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Concept design for enhanced ballistic protection driven by numerical simulations

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ABSTRACT

In the security sector, the partly insufficient safety of people and equipment caused by failing industrial components are ongoing problems that arouse great concern. Since computers and software have spread into all fields of industry, extensive efforts are currently being made in order to improve the safety by applying certain numerical solutions. This work presents a set of numerical simulations of ballistic tests which analyze the effects of modern armor. The goal is to improve the material and structures in order to be able to cope with the current challenges. Without questions, the maximization of security is the primary goal, but keeping down the costs is becoming increasingly important. This is why numerical simulations are more frequently applied than experimental tests, which are thus being replaced gradually.

1. INTRODUCTION

The threat imposed by terrorist attacks is a major hazard for military installations, vehicles and other items. The large amounts of firearms and projectiles that are available, pose serious threats to military forces and even civilian facilities. An important endeavour of international research and development is to avert danger to life and limb. If military facilities and other structures are subjected to heavy fire from terrorists or assassins, then it is the engineer's responsibility to prepare for them.

However, before design codes will be further developed or adequate protections created, it is necessary to gain a better understanding of the complex interactions between modern armor and projectiles. Yet ballistic testing is limited due to costs and permissions for experimental results. Therefore, anyone interested in examining the effects of an impact on a structure needs to look for alternatives to experimental testing. One such alternative has become available in the form of advanced computer programs called hydrocodes.

This paper will evaluate the effects of modern armor with numerical simulations. It will also provide a brief overview of ballistic tests to offer some background knowledge

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of the subject, serving as a basis for the comparison of the simulation results. The objective of this work is to develop and improve the modern armor which is being used in the security sector. Instead of running expensive ballistic tests, numerical simulations should identify the vulnerabilities of items and structures. By progressively changing the material parameters, the armor will be optimized. Using a sensitivity analysis, information about decisive variables is yielded, vulnerabilities are easily found and can be eliminated afterwards. To facilitate the simulation, advanced numerical techniques have been employed in the analyses.

2. METHODS

In order to deal with problems involving the release of a large amount of energy over a very short period of time, e.g. explosions and impacts, there are three approaches: as the problems are highly non-linear and require information regarding material behavior at ultra-high loading rates which is generally not available, most of the work is experimental and thus may cause tremendous expenses. Analytical approaches are possible if the geometries involved remain relatively simple and if the loading can be described through boundary conditions, initial conditions or a combination of the two. Numerical solutions are far more general in scope and remove any difficulties associated with geometry (Zukas 2004). They apply an explicit method and use very small time steps for stable results.

With regard to problems of dynamic fluid-structure interaction and impact, there is no single best numerical method which is applicable to all parts of a problem. Techniques, which couple types of numerical solvers in to a single simulation, allow the use of the most appropriate solver for each domain of the problem.

The goal of this paper is to evaluate a hydrocode, a computational tool for modelling the behavior of continuous media. In its purest sense, a hydrocode is a computer code for modelling fluid flow at all speeds (Collins 2002). For that reason, a structure will be split into a number of small elements, which are connected through their nodes (Fig. 1).

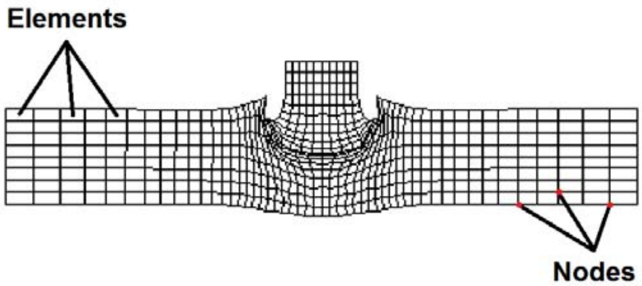

Fig. 1 Example grid

The behavior (deflection) of the simple elements is well-known and may be calculated and analysed using equations called shape functions. By applying coupling conditions between the elements at their nodes, the overall stiffness of the structure may be build up and the distortion of any node - and subsequently of the whole structure - can be calculated by approximation (Fröhlich 2005).

