Engineering Structures 130 (2017) 216–228

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experiments and simulations of empty and sand-filled aluminum alloy panels subjected to ballistic impact

Jens Kristian Holmen [*], Tore Børvik, Odd Sture Hopperstad

Structural Impact Laboratory (SIMLab) and Centre for Advanced Structural Analysis (CASA), Department of Structural Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ARTICLE INFO

Article history:
Received 23 September 2015
Revised 26 September 2016
Accepted 27 September 2016
Available online 31 October 2016

Keywords:
Small-arms bullets
Discrete particle method
Finite element method
Granular materials
Protective structures
Soil-structure coupling

ABSTRACT

In this study, we use a discrete particle method in combination with finite element analysis to describe the interaction between structures and granular media during ballistic impact. By applying a discrete particle method to model granular materials, issues like mesh distortion and element deletion can be avoided. This paper presents experiments and numerical simulations on the perforation of empty and sand-filled aluminum alloy panels subjected to impacts by small-arms bullets. The simulations of the sand-filled panels were conducted using a combined discrete particle–finite element approach that accounts for the coupling between structure and sand. The ballistic capacity of the sand-filled aluminum panels was more than 40% higher than that of the empty aluminum panels. Overall, the results from the numerical simulations describe the trends from the experiments. The predicted ballistic capacity of the empty panels was within 5% of the experimentally determined value and the critical velocity of the sand-filled panels was predicted within 11% of the experimentally determined critical velocity. The scatter in residual velocity was similar in simulations and experiments. However, in its current form the discrete particle method needs different calibrations for different velocity regimes to obtain accurate description of the sand behavior.

1. Introduction

Extruded aluminum panels are used in a number of engineering structures due to their low weight-to-stiffness ratio. Børvik et al. [1,2] showed experimentally that AA6005-T6 aluminum panels filled with granular materials can be used with success to mitigate the possibly lethal effects of explosions, and impacts by projectiles or debris. The resistance against explosions was simulated with a finite element model where the response of the granular material was approximated by a constitutive model originally intended for foams. However, the foam model was not deemed accurate enough for perforation simulations, so the ballistic behavior was not analyzed numerically in that study. A significant grain-size effect was revealed in ballistic tests with gravel. Here, grains larger than 2 mm were found to have greater resistance against perforation than typical sand with median grain diameter smaller than 2 mm. The material parameters for the AA6005-T6 aluminum panels were determined some years earlier and numerical simulations of ballistic perforation of empty panels by 20 mm ogival-nosed projectiles were presented in Ref. [3].

In the current study we use the same type of AA6005-T6 aluminum panels as were used in Refs. [1–3]. They are in the numerical simulations modeled as a continuum with finite elements. The sand is, on the other hand, modeled with a discrete particle method as rigid spherical particles that transfer forces through a penalty-based contact formulation. This method was proposed by Olovsson et al. [4,5] and was initially developed to handle the gas–fabric contact issues in airbag-deployment simulations before it was applied to represent close-range blast loading and the interaction between high explosives, air, and sand. The discrete particle method is available in the explicit nonlinear finite element code IMPETUS Afea Solver [6] and it was thoroughly described and used for combined sand impact and blast loading on structures by Børvik et al. [7] and Wadley et al. [8]. More recently, Holloman et al. [9,10] applied this discrete particle method to gain insight into the impulse transfer between sand ejecta from buried charges and structural components. The case of deep penetration by small-arms bullets into granular materials was studied in detail by Børvik et al. [11] and the results from these simulations showed that the method was able to describe several experimentally observed phenomena.

---

[*] Corresponding author.
E-mail address: jens.k.holmen@ntnu.no (J.K. Holmen).
URL: http://www.ntnu.edu/casa (J.K. Holmen).

http://dx.doi.org/10.1016/j.engstruct.2016.09.057

Discrete numerical modeling of granular materials has been researched extensively since Cundall and Strack [12] presented their distinct element model in 1979. Combined discrete particle–finite element approaches like the one presented above have been used, e.g. by Oñate and Rojek [13]. Solid materials such as rock and concrete can also be represented by discrete particles by introducing a cohesive law between individual particles [14]. On an even lower scale, agglomerates of discrete sub-particles can represent larger particles to model cracking and fracture in granular materials as shown by Cil and Alshibli [15]. Discrete particle methods have the advantage of needing relatively few input parameters and the complicated bulk material behavior arises as a consequence of relatively simple assumptions on the particle level [16]. Continuum models, on the other hand, require constitutive equations for the bulk sand and numerical issues might arise in the mesh discretization and with element erosion. Individual sand grains can in some cases be represented by finite elements to allow for crushing. This has been shown to be important in high velocity penetration of sand [17–19], but the added complexity comes at a significant computational cost.

High strain rate behavior of sand and its behavior during rapid penetration has been carefully reviewed by Omidvar et al. [20,21]. It is clear from centuries of research that the resistance of sand against a high-velocity intruder such as a bullet is affected by a myriad of parameters on several scales. The most relevant for perforation problems are the shape, trajectory, obliquity, mass and velocity of the bullet; and the density, packing density, grain size and moisture content of the sand. In addition, the frictional effects between the bullet and the sand come into play.

