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ANALYSIS OF ARMOURED VEHICLES BLAST PROTECTION BY USING FINITE ELEMENT CODES

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This paper presents an example of the use of numerical methods to design a satisfactory protection against landmines for an ideal armoured vehicle. Starting with the simulation of the unprotected part of the vehicle, a protection is proposed and is improved step by step, after analysing the results of each simulation. Four iterations are needed to achieve a satisfactory configuration and each iteration fails because reasons not easily predictable before the simulations. Without the numerical methods help, all this process would have implied five real tests and therefore, lots of time and five real vehicles destroyed. The numerical simulations allow the approach to a reasonable configuration, saving considerable amounts of money and time.

INTRODUCTION

Usually Infantry Fighting Vehicles (IFV) have been designed to provide protection against several ballistic threats. However, the deployment of peace keeping military forces in low conflict areas, has shown that IFV present low levels of protection [1] and some fatal casualties have been reported. This fact has emphasized the need of protection improvement.

A reasonable protection level against many ballistic threats can be achieved by using simple rules. But in the case of blast and landmine protection this is not possible since there are many parameters playing a role as important as the material or the landmine charge: the distance between the vehicle and the landmine, the landmine burial conditions, the vehicle's plates boundary conditions…etc. Therefore it is very difficult to design an optimised protection configuration for a given case, for example the landmine explosion under an IFV belly.

On the other hand, the experimental approach has also many problems. While armour design to defeat a given projectile can be performed by testing a few plates, in the case of blast protection full scale testing is necessary. That means actual vehicle testing (and destruction) or at least full scale mock-ups testing. Obviously, such testing is very time and money consuming, thus protection design based exclusively on experimental tests is not affordable. Therefore the numerical approach appears as the most suitable one. Although the experimental work can not be fully avoided, it can be considerably reduced. One reasonable approach could be to perform simple experimental tests to adjust the numerical parameters needed for the simulations besides an extensive numerical simulation work to optimize the protection. Finally, only a few full scale experimental tests for verification and for comparison between the best proposals would be performed to confirm the results.

In the EUCLID framework [2], such scheme has been followed to design the protection of light armoured vehicles, providing successful results.

This paper describes the simulation process to improve the belly protection of an ideal IFV.

EXAMPLE SET-UP

The aim of the paper is the protection of an ideal IFV to withstand safely landmine explosion under its belly. For such purpose, a wide section of the vehicle is modelled (Figure 1). It consists on a bottom plate, two lateral plates as well as two upper plates that conforms the wheel bay. All these plates have the same thickness and are connected by welds. Two wheels are placed on both sides, attached to the vehicle by their corresponding suspension sets. Both suspensions are connected to one another through a transversal stiffener to provide structural stiffness to the body. The tires have been modelled via membrane elements, thicker on the tread and thinner for the sidewalls.

The landmine is represented by an explosive load placed under the belly. To avoid the influence of parameters such as the confinement, the burial or the soil type, the landmine has been simulated by an explosive charge inside a cylindrical confinement as illustrated in Figure 2a. As shown in Figure 2b, the axis of the explosive charge coincides with the perpendicular through the geometric centre of the bottom plate.

Figure 1. Part of the ideal vehicle simulated

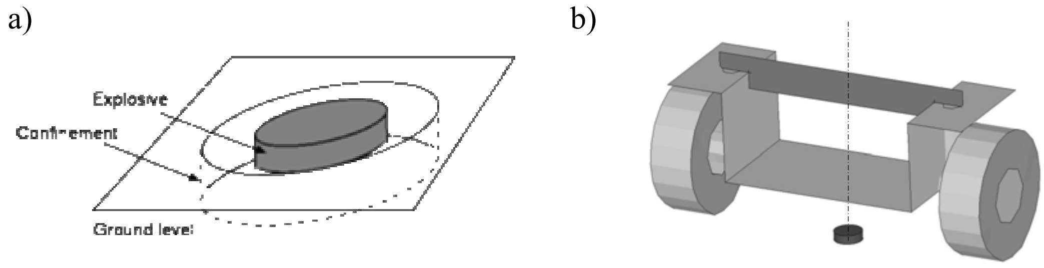


Figure 2. a) Position of the explosive inside the confinement; b) position of the explosive regard the vehicle.

