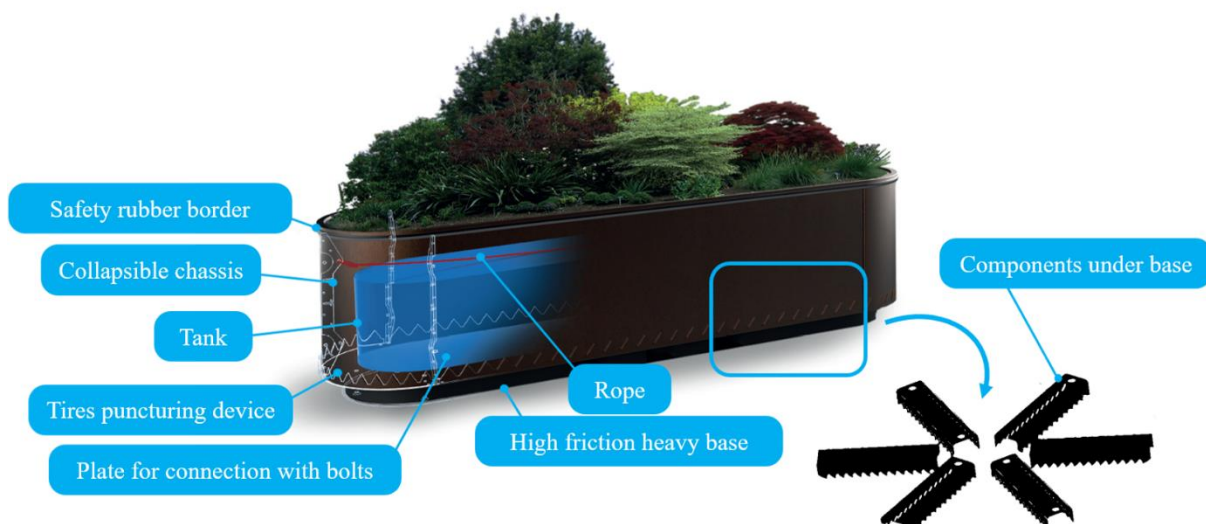
2. Materials and Methods

Figure 1. Designed mobile blocker [9].

The analyses start from the simulations already described in [1] and [9], in which the designed blocker and the techniques adopted are already presented. The designed vehicle blocker (Figure 1) is mobile so that it can be used whenever and wherever it is needed. It is mainly made of metal, with a base made up of three iron blocks and the perimeter sheets made in S235JR, 4 mm thick. The blocker can also be used as street furniture since a plastic plate on top of the device can hold flowers. A 10 mm plate is inserted between the perimeter sheets in the areas where the sheets are connected by bolts. The purpose of the notches created in these plates is to reduce the stiffness of the barrier so as to have high strain energy dissipation. The device placed in the lower part of the blocker can puncture the tires of the impacting vehicle. As demonstrated in a previous work [9], this puncturing system has a twofold function: it can make driving the vehicle difficult due to tire damage but it also sticks to the ground, causing rapid braking. The overall size of the barrier structure is 3000 mm x 860 mm x 1010 mm and its mass is about 2050 kg. A polymeric bag contains 1550 kg of water. Thanks to the use of water, the system can reach a significant mass, useful for friction dissipation, after its positioning, with a considerable advantage in transportation. The leakage of huge quantities of water as a result of the

impact allows for a lot of the energy to be removed, which is converted into potential and kinetic energy. The remaining part is transformed by the structure of the blocker into strain and friction energy. Friction dissipation is favored by the presence of twelve devices arranged in two radial patterns, as shown in Figure 1. Four restraint systems made with S235JR plates are placed on the top of the blocker to avoid enormous deformations of the perimeter plates under the pressure of the contained water. These systems are notched so as to cause them to break during impact, resulting in energy dissipation and reduction of system stiffness. A rope connects the two sides of the blocker. Thanks to the plastic strain of the sheets, the partial transformation of the vehicle energy into kinetic, potential and viscous energy supplied by water and the friction dissipation between the barrier and the ground, this mobile blocker can stop a 3500 kg van driven at 64 km/h in less than 5 meters, as demonstrated experimentally in [1]. The barrier is certified.