Due to the fact that all engineering simulations are based on geometry to represent the design, the target and all its components are simulated as CAD models. Using a CAD-neutral environment that supports bidirectional, direct, and associative interfaces with CAD systems, the geometry can be optimized successively (Woyand 2004). Therefore, several runs are necessary: from modelling to calculating to the evaluation and the subsequent improvement of the model (see Fig. 2).

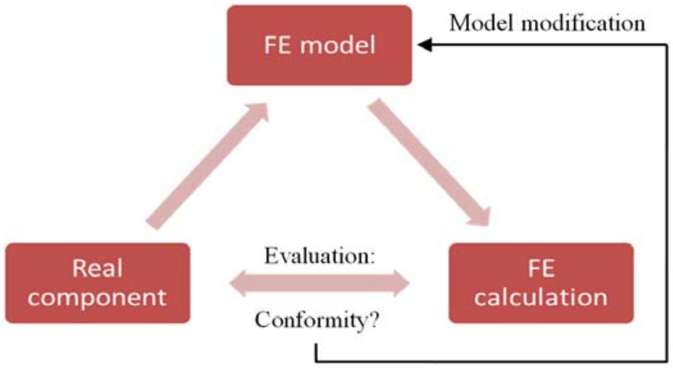

Fig. 2 Basically iterative procedure of an FE analysis

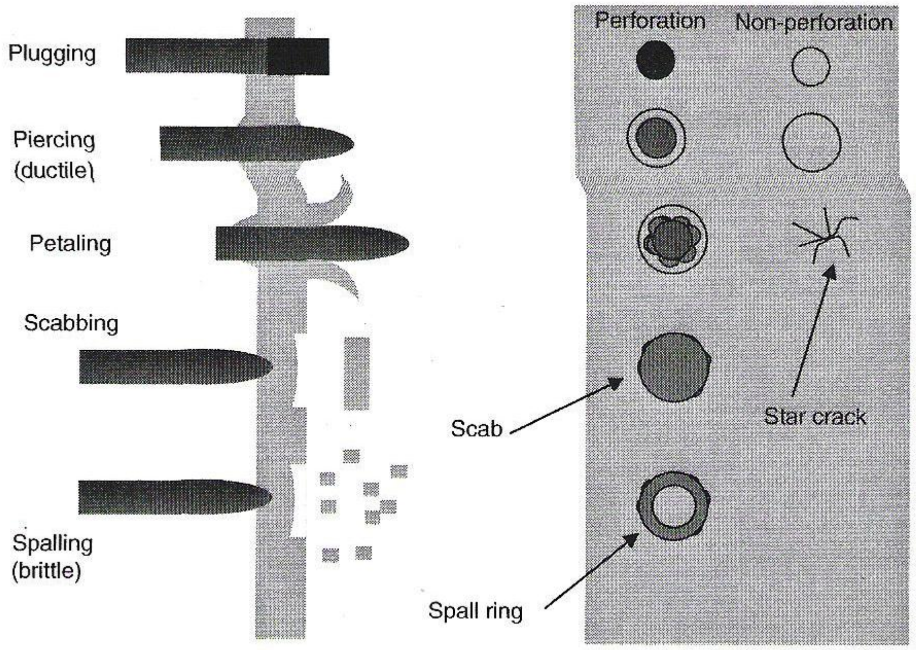

Fig. 3 Target failure modes (Carlucci 2008)

Bullet-resistant materials are usually tested by using a gun to fire a projectile from a set distance into the material in a set pattern. Levels of protection are based on the ability of the target to stop a specific type of projectile traveling at a specific speed (Frieß 2008). In order to introduce new materials and structures, all protection levels have to be tested in numerical simulations. For that reason CAD models of all projectiles were created and are used in various scenarios.

3. BALLISTIC TESTS

Ballistics is an essential component during the evaluation of our results. Here, terminal ballistics is the most important sub-field. It describes the interaction of a projectile with its target. The different types of impact are summarized in Fig. 3.