Materials

All vehicle plates are made of RHA steel, while transmission and suspension elements are made of mild steel. Both steels were modelled by using a simple elastic-plastic material model with Mises plasticity and kinematic hardening.

Welds were modelled by connecting coincident nodal pairs all through the shared edges of the plates. When one of the elements surrounding the nodal pair reached the yield stress, the nodal connection was released, behaving as a brittle weld.

For the tires behaviour a rough simplification was taken, assuming isotropic linear elastic behaviour up to failure, and a maximum stress obtained applying the rule of mixtures for a typical steel-rubber tire composite. Obviously actual tires behaviour is more complicated but the tire influence on this kind of problem is almost negligible.

Ideal gas gamma equation was used for the air; the explosive was modelled by using the JWL equation of state [3]. In the literature many sets of parameters to feed this equation can be found (see [4], for example), although it would be always preferable to tune them by comparison with simple field testing.

Numerical simulations features

Nowadays there are many numerical codes able to perform this kind of simulations. Besides their ability to model dynamic material behaviour, they provide a wide variety of material models and day after day they become more "user friendly". This is another advantage of the numerical codes against direct explosive testing: while explosive modelling is an issue available in the most widely used commercial explicit codes, the facilities and licenses needed to perform experimental testing involving explosives are not easily available.

In this paper, the LS-DYNA3D 970 [5] code has been used. An *Arbitrary Lagrangian-Eulerian* (ALE) mesh was used for both explosive load and air, while

Lagrangian meshes were used for all the vehicle parts. Both kind of meshes (ALE and *Lagrangian*) were coupled by using the so called *Fluid Structure Interaction* technique.

SIMULATIONS AND PROTECTION DESIGN PROCESS

Unprotected vehicle

The first simulation corresponds to the detonation of the landmine under the vehicle without any kind of protection improvement. Figure 3a shows the initial configuration of the model with the lagrangian and the ALE meshes used.

The main result obtained from this simulation is that, a few milliseconds after the explosion, the bottom plate of the vehicle fails and a big hole is opened (Figure 3b). Obviously this situation is not acceptable since the bottom plate failure would let the blast entrance inside the vehicle what would be lethal for the crew. On other hand, such failure would produce a large amount of debris flying inside the vehicle.

a) b)