A study which involves theoretical modelling, numerical modelling and experimental tests is powerful because it allows to compare the results of the three approaches and therefore to reduce the possibility of mistakes, taking into account the most important parameters of the phenomenon studied. In this work, only numerical models were created, as the FE model was validated based on the results of the experimental crash test in [9] regarding the impact of a van.

For impact analyses, FE calculation with explicit time integration is recommended [12-14]. Abaqus/Explicit 6.14-5 was adopted for the analyses presented in this work. The water in the blocker was modelled with SPH. The polymer bag was not implemented in the model due to its negligible strength. The simulations described in this paper concern the impact of a 7500 kg truck running at 64 km/h. Today there are many models of trucks on the market and this variability was not taken into account in this study. In addition, modelling a vehicle is difficult because the FE models created cannot contain all the vehicle components in order to ensure a reasonable computational cost. The constitutive laws should be simplified for the same reason. However, even if simplified, the vehicle model must reproduce the behavior and in particular the overall stiffness of the real truck. The geometry of the modelled truck derives from Iveco Eurocargo ML120E24 (data in Table 1, [15]) and is composed of two parallelepipeds of shells of appropriate width (6/8 mm) and a frame made of shell elements added in a second moment on the bodywork to act as ballast. The geometry was improved based on the results of the simulations and for this reason a comprehensive description of the geometry evolution is described in the following section. The experimental test was not carried out due to its high cost. Since no experimental data were available, the wheels were modeled with linear elastic material assuming therefore, as a precaution, that they resist impact.

Table 1. Data of truck [15].

Feature	Value	Note
Name	Iveco Eurocargo ML120E24	/
Wheelbase	4185 mm	/
Mass	7500 kg	With ballast
Height from the ground	358 mm	Frontal part
Position of the centre of gravity in longitudinal direction	1785 mm	From front axle
Position of the centre of gravity in vertical direction	970 mm	From ground

In the FE model the restraint systems were modeled with shell elements due to their reduced thickness of 5 mm. The tires puncturing device was also modeled with shell elements. A coefficient of friction with the ground equal to 1 was implemented to model the actual locking mechanism in the ground. The components arranged in a radial pattern under the base of the blocker, such as the 10 mm

plates placed at the joint of the perimeter sheets, were not implemented in the model. Regarding the latter, the assigned shell thickness guarantees the total actual thickness, as explained in [9]. Table 2 shows the material properties implemented in the FE model, taken from [9] and [16]. The properties of S235JR were assigned to the blocker sheets and the vehicle surfaces, with a density value which ensured the correct positioning of the center of gravity. The properties of cast iron were assigned to the elements which model the base of the barrier, while for water the energy equation of Wilkins [17] was adopted. For the jersey barrier model, the properties of the concrete reported in [16] were implemented. The dimensions of the jersey barriers studied are shown in Figure 2 and are as follows: 3000 mm x 580 mm x 1000 mm, length x width x height [18]. The ground was modelled as a surface of shell elements with high stiffness all fixed nodes.

Table 2. Material properties implemented in the FE model [9,16].

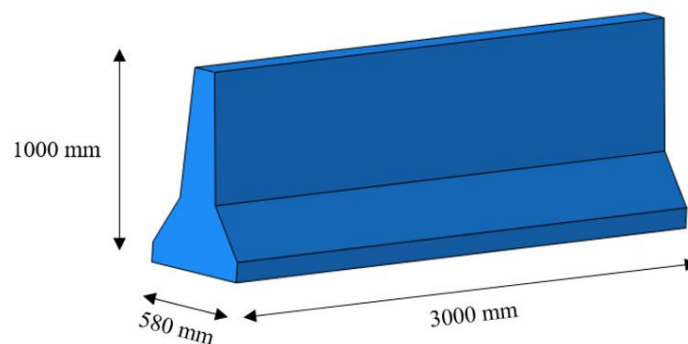| Material	Assigned to	Density	Young's modulus	Poisson's ratio	Yield stress	Reference sound speed	Slope of the Us-Up curve	Gruneisen ratio
		(kg/m^3)	(MPa)		(MPa)	(m/s)		
S235JR (elastic-perfectly plastic)	Perimeter sheets Vehicle	7800	206000	0.30	235			
Cast iron (elastic-perfectly plastic)	Base	7300	120000	0.26	250			
Water	Fluid	1000				1450	0	0
Concrete	Jersey barrier	2300	30000	0.20				

Figure 2. Geometry of jersey barrier implemented in FE model [18].