Spalling is very common and the result of wave reflection from the rear face of the plate. It is common for materials stronger in compression than in tension. Scabbing is similar to spalling, but the fracture predominantly results from a large plate deformation which begins with a crack at a local inhomogeneity. Brittle fracture usually occurs in weak and lower density targets. Radial cracking is common in ceramic type materials where the tensile strength is lower than the compressive strength, but it does occur in some steel armor as well. Plugging can be found in materials that are fairly ductile, usually when the impact velocity of the projectile is very close to the ballistic limit. Petaling occurs when the radial and circumferential stresses are high and the projectile impact velocity is close to the ballistic limit (Carlucci 2008). The task is to analyse and evaluate the impact and its various outcomes. This provides information on the effects of the projectile and the extinction risks.

The ballistic tests are thoroughly documented and analysed - even fragments must be collected (see Fig. 4). They provide information about the used armor and the projectile after the fire. This must be consistent with the simulation results.

In order to create a basis for the numerical simulations, we have to perform many experiments. Ballistic tests are recorded with high-speed videos and analysed afterwards. Of particular importance are the moments before and after the impact (see Fig. 5). Here, even the fragmentation must precisely match later simulations. The projectile is also examined after the impact, regarding any kind of change it might have undergone. The targeted effect is that of deflection, deforming and ricocheting of a projectile.

Fig. 4 Ballistic tests and impact analysis

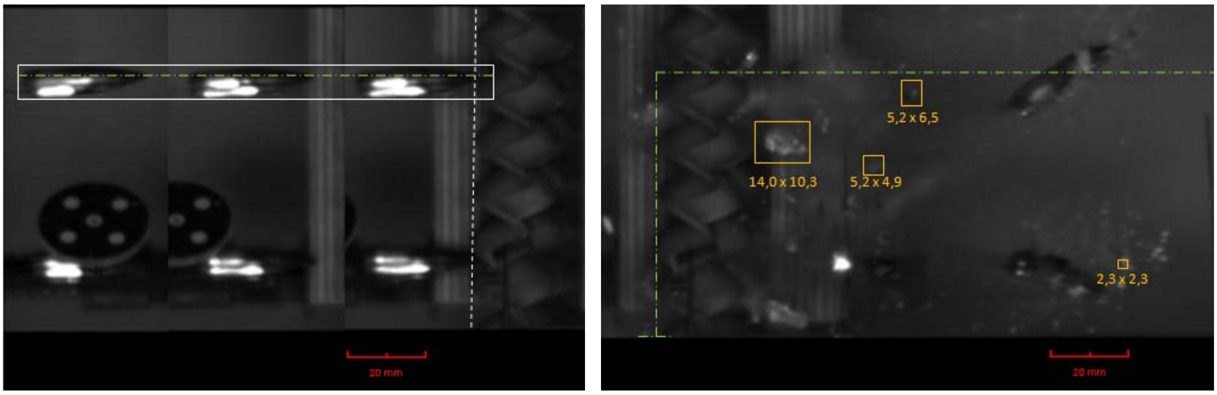

Fig. 5 Video analysis with a high-speed camera

4. SIMULATION RESULTS

The behavior of an actual projectile and the armor plate it hits depends on many effects and mechanisms, involving their material structure and continuum mechanics, which are very difficult to predict. Hence, using only a few basic principles will not yield a model which could function as a good enough description of the full range of possible outcomes. For that reason, the ballistic tests are followed by the modelling of the experimental set up. Then, the experiment is simulated using numerical simulations based on the finite element method (FEM).

This paper deals with a 7.62 x 51 mm NATO rifle cartridge with a steel base and brass jacket. The armor plate (110 x 110 mm) is made of corrugated iron and the CAD model contains parabolic elements. Corrugated armor can increase protection by a mechanism such as shattering of a brittle kinetic energy penetrator, or a deflection of that penetrator away from the surface normal, even though the area density remains constant. These effects are strongest when the projectile has a low absolute weight and when it is short relative to its width.

