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EXPERIMENTAL AND NUMERICAL SIMULATION OF SECONDARY BEHIND ARMOR EFFECTS INSIDE A COMPARTMENT PERFORATED BY A KINETIC ENERGY PROJECTILE

Andreas Heine[1] and Matthias Wickert[2]

[1] Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut (EMI), Eckerstr. 4, 79104 Freiburg, Germany, Phone: +49 761 2714 435, Fax: +49 761 2714 1435, e-mail: andreas.heine@emi.fraunhofer.de
[2] Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut (EMI), Eckerstr. 4, 79104 Freiburg, Germany, Phone: +49 761 2714 384, Fax: +49 761 2714 1384, e-mail: matthias.wickert@emi.fraunhofer.de

We consider the behind armor effects inside a compartment that is perforated by a projectile. Besides the residual projectile and the behind armor debris, secondary effects exist that may constitute a threat for a crew inside an armored vehicle – such as pressure and temperature rise. While this has been investigated earlier for the cases of shaped-charge attack or for hypervelocity impacts of small spheres on spacecraft structures, we report on an approach towards the investigation of the secondary effects after long rod perforation at velocities of about 1500 m/s.

For this purpose, numerical simulations have been performed and a small vessel with exchangeable front and back plates has been equipped with pressure and temperature sensors in order to estimate upper limit values experimentally. The design of this simulator allows for a flexible instrumentation adapted to the purposes of individual requirements. Furthermore, the exchangeable target plates permit to investigate the influence of different target materials.

First experimental and numerical results give a preliminary estimate of the aforementioned secondary effects.

INTRODUCTION

The residual projectile and the behind armor debris constitute the main threat for the crew inside a perforated vehicle. However, there are additional risks due to secondary effects like pressure and temperature rise. So far, experimental estimates of the secondary effects connected with kinetic energy (KE) perforation have only been published in the context of spacecraft vulnerability studies [1][2]. For example, peak overpressures resulting from KE perforation of up to 276 kPa have been observed in [2].

As the aim of these investigations was to simulate space debris and meteoroid impacts, small metal spheres with velocities larger than 6000 m/s were used as projectiles. Hence, these parameters differ from those relevant for the assessment of the risks inside military armored vehicles that are attacked with KE ammunition. The present paper therefore focuses on the crew cabin perforation by long rods in the velocity regime at 1500 m/s. Our investigations are also complementary to existing results on the behind armor blast effects of shaped charge attacks [3][4].

EXPERIMENTAL SETUP

In order to investigate the secondary effects connected with KE perforation in the laboratory, a model-size setup had to be chosen. Therefore, a cylindrical vessel with exchangeable front and back plates was instrumented with different pressure gauges and temperature sensors (**Figure 1**). This vessel will be referred to as *simulator* in the following.

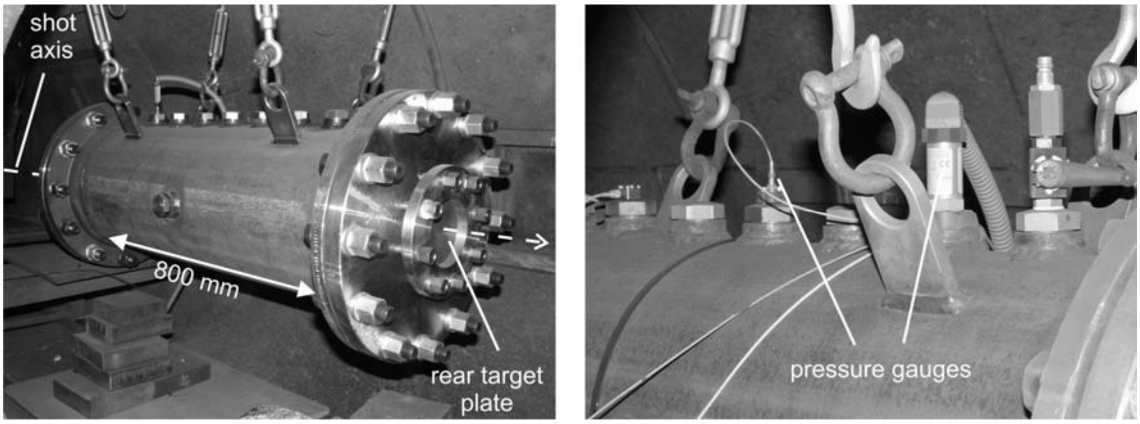

Figure 1: Photographs of the experimental setup.