All FE analyzes carried out consist of two calculation steps: a first of 20 ms, in which the components come into contact thanks to the gravitational load applied, and a second of 400 ms, in which the collision between the vehicle and the obstacle occurs.

The junctions between the model parts were modeled with kinematic connections. A general contact without friction was implemented throughout the model to prevent all parts from interpenetrating. Table 3 shows the implemented friction coefficients for the other specific interactions defined in the model [9]. To simulate the rolling friction, a very small coefficient of friction was adopted for the interaction between the ground and the wheels, as the wheels are unable to rotate in the model. Table 3 shows two values relating to the coefficients of friction between the wheels and the barrier. The zero coefficient of friction was adopted in the case in which it was assumed that, after the impact, the front axle was not damaged, as it can be seen in the section "Results and discussion" for Version 5 of the truck.

Table 3. Coefficients of friction for interactions implemented in FE model [9].

Interaction	Coefficient of friction
Ground – Base of blocker	0.65
Ground – Vertical sheets of blocker	0.40
Ground – Tires puncturing device	1.00
Ground – Wheels	0.01
Vehicle – Vertical sheets of blocker	0.10
Vehicle – Base of blocker	0.20
Vehicle – Tires puncturing device	0.10
Wheels – Base of blocker	0.70/0
Wheels – Vertical sheets of blocker	0.70/0
Wheels – Tires puncturing device	0.70/0
Whole model – Whole model	0.00

S4R and C3D8R elements were adopted respectively for the mesh of the surface and volume components. The generated mesh was as symmetrical as possible. The congruence of the meshes of the interacting objects was ensured.

3. Results and discussion

As stated before, the geometry of the truck was improved based on the results of the FE analyses carried out. Five different versions of truck geometry were tested:

- Version 1: Truck modeled only with cab and flatbed;
- Version 2: Version 1 with the addition of a frame of shell elements to simulate the load (the ballast) and consequent redistribution of the masses;
- Version 3: Version 2 stiffened with a deformability of 20%, it was assumed that part of the impact energy causes the deformation of the truck;
- Version 4: Version 3 with the addition of two side members and a cross-member to limit the bending of the front and the body;
- Version 5: Version 4 with the addition of a second cross-member under the body.

The first version of truck was created by modeling the vehicle in the simplest possible way: a parallelepiped was used for the cabin and a second parallelepiped for the body. This version was made to study the dynamics of the impact and understand which parts of the truck would need to be refined. The wheels were modeled as simple semicircular prisms attached to the rest of the vehicle, with no distinction between rim and wheel.

Version 2 was studied by modeling the presence of a load on the vehicle body in such a way as to reach the total mass of 7500 kg, assigning the truck the specified tare weight and assigning the rest of the mass to the load. The latter was modeled as a rectangular frame of shell elements extruded from the caisson. The choice to use only the frame was due to the fact that the load is not a structural component of the truck.

Due to the high deformability of the vehicle observed with the previous model, the stiffness of the truck was modified to absorb 20% of the total plastic energy dissipated in the simulation. To enforce

this condition, several attempts were made to determine the suitable thicknesses of the shells. Excellent behavior was found with thicknesses of 8 mm.

To create a more reliable and realistic model, two side members were added to prevent unreal deformations from occurring. Having no indications, the side members were made as square profiles. The sheets of the cab and side members were designed to maintain deformability at 20%. The deformation now mainly affects the front area thanks to the addition of a cross-member in the center of the wheelbase to avoid plastic deformations of the body.

Version 5 of the truck model is Version 4 with the introduction of a second cross-member under the body. This modification was introduced to further stiffen the body.