4.1 Iterative Optimization of Material Models

Fig. 6 shows a simulation of this type of experiment. The projectile itself is divided into two parts - the jacket and the base - which have different properties and even different meshes (see Fig. 7). These elements have quadratic shape functions and nodes between the element edges. In this way, the computational accuracy as well as the quality of curved model shapes increases. Using the same mesh density the application of parabolic elements leads to a higher accuracy compared to linear elements (1st order elements). The choice of element type predetermines the type of geometry simultaneously. The FE mesh, i.e. the number and the distribution of the elements, has a very important influence on the precision of analysis results. An even and harmonic element distribution and well-shaped elements are the primary prerequisites for sound results (Fröhlich 2005).

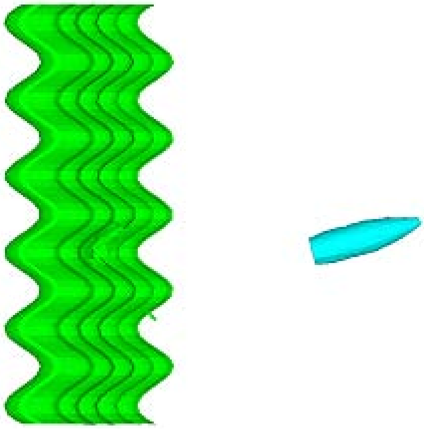

Fig. 6 Simulation of an impact without fragmentation

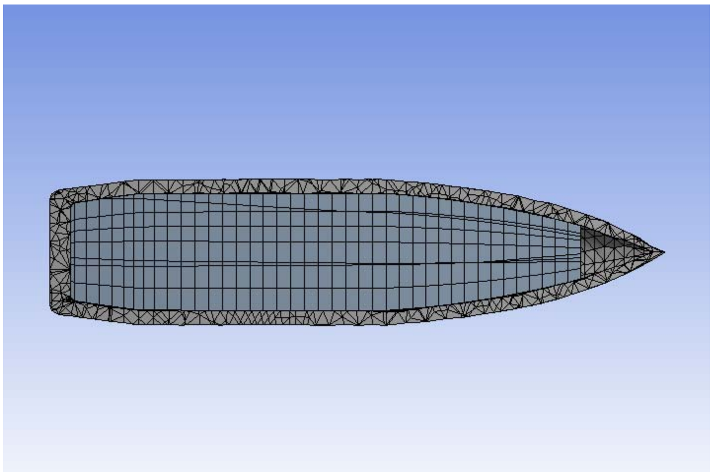

Fig. 7 CAD model of a 7.62 NATO

The phenomena which occur in the ballistic tests can all be detected through this simulation. With an impact velocity of 830 m/s and energy of 3500 Joule the projectile is deflected by the armor plate and only slightly deformed after the impact. There is also local damage on the armor plate, but there are no remarkable fragments or other effects. With 762 m/s the projectile still has a high velocity after the impact and with a total energy of approximately 2900 Joule it poses a substantial threat.

The simulation results in Fig. 6 are not consistent with those of our ballistic experiments. There is no obvious fragmentation and only a slight deflection of the projectile. Also, the front is still intact. Consequently, the aim is to adjust the parameters to improve the simulation results. In so doing, a convincing statement will be possible.

By progressively changing the material parameters, the simulation will be optimized in an iterative process. Here, the adjustment of the effective strain is a useful method to improve the material models. The effective strain is directly calculated from the principal strain components:

$$\varepsilon_{eff} = \frac{2}{3}\left[\left|\left(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2\right) + 5\left(\varepsilon_1\varepsilon_2 + \varepsilon_2\varepsilon_3 + \varepsilon_3\varepsilon_1\right) - 3\left(\varepsilon_{12}^2 + \varepsilon_{23}^2 + \varepsilon_{31}^2\right)\right|\right]^{1/2} \quad (1)$$

Another possibility to optimize the simulation results is to vary the strength models. The original formulation of material strength effects considered that materials were elastic - perfectly plastic. However, it is possible to generalize the approach by making the yield function Y a function of material properties such as strain, strain rate, energy, temperature etc. without excessively complicating the resultant calculations. Several of these more sophisticated treatments have been implemented in FEM libraries. One of them is the Johnson-Cook Model. This constitutive model aims to model the strength behavior of materials subjected to large strains, high strain rates and high temperatures. Such behavior might arise in case of intense impulsive loading, due to high velocity impact and explosive detonation. Therefore, the Johnson-Cook Model is used for most materials. In many cases, the stress-strain curve of a particular material has to be extrapolated to higher strain values (see Fig. 8).