The simulator has an inner diameter of approximately 300 mm and a total outer length of about 1100 mm, depending on the thickness of the target plates. For experimental investigations the vessel is installed inside the impact tank at one of the gun facilities (LLGG) at Fraunhofer EMI. The gun can be operated as powder gun or as two-stage light gas gun. The used projectiles are tungsten-heavy-alloy rods of length-to-diameter ratios of 15 that perforate the vessel along its cylinder axis. The setup has several advantages:

- As the target plates are exchangeable, the simulator can be re-used and target plates of different thickness and material may be tested.

- It is possible to open the simulator and to place objects, e.g. samples of different materials, inside the simulator.
- The simulator can be filled with gases different from air, such as nitrogen or helium.
- As the sensors are mounted with thread inserts, the instrumentation can easily be adapted to the purposes of individual experiments.
- The complete technical environment of the LLGG laboratory at Fraunhofer EMI (e.g. x-ray, high-speed photography) is available for the experiments.

NUMERICAL SIMULATION

Before a detailed description of the experimental results is given, we will present some numerical simulations. Hydrocode calculations with coupled Eulerian and Lagrangian grids have been performed in Autodyn v6 [5] for a 2D axial symmetric setup. The numerical results will assist in interpreting the more complex experimental findings described below.

The upper part of **Figure 2** shows the perforation of the simulator by a tungsten rod with a velocity of 1550 m/s at two different times, 250 and 750 µs, after impact of the projectile. (The numerical description is simplified: not all details of the real setup could be included in the simulations due to the finite grid resolution and the rotational symmetry). According to the velocity of sound in air of 343 m/s at a temperature of 20 °C, the shock wave surrounding the projectile has the shape of a Mach cone with a full cone angle close to the theoretical value of approximately 26 degrees for a projectile with zero lateral extension. The pressure gauge also indicated in **Figure 2** is first hit by the Mach cone approx. 750 µs after the impact of the projectile on the front target plate. Accordingly, the overpressure-time-history recorded at the pressure gauge shows the first pressure peak exactly at that time (750 µs). At the same time – this is a coincidence in time which is due to the chosen dimensions and the specific projectile velocity – the projectile is penetrating the back plate, i.e. it is already leaving the simulator. The quasi-periodic overpressure-time history results from multiple reflection of the initial air shock wave at later times. The calculated maximum overpressure is 18 kPa, and the period of the quasi-periodic signal is approx. 1 millisecond. Note that the recorded pressures are due to the static overpressure in the vicinity of the wave front. Dynamic pressure does not contribute significantly to the total overpressure.

EXPERIMENTAL RESULTS

First, we present experimental results for the case where the simulator is completely perforated by a KE projectile, i.e. the projectile enters through the front target plate and leaves the simulator by perforating the rear target plate (as in the above simulation). In all experiments presented here, the projectile was a tungsten-heavy-alloy rod of length 90 mm and diameter 6 mm, with an initial velocity of approx. 1550 m/s. Four different target material combinations have been investigated. For the target plate material aluminum of 20 mm thickness and steel of 10 mm thickness has been tested. The experiments have been performed for air and nitrogen fillings of the simulator. The experimentally obtained overpressure-time histories for all four combinations are shown in **Figure 3**.

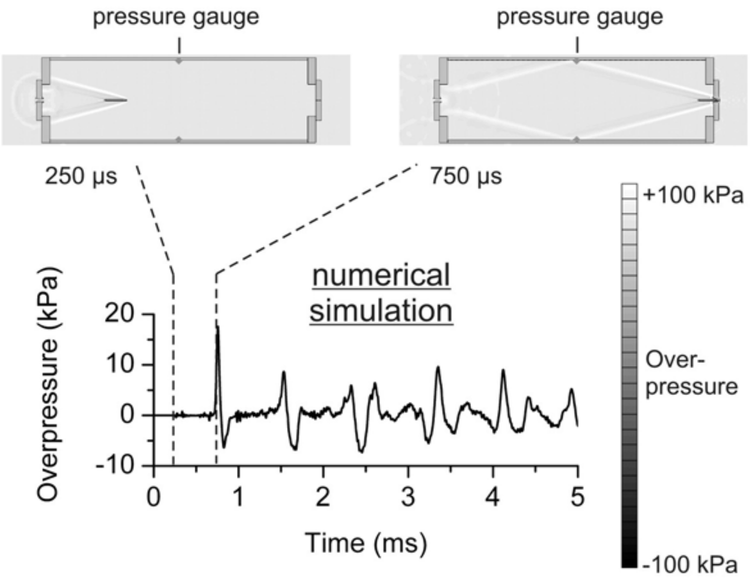

Figure 2: Pressure-time history (0-5 ms) and spatial pressure distributions 250 µs and 750 µs, respectively, after the first impact of the projectile (numerical simulation).

For aluminum target plates the maximum overpressures are approx. 25 and 50 kPa for nitrogen and air filling, respectively. The mean overpressures during the first 5 ms are 3.5 and 7.5 kPa, i.e. the maximum as well as the mean overpressure is twice as high, if air instead of nitrogen is filled in the simulator.