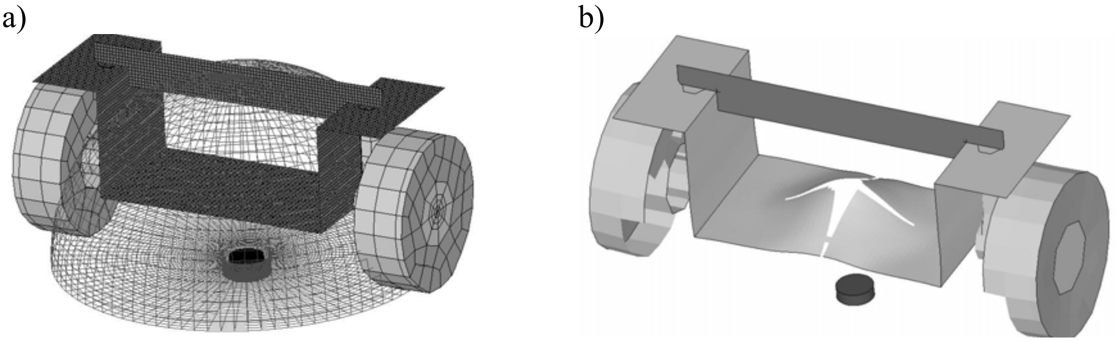


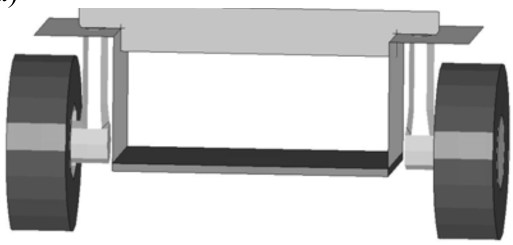
Figure 3. a) ALE and lagrangian meshes used in the simulations; b) Failure and hole opened on the unprotected vehicle bottom plate.

First protection proposal

Looking at the Figure 3b, the first idea to improve the protection is to reinforce the original bottom plate, fixing a thicker plate to the original one (Figure 4a).

The result for this configuration is shown in Figure 4b. Now the bottom plate withstands the explosion without a hole, but welds connecting the bottom and the lateral plates of the vehicle fail and leave the bottom plate plus the add-on plate set free to fly upwards, becoming a heavy projectile inside the vehicle and also allowing again the entrance of the blast inside the vehicle.

a)



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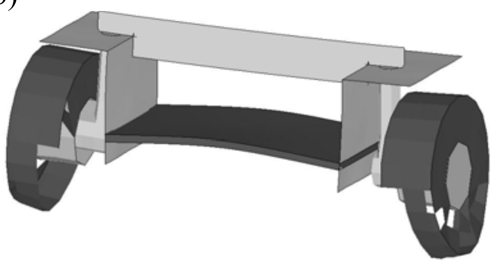
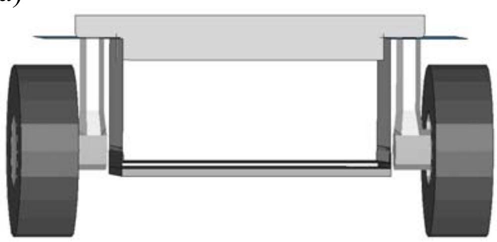


Figure 4. a) First protection proposal configuration; b) Vehicle condition after some milliseconds: it can be appreciated how the welds have failed and the bottom plate moves upwards.

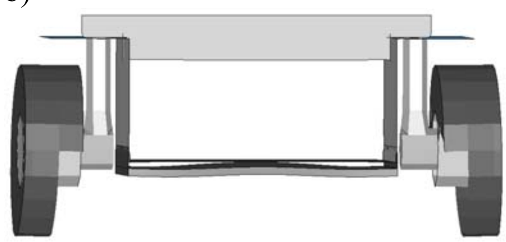
Second protection proposal

The thickness increase of the bottom plate has permitted to withstanding the explosion but the problem of the first protection was the welds weakness. So it seems a good idea to keep the add-on plate in the same position, but avoiding the connection through the original welds. Figure 5a shows a new proposal having the same add-on plate but fixed to the vehicle by means of two lateral flanges connected to the lateral plates of the vehicle. In this connection between the lateral flanges and the original lateral plates no weld failure has been modelled, assuming that this connection is strong enough to avoid any failure (by using bolts, special welding procedures…etc).

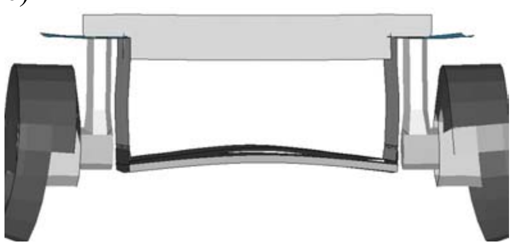
a)



b)



c)



d)

Figure 5. Sequence showing the behaviour of the second protection proposal: a) shows the initial condition as well as the protection configuration; b), c) and d) shows the vehicle deformation during several steps as the time increases.