The results obtained with the different versions of truck model tested, which are shown in Figure 3, are described in the following lines. In the figure, some faces are sometimes hidden to show the inside of the truck model.
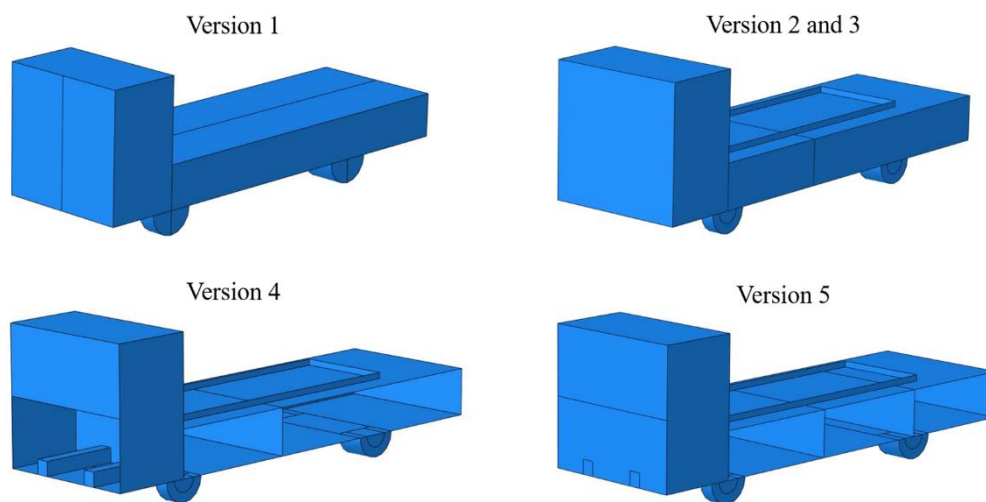

Figure 3. Versions of truck geometry implemented in FE model.

3.1. Version 1

Before starting with the simulations of the impact between the truck and the barrier, a simulation of the impact against a jersey barrier with a length of 3000 mm and a weight of 2000 kg was carried out in order to compare the performance between the existing solution and the one designed. Two different configurations were tested: one with a poorly deformable truck and a second with a deformable truck. With the first configuration, after the collision, the truck and the jersey barrier no longer came into contact until the end of the simulation, having still residual speed. In the second case, after the impact, the jersey barrier got stuck under the truck cab, making the vehicle stop in 46 meters. The results are shown in Figure 4.
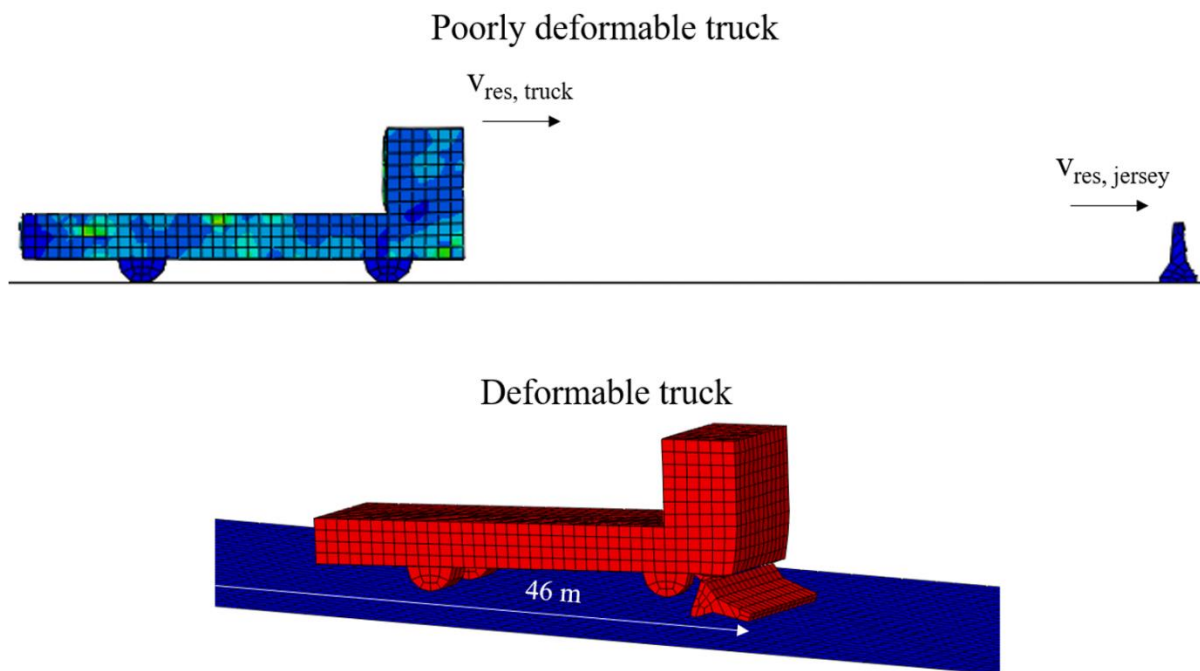
Figure 4. Results of impact between truck and jersey barrier.