In the case of steel target plates, the typical maximum overpressures are also approx. 50 kPa, largely independent from the gas filling. The mean overpressure (0-5 ms) for an air filling (5.4 kPa) is only slightly higher if compared to the value for nitrogen filling (4.1 kPa). The large pressure peak at approx. 0.9 ms for the steel target plates and air filling of the simulator obviously is an outlier. Its maximum is approx. 170 kPa and thus more than a factor of 3 larger than the other peaks. This must be caused by an impact of small debris on the sensor.

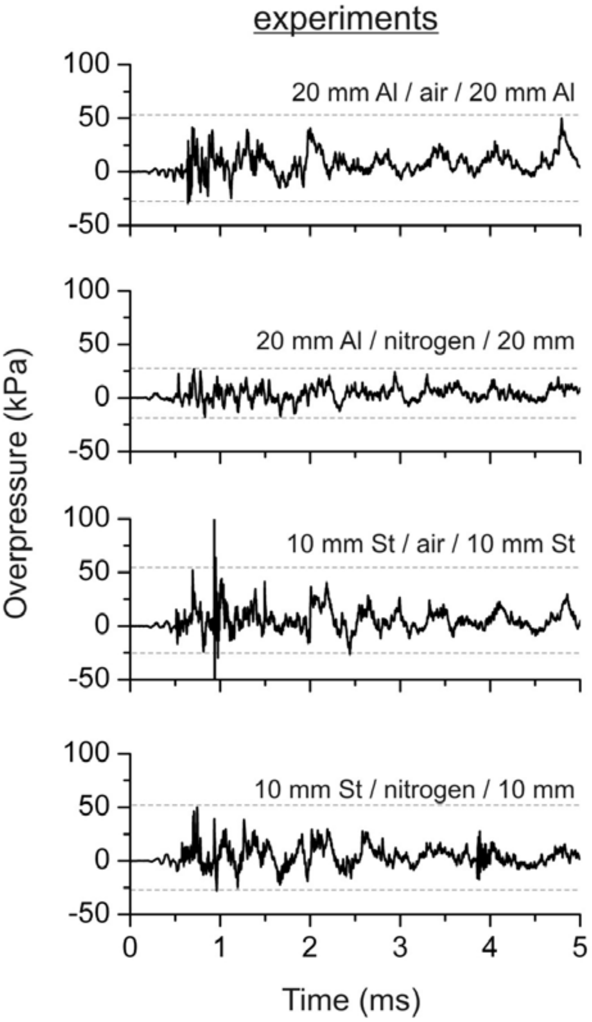

Figure 3: Experimentally obtained overpressure-time histories for different material combinations (0-5 ms).

The time structure of the recorded signals is complex and shows many fast oscillations. In contrast, the numerical result (see **Figure 2**) shows overpressures of less than 20 kPa and a much simpler pressure-time profile that consists of quasi-periodic repetitions of sharp pulses with a period of about 1 ms. However, a overpressure-time history almost identical with the numerical result is obtained experimentally, if the target plates are removed and the projectile passes through the open simulator without experiencing any penetration or perforation process (**Figure 4**).

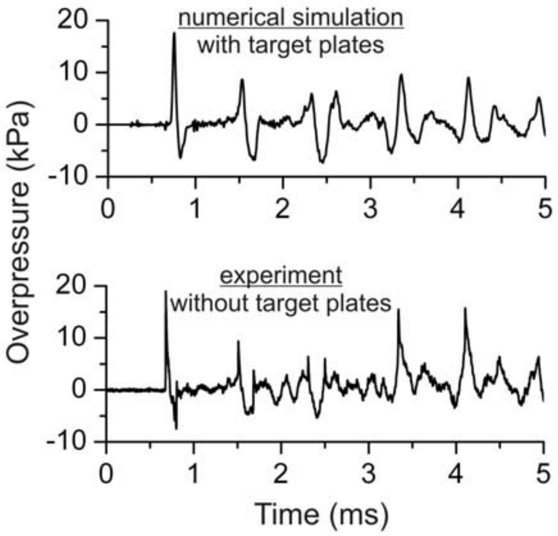

Figure 4: Comparison of experimental and numerical overpressure-time histories (0-5 ms).