Figure 5 shows a sequence of the protection behaviour during the explosion. It can be observed how the add-on plate and the lateral flanges used for the connection are able to withstand the explosion. However, after some milliseconds, the add-on plate strikes the original bottom plate, and its weldments fail again due to the high impulse received. Again the protection improvement is not valid.

Third protection proposal

The main problem of the previous proposal was the strike of the add-on plate against the original bottom plate. The next idea to solve the problem could be to place the add-on plate away from the bottom plate, allowing larger deformations and avoiding the strike. This idea involves that the add-on must be close to the ground level (Figure 6a). From the operational point of view, this is not a plausible solution, since it decreases the gap between the ground and the vehicle, reducing its off-road capabilities however, for protection improvements it is worth to study this configuration.

Figure 6b shows how the vehicle final condition seems to be even worse that the previous one. Although there is more room between the two plates, the momentum received by the add-on is much higher due to its vicinity to the landmine, resulting after a few milliseconds on a full fracture of the add-on plate, enabling blast entrance into the gap between both plates, and producing a high deformation of the bottom plate.

The situation is even worse after some milliseconds, when the two halfs of the broken add-on strike the original bottom plate.

a) b)

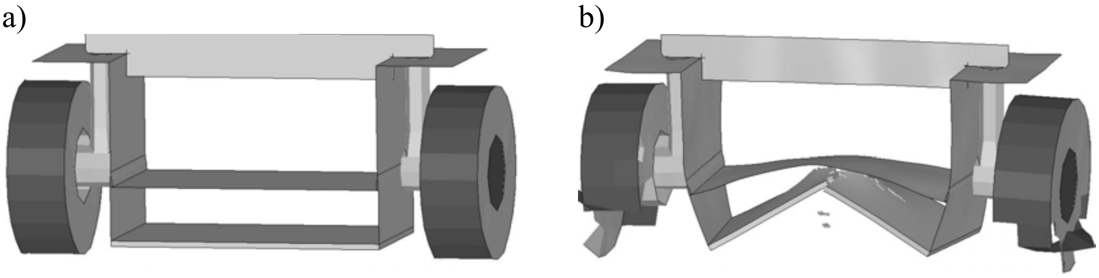


Figure 6. a) Third protection proposal configuration; b) Vehicle condition after some milliseconds: it can be appreciated how the broken add-on plate strike the original bottom plate.

Fourth protection proposal

The last protection proposal derives from the analysis of the second and third proposals. If the second one failed because the add-on plate was too close to the bottom plate and the third one failed because it was too close to the landmine, it can be assumed that a better solution lies between these two extremes. Raising the add-on plate from the position used in the previous proposal, we can reduce the momentum absorbed by the protection (Figure 7a). Despite the add-on plate will probably strike the original bottom plate hopefully it will not be strong enough to produce neither weldments not plate failure .

Figure 7b shows the final condition of this proposal and it is far better than all the previous ones. It seems to be a reasonable protection improvement.

a) b)

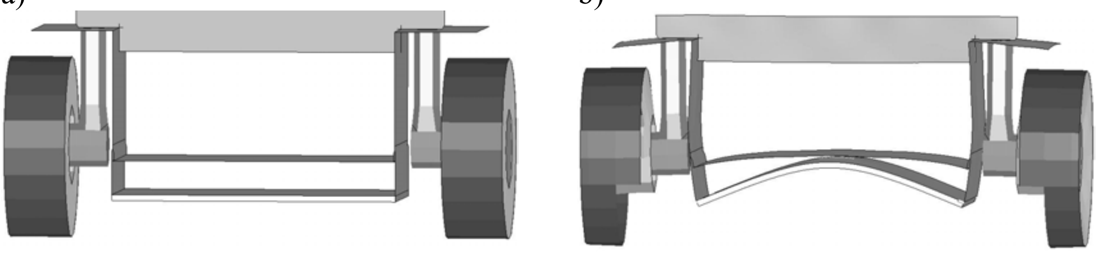


Figure 7. a) Fourth protection proposal configuration; b) Vehicle condition after some milliseconds: despite the add-on has stroke the original bottom plate, it maintains a relatively good condition.