The other simulations performed with Version 1 are as follows:

- Case 1.1: Impact against single blocker;
- Case 1.2: Impact against a single blocker modified with rubber on side walls;
- Case 1.3: Impact against single barrier modified with rubber on the support base;
- Case 1.4: Impact against single barrier modified with rubber on the side walls and on the support base.

The last three cases were studied to determine the effect that greater friction could have between the ground and the barrier, as well as between the barrier and the vehicle. This is to increase the braking action exerted by the barrier and decrease the displacement of the vehicle. The presence of rubber was modeled only by increasing the coefficient of friction to 0.9. Table 4 and Figure 5 summarize the results in terms of displacement.

Table 4. Displacements obtained for impact between Version 1 and designed blocker.

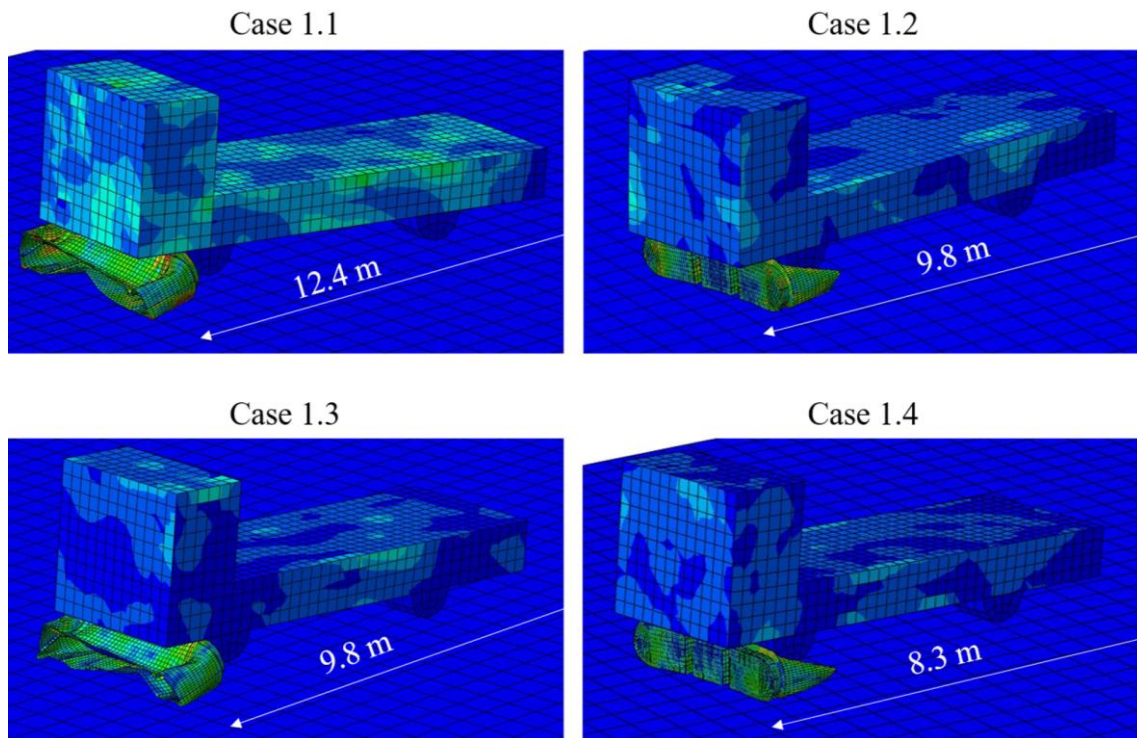| Case (Version 1 of truck)	Displacement (m)
Case 1.1: Impact against single blocker	12.4
Case 1.2: Impact against a single blocker modified with rubber on side walls	9.8
Case 1.3: Impact against single barrier modified with rubber on the support base	9.8
Case 1.4: Impact against single barrier modified with rubber on the side walls and on the support base	8.3