This leads to the following conclusions: The experimentally observed pressure rise after perforation of the simulator by the projectile to the larger extent stems from processes not included in the hydrocode simulation. Combustion of parts of the aluminum must play an important role, because the pressure rise is suppressed in the absence of oxygen in the interior (combustion still is possible as air is venting from the outside). On the other hand, the simulation clearly shows which part of the pressure rise is solely caused by the passage of the projectile through the simulator. In that sense, the simulation correctly describes the secondary effects in the absence of debris and chemical reaction. The latter, however, dominates and is surely the main cause of the observed pressure rise after perforation. As the sensor signals obtained for aluminum target plates differ in amplitude for different gas fillings by a factor of 2, it can also be excluded, that the recorded signals are due to mechanical vibrations of the setup that are caused by the projectile impact. Such vibration-induced signals should always be similar in time structure and amplitude.

In order to investigate the importance of the *partial* combustion of the aluminum, we performed another experiment, where samples of aluminum foam were placed inside the simulator along the shot axis. Foam material has a large surface at a given mass and should therefore be extremely reactive. As before, the measured mean overpressures are larger for air than for nitrogen filling. Remarkably, in both cases – even for nitrogen – the observed pressures are higher than for all experiments described above (**Figure 5**). The mean overpressures during the first 5 ms are 9.8 kPa for nitrogen and 14.7 kPa for air filling. This supports the conjectures that combustion is the main cause of the observed pressure rises *and* that the oxygen necessary for the combustion in part vents from the outside, i.e. the oxidation processes during the first milliseconds take place in the vicinity of the perforation holes. The effects of the combustion of parts of the foam, however, appear on a different time scale. **Figure 6** shows the gas pressure and the temperature inside the simulator for the first 100 milliseconds. Due to a finite rise time of the temperature sensors (<50 ms) the temperature signal is delayed with respect to the pressure signal. In the case of the air filling, overpressures of up to 100 kPa and temperatures of approx. 200 °C are reached for several tens of milliseconds. For the nitrogen filling these effects are significantly reduced and in this case the smooth pressure rise shown in **Figure 6** is mainly caused by the blast of the gun, which enters the simulator from the outside. The extreme pressure and temperature rise for air filling, however, is obviously due to the high reactivity of the aluminum foam.

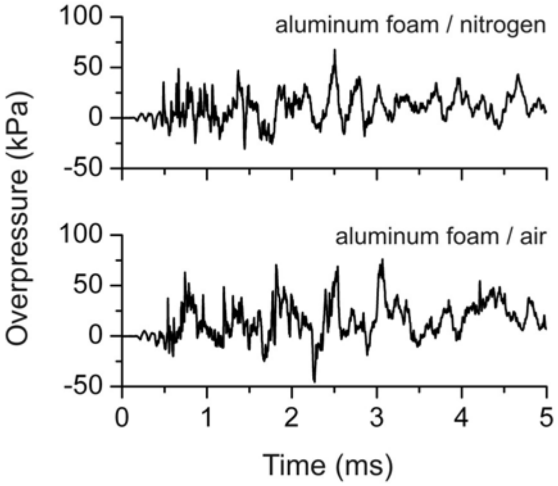

Figure 5: Experimental overpressures for a perforation with aluminum foam inside the simulator (0-5 ms).

SUMMARY

A setup for the systematic investigation of secondary effects inside perforated compartments in the laboratory has been developed. So far, experimental results for the resulting overpressures have been obtained and compared to numerical results. The combined experimental and numerical approach allows identifying the possible origin of the experimentally observed overpressures – mainly chemical reaction (combustion of metal). For samples of aluminum foam inside the simulator, overpressures of up to 100 kPa and temperatures of up to 200 °C have been observed, experimentally. Potential extensions of the present investigations are more detailed temperature and light measurements as well as systematic experiments with different materials. A main task, however, will be the assessment of the results with respect to the risks for a crew inside a perforated compartment [6][7][8][9]. We provide an experimental basis for such future assessments.

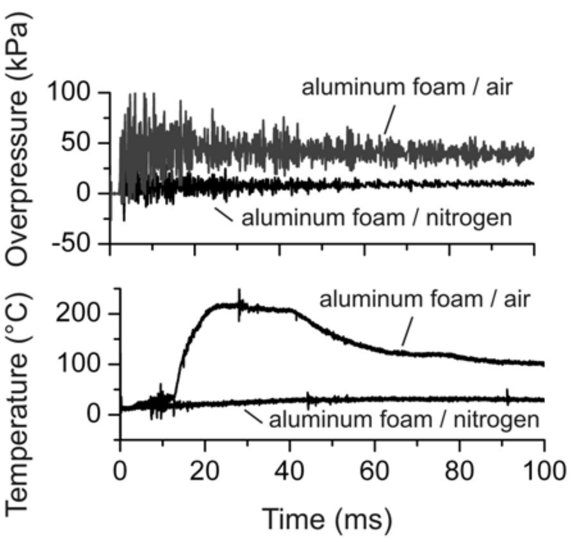

Figure 6: Experimental overpressure and temperature history for a perforation experiment with aluminum foam inside the simulator (0-100 ms).

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