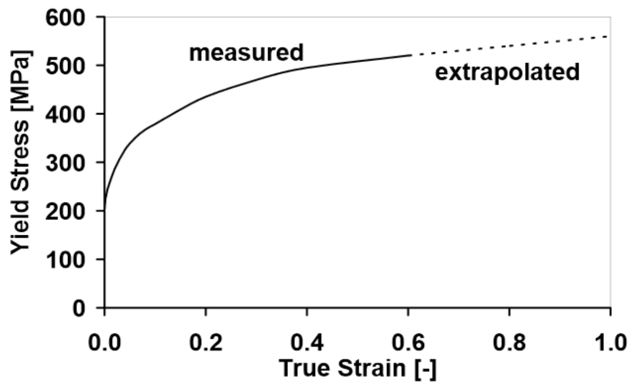

Fig. 8 Extrapolated stress-strain curve

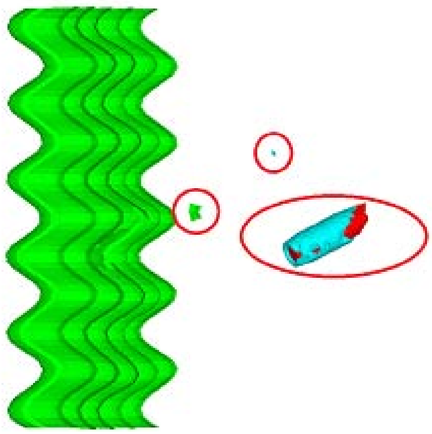

Fig. 9 Optimized material parameters and improved simulation results

After the adjustment and optimization of the material parameters, the simulation results reflect the observations of the experiments very well (see Fig. 9).

Fragmentation and deflection are almost equal to the ballistic test shown in Fig. 5. Small fragments are automatically deleted from the program to reduce computing time. Regarding the protection level of our structures, these fragments are hardly of any importance. The front of the projectile breaks apart and is damaged through the impact. The same phenomenon can be observed in the ballistic experiment (see Fig. 10). The projectile loses kinetic energy and poses a lower threat to other structures.

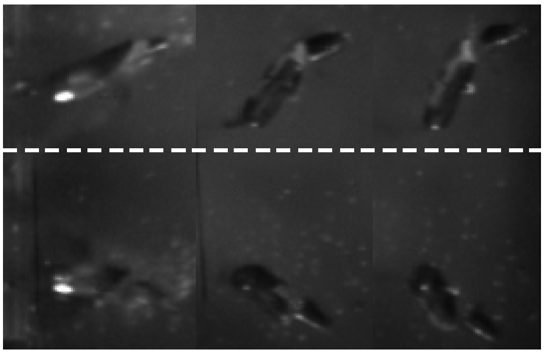

Fig. 10 Projectile after it hits the armor plate – two perspectives

4.2 Improvement of Armor Structure

Other structures as well as new materials can be used to increase the security of the armor plate. Simulations with different parameter configurations demonstrate the effect of the projectile at other impact points. For instance, the projectile either hits the armor plate in the middle of the crest or in the trough. In both cases there is no discernible deflection, apart from the front of the projectile, which is being slightly distorted.

Fig. 11 shows a new concept for a corrugated armor plate. It is a row of crests which improves the effect of deflection and deformation of the projectile. It requires no additional space and can be used in existing structures. Furthermore, the conditions being equal, there is no significant increase of mass.

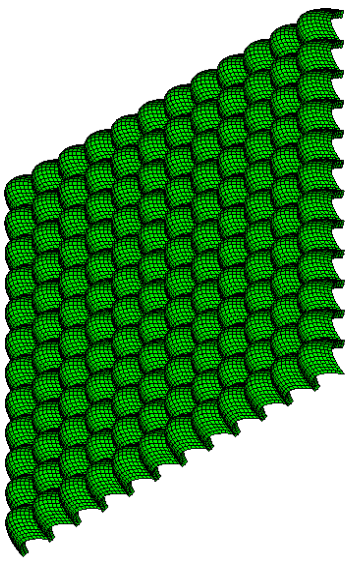

Fig. 11 Improved corrugated armor plate

The improved corrugated armor plate is tested for every protection level with numerical simulations. The results indicate an improvement at each spot where the projectile hits the target. On average, the velocity of the projectile decreased by more than 10 per cent. This, in turn, increases the safety of the structure (see Fig. 12).