CREW SAFETY ANALYSIS

Another issue where the numerical approach becomes very helpful is the occupants' safety analysis.

When analysing landmine protection, although many injury causes can be found in the literature, depending on the authors (see for example [6-8]), all of them can be classified into three major categories: overpressure inside the vehicle, accelerations suffered by the occupants and debris and loose objects ejection during the explosion. The overpressure can be avoided by ensuring the vehicle integrity, which was the goal of the previous section. However, occupants protection against the two other threats requires further analysis and numerical simulations arise as a helpful tool for such purpose.

When facing the accelerations problem, the DRI index is one of the preferred tools. This index was first developed for the study and design of ejection seats on the aircraft industry and is related with the maximum deflection measured in a simple one-dimensional oscillator model, whose frequency and damping parameters are set to approach the thora-columbar spine behaviour of the human body subjected to a sudden vertical acceleration. The DRI is obtained as:

$$DRI = \frac{\varpi^2 Z_{\max}}{G} \qquad (1)$$

Where ω, is the angular frequency of the oscillator, G the acceleration of gravity and Z_{max} the maximum deflection of the oscillator given by:

$$\ddot{Z} + 2\zeta\varpi\dot{Z} + \varpi^2 Z = A(t) \quad (2)$$

Where ω and ζ are the angular frequency and the damping coefficients respectively (having values of 52.9 s^{-1} and 0.224 respectively), *Z* the spine deflection and *A(t)* is the vertical acceleration history suffered by the occupant. For further information about the DRI, the reader is addressed to [8].

Table 1 shows the DRI obtained in all the configurations presented in the preceding section. The rigid body vertical acceleration history for the original bottom plate was used for *A(t)*.

Regarding loose objects and debris ejection, it will be decreased by preserving the vehicle integrity (analysed in the previous section) and reducing as much as possible the vehicle plates velocity and acceleration, as well as the distortion of the hull. Large accelerations increase the probability of fixings failure. A similar reasoning can be applied to the vehicle distortion: large distortions induce the rupture and failure of internal items that are not included in the model (since they do not contribute from the structural point of view) and once those objects are released, they become projectiles inside the vehicle.

Therefore, displacement (as well as velocity and acceleration) histories are very important to ensure occupants safety. With numerical simulation obtention of such histories is straightforward, by experimental testing however it highly increases the experimental set-up complexity and costs, since the data acquisition systems are very expensive and usually they are destroyed during the test. For the simulations described above, rigid body vertical acceleration histories obtained at the bottom plate are shown in Figure 8a. Figure 8b shows the history of distance between the bottom plate and the transversal stiffener between wheels (see the sketch included in the figure).

Analyzing both time-history plots, as well as DRI data, the fourth proposal remains as the best configuration. However it must be pointed out that how there is not a clear relationship between the different parameters obtained. See for instance acceleration history plots and DRI coefficients of the first and second proposals, although they present very similar acceleration peak values, their DRIs are very different. This result shows again the difficulties associated with this kind of design.

Configuration	Unprotected	1^{st} Proposal	2^{nd} Proposal	3^{rd} Proposal	4^{th} Proposal
DRI	325.2	67.0	111.3	56.5	54.8