Figure 5. Displacements for impact between Version 1 and designed barrier.
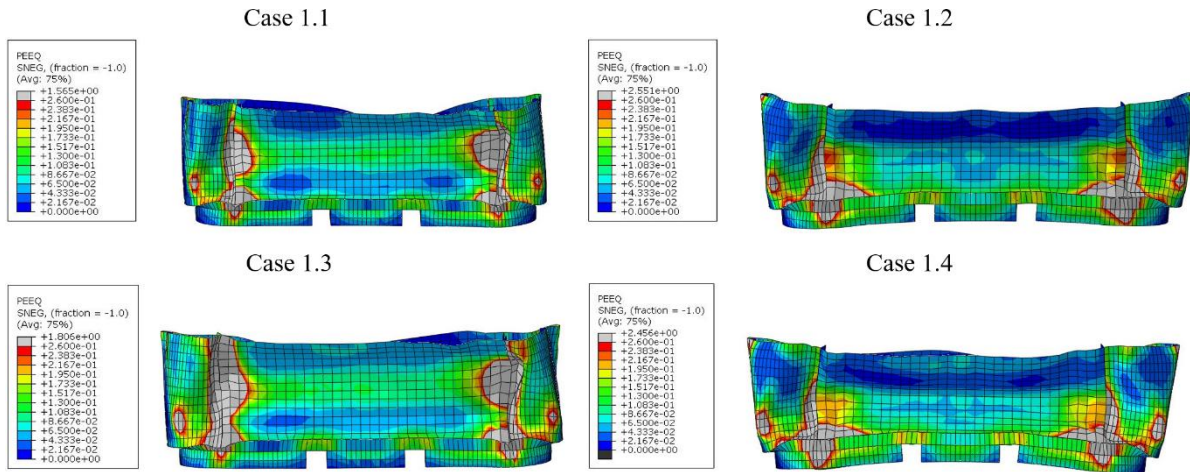

Figure 6. PEEQ for impact between Version 1 and designed barrier.

The analysis of the equivalent plastic strain (PEEQ) of the sheets was also carried out and is shown in Figure 6. Only the front part of the barrier was analyzed, the one on the impact side, as the rear sheets do not undergo such deformations as to cause them to break. The overturning of the blocker, which does not occur in all cases, leads to the deformation of the rear sheets due to the landing of the truck on top of them. In the case of the impact against the standard barrier, it can be seen that the areas corresponding to the connections between the sheets are colored gray. This means that in those points the sheets exceeded the limit value of percentage elongation, A%=26% [19], with consequent failure. The areas in grey are very extensive and therefore the detachment of the front sheet from the base and from the curved sheets may occur. In the case with rubber on the side walls, it can be seen that there is a localization of the failures in the lower area of the barrier which does not cause the complete

breakage of the front sheet. In the case of the barrier with rubber on the support base, it can be noted that there is a more pronounced surface with PEEQ higher than the threshold value. This is due to the fact that, with greater adherence of the support base to the ground, the time required to accelerate the blocker after the impact increases. This results in a greater penetration of the truck towards the inside of the tank, resulting in the certain failure of the front sheet, the detachment of the vertical supports and the crushing of the tank. In the case of the barrier with the entire external surface covered with rubber, a better redistribution of the deformations can be noted. In particular, the lower part of the sheets is the critical area but the complete detachment of the sheets does not occur.

3.2. Version 2
The simulations performed with Version 2 are as follows:

- Case 2.1: Impact against single barrier without coupling between front wheels and puncturing system;
- Case 2.2: Impact against single barrier with coupling between front wheels and puncturing system.

The decoupling of the components was modeled allowing their separation after contact. Table 5 summarizes the results in terms of displacement. As it can be seen, there is no difference in terms of stopping space between the two cases.

Table 5. Displacements obtained for impact between Version 2 and designed blocker.