Another concept, which is currently being tested, contains two corrugated armor plates – one behind the other. Both plates are comparatively thin and have a distance of 30 mm (see Fig. 13). The aim is to cause a deflection and deformation of the projectile, even if a crest or a trough is hit. At the same time, the mass of the structure may not be significantly increased.

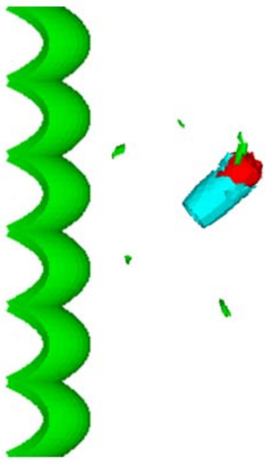

Fig. 12 Optimized armor structure and improved simulation results

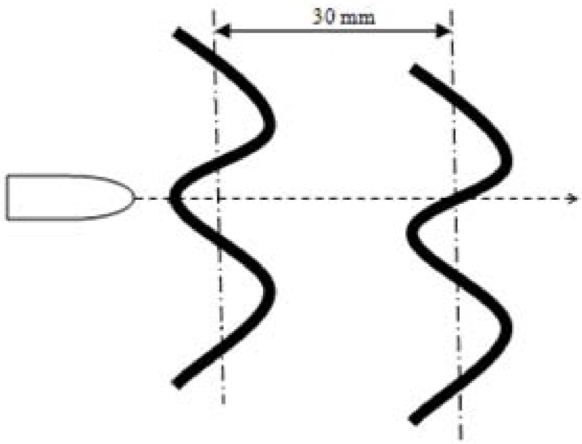

Fig. 13 Modified armor structure with two corrugated plates

Fig. 14 illustrates a typical simulation of an impact, where a 7.62 x 51 mm NATO rifle cartridge hits a structure with two corrugated armor plates. The simulation results show an intensive deformation of the projectile. The jacket has completely come off and the front is damaged. The projectile is strongly deflected and loses a large amount of energy.

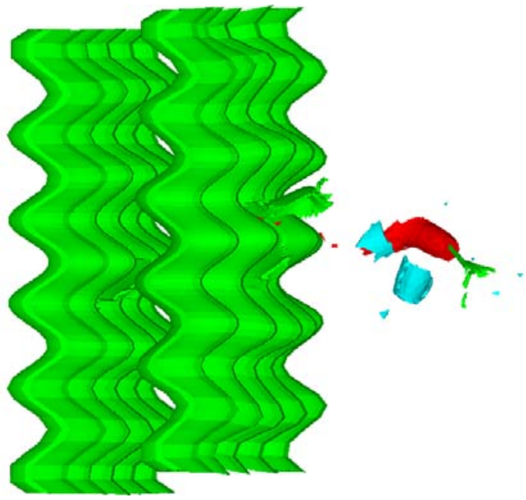

Fig. 14 Numerical simulation of an impact with two corrugated armor plates

5. CONCLUSIONS

New concepts and models can be developed and easily tested with the help of modern hydrocodes. The initial design approach of the units and systems has to be as safe and optimal as possible. Therefore, most design concepts are analyzed on the computer. FEM based simulations are well-suited for this purpose. Estimates based on experience are being more and more replaced by software.

In this paper, existing material models were optimized to reproduce ballistic tests. High-speed videos were used to analyze the characteristics of the projectile – before and after the impact. The optimized results can be applied to them.

Subsequently, modern armor constructions were tested in numerical simulations. First, CAD models were roughly created, before the structures could be improved trough an iterative optimization process. The experience we gain is of prime importance for the development of modern armor.

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