Table 1. Crack patterns at 1.8 μs and 4 μs alter impact

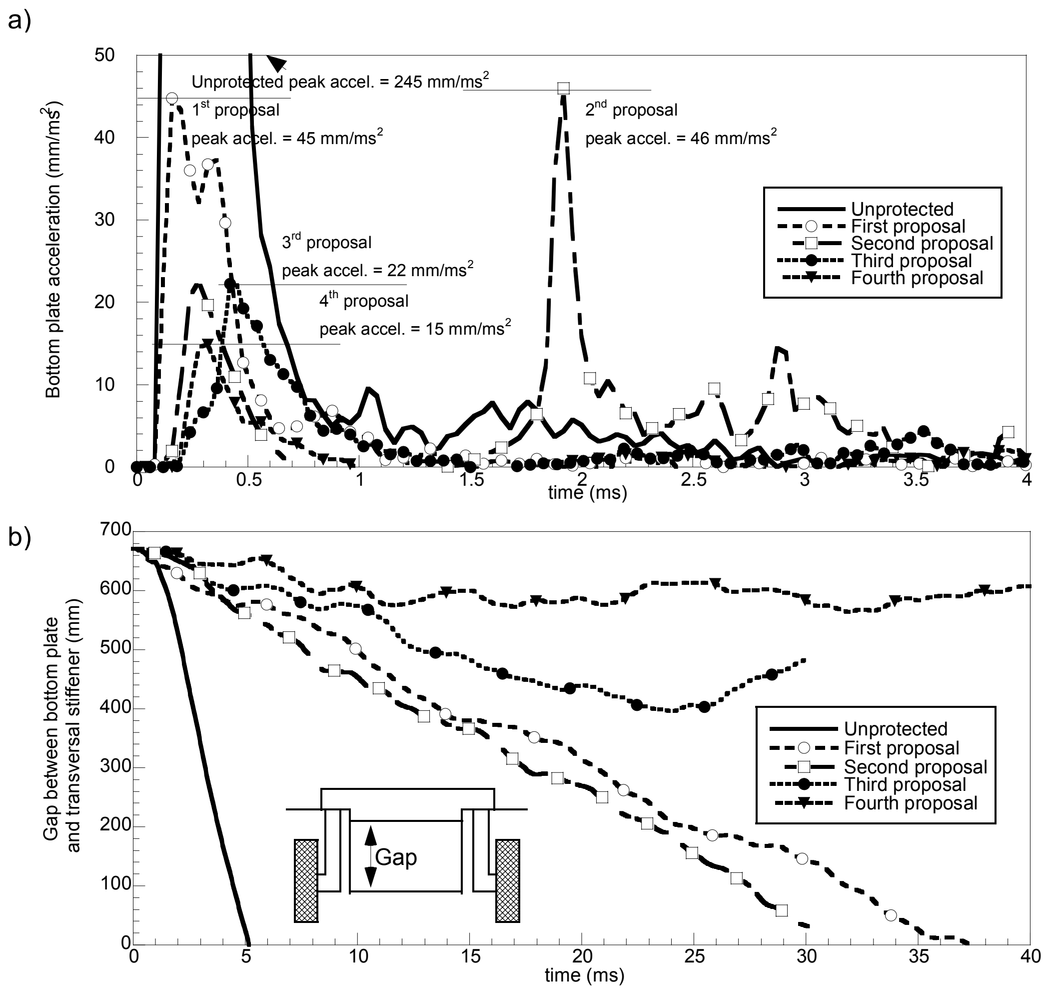


Figure 8. a) Bottom plate rigid body acceleration histories; b) Bottom plate-transversal stiffener gap histories.

CONCLUSIONS

The main conclusion of this paper is that numerical methods being always a useful tool for ballistic protection design in the case of landmine protection are almost unavoidable since they permit to reduce dramatically the experimental work and cost. The main reason is that in protection against landmines design, there are many factors influencing the problem and they can not be taken into account by simple reasoning as it has been shown in this paper.

Besides the previous conclusion, it is also remarkable that any protection proposal must take into account, not only the material (as usually happens in the case of ballistic protection) but also the weldments (or any other kind of fixation) resistance between plates, the gap between the vehicle and the landmine, the geometry …etc.

In this particular case of the protection of an IFV against a landmine under its belly, it has been shown how the distance between the landmine and the add-on protection can be optimized between an excessive wide gap, which causes the strike of the add-on on to the original bottom plate, and a reduced gap, which causes the add-on failure due to the large momentum absorption.

Acknowledgements

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