The objective of this study is to evaluate a numerical technique for design of protective structures consisting of sand in combination with ordinary solid materials. To this end we first experimentally determine to which degree filling an aluminum panel with sand increases its capacity against perforation by small-arms bullets; we present a simple calibration method for the discrete particle method; and lastly we use the calibrated discrete particle method in combination with finite elements in an attempt to simulate the entire problem including the sand–structure interaction. By using this approach, we can describe, at least qualitatively, the response of protective structures consisting of a combination of a solid structure and a discrete filling.

2. Experimental study

2.1. Component test setup

All the ballistic tests were conducted in a ballistic laboratory where a smooth-bored 7.62 × 63 mm Mauser rifle launched the armor piercing (AP) bullets shown in Fig. 1 toward the target panels shown in Fig. 2 at predefined approximate velocities between 400 m/s and 900 m/s. The nominal mass of the complete bullet was 10.5 g and it consisted of a brass jacket, a lead cap and an ogive-nosed hardened steel core with a nominal mass of 5.0 g, a caliber radius head (CRH) of 3 and a Rockwell C hardness of 63. During testing, 300 mm long sections of the panels were mounted in a rigid frame, and only the bottom and top 30 mm were constrained in the direction of perforation. For the impact conditions considered here the boundary conditions are believed to be of minor importance. The impact point was chosen 27.5 mm from the center line of the panel as indicated in Fig. 2, meaning that the projectile also had to perforate the oblique web. For the tests without any sand, at most 10 shots were fired at a 300 mm high profile, leaving 50 mm between each shot. For the remaining tests, sand was filled inside the cavities of similar profiles and the sides of the panels were gently tapped with a rubber hammer to compact the sand. The panels were mounted on a specially designed steel plate and another steel plate was put on top of the panels before each test. At least 70 mm was left between each impact point and the sand was replaced at irregular intervals. Small pitch angles, $\alpha \leqslant 3^\circ$, were observed in some of the tests. This is commented upon in Section 3. No spin was given to the bullet, the effects of which were commented on by Børvik et al. [11]. Initially, 49 tests were performed, but nine additional tests were conducted on the B95 sand (see Section 2.2) to further investigate the repeatability of the test setup, giving 58 component tests in total.

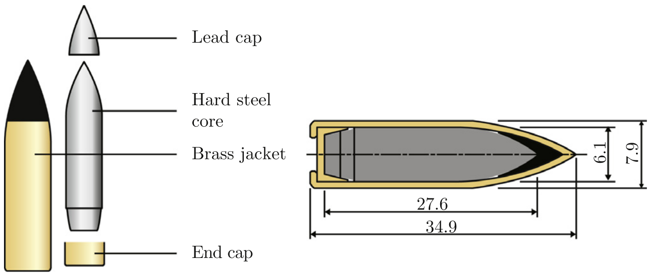

Fig. 1. Geometry of the AP-bullet used in this study.

Two Phantom v1610 high-speed video cameras were used to capture the perforation process. A Nikon 80-200 1:2.8D lens and a Nikon 70-300 1:4.5-5.6G lens were mounted on the cameras, an exposure time of 0.001 ms was used and an area of approximately 150 mm × 75 mm was covered by each camera. Two Cordin Model 659 flashes were used as light sources. A resolution of 512 × 304 pixels and a frame rate of 80,000 frames per second for both cameras were sufficient to optically measure the initial and residual velocities of the bullets.

2.2. Sand characteristics

Three types of sand delivered from AB Baskarpsand in Sweden were used in this study: B15, B55 and B95 with respective median grain sizes (diameters) of 0.15 mm, 0.55 mm and 0.95 mm. The main constituents of the sand are quartz (SiO_2) and alumina (Al_2O_3), with minor fractions of other elements. B15 consists of 88.5% quartz and 6.3% alumina; B55 consists of 90.1% quartz and 5.3% alumina; while B95 consists of 77.1% quartz and 12.5% alumina. Table 1 provides some material data for the sand. The grain size curves that show the proportion of grains smaller than a certain size are shown in Fig. 3 and the grain size distribution is visualized in Fig. 4. The moisture content was measured to be less than 0.5% for all the sand types. Figs. 3 and 4 also show that B95 sand is the least uniform material. This means that the porosity is lower than for B55 and B15 which is why the bulk density is highest for this sand type. The bulk density in Table 1 was measured with a 1000 cm^3 container normally used for concrete aggregates. However, in relation to the additional ballistic tests we measured the bulk density of the B95 sand when it was filled in the aluminum panels just before impact-testing: no measurement differed more than 2% from the reported value.

2.3. Results from tests on empty aluminum panels

The residual velocities v_r from the tests on the empty aluminum panels plotted against their respective initial velocities v_i are shown in Fig. 5. The solid line was calculated from a generalized version of an analytical model originally proposed by Recht and Ipson [22], also called the Lambert and Jonas equation [23],

$$v_r = a\left(v_i^p - v_{bl}^p\right)^{1/p} \tag{1}$$

where the model parameters a and p, as well as the ballistic limit velocity v_{bl} were simultaneously obtained with a least-squared-