Case (Version 2 of truck)	Displacement (m)
Case 2.1: Impact against single barrier without coupling between front wheels and puncturing system	8.3
Case 2.2: Impact against single barrier with coupling between front wheels and puncturing system	8.3

3.3. Version 3
The simulations performed with Version 3 are the following:
- Case 3.1: Impact against single barrier without coupling between front wheels and puncturing system;
- Case 3.2: Impact against single barrier with coupling between front wheels and puncturing system.

Table 6 summarizes the results in terms of displacement. As it can be seen, there is no difference between the two cases.

Table 6. Displacements obtained for impact between Version 3 and designed blocker.

Case (Version 3 of truck)	Displacement (m)
Case 3.1: Impact against single barrier without coupling between front wheels and puncturing system	8.8
Case 3.2: Impact against single barrier with coupling between front wheels and puncturing system	8.8

3.4. Version 4

In the simulation carried out on the collision between Version 4 truck and single barrier (Case 4), the resulting displacement is 9.3 m, half a meter more than in the case with Version 3. This is due to the further stiffening achieved with the introduction of the side members.

3.5. Version 5

For the first time it was assumed that, after the impact, the front axle would not be damaged in such a way, preventing the rotation of the wheels. In this way the friction coefficient between the wheels and the barrier plates changed, which from 0.7 assumed in the previous simulations passed to rolling friction equal to 0, as a precaution. Table 7 summarizes the results in terms of displacement for the tested case which are the following:

- Case 5.1: Impact against single barrier without coupling between front wheels and puncturing system;
- Case 5.2: Impact against single barrier with coupling between front wheels and puncturing system.

Figure 7 shows the results in terms of displacement and PEEQ for Case 5.1. The restraint systems would fail, as would perimeter sheets in areas where the front of the truck hits the blocker.

Table 7. Displacements obtained for impact between Version 5 and designed blocker.

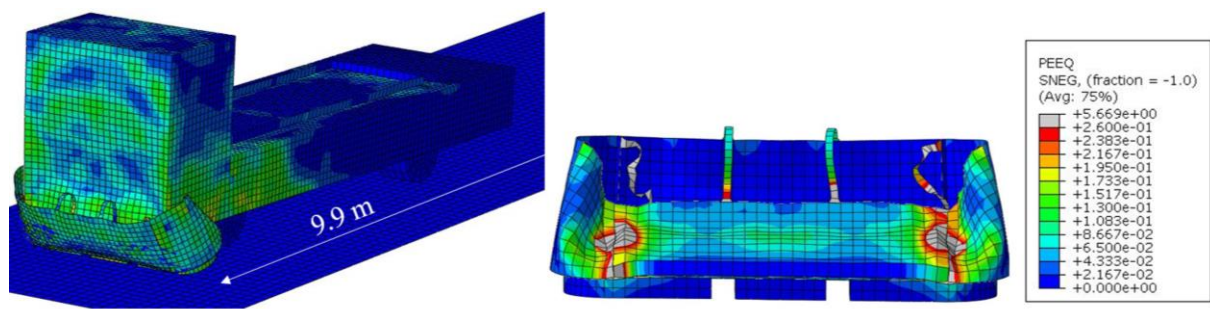| Case (Version 5 of truck)	Displacement (m)
Case 5.1: Impact against single barrier without coupling between front wheels and puncturing system	9.9
Case 5.2: Impact against single barrier with coupling between front wheels and puncturing system	9.5

Figure 7. Displacement and PEEQ for impact between Version 5 and designed barrier.

4. Conclusions

The aim of this work is to study the impact between a 7500 kg truck launched at 64 km/h and a single blocker designed by the authors and presented in previous papers, comparing the performance of the barrier with that of the jersey barrier. The barrier is mainly made of metal and uses its deformability and the escape of water to subtract energy. As regards the modeling of the truck, the geometry, which started from a simple base with only the cabin and rear floor, was developed in order to guarantee reduced computational cost and avoid anomalous deformations. According to the results of the FE analyzes conducted, a 3-meter concrete jersey barrier seems to be able to stop the truck in 46 meters. Assuming that the front axle of the truck is not damaged as a result of the impact, a braking distance of approximately 10 m can be obtained in the event of a collision with the metal barrier.

Acknowledgments

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