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Low-velocity impact on multi-layered dual-phase steel plates

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ABSTRACT

In this paper an experimental program investigating the behavior of monolithic and multi-layered configurations of 0.8 mm and 1.8 mm medium-strength steel plates is presented. We have considered impacts by blunt-ended and ogival-ended impactors in the low-velocity regime (≤16 m/s). Experimental outputs include measurements of force and velocity, and deformation fields. Force and velocity readings were provided by a strain-gauge instrumented striker, while digital image correlation was used to obtain the displacement field from the rear side of the bottom plate. For the 0.8 mm plates a near linear relationship between the number of layers and the ballistic limit velocity was found. The plates' resistance against perforation was found to be higher for the blunt-ended impactor than for the ogival-ended impactor. This can be explained by the failure mechanisms. The monolithic plates have a higher capacity than layered plates with the same total thickness: this is particularly clear for plates struck by the ogival-ended impactor. The experiments provide ample data to validate the subsequent 3D numerical simulations. The analysis model is double-symmetric in simulations using the ogival-ended impactor, while only a 10° slice of the plate and impactor is needed in simulations using the blunt-ended impactor. A thermoelastic–thermoviscoplastic constitutive relation combined with the Cockcroft-Latham criterion for failure is implemented in IMPETUS Afea Solver, and used in all simulations. The simulations predict the failure modes fairly well, and the numerical results are within the range seen in previous publications. Sensitivity studies regarding friction, mesh refinement, thermal formulation and strain-rate dependence are conducted and discussed.

1. Introduction

Numerous factors influence the penetration and perforation processes in structural impact events, and for each of these factors there are several approaches to investigating the different effects. Impact loading of plates has for a long time been of interest, and the mechanisms of penetration and perforation of different layer configurations due to impact from various projectile shapes are well documented, especially for relatively thick targets, see e.g. Refs. [1–4]. More recently, Kpenyigba et al. [5] used 30 g projectiles and 100 mm spanned thin steel plates to perform an experimental, analytical and numerical study on the influence of projectile shape in impact events. It was found that the capacity of plates subjected to impact by hemispherical-ended penetrators is larger than that of plates struck by ogival-ended penetrators and blunt-ended penetrators. A similar numerical study was performed using 52.5 g penetrators by Iqbal et al. [6] where the results indicate a positive correlation between increased target span and ballistic limit. The study indicated that a plate can resist impacts by blunt-ended penetrators better than impacts by ogival-ended penetrators. For the smallest span, however, the opposite was found, showing that a plate's capacity is highly dependent on its configuration. Monolithic targets were found to be stronger than layered targets in contact and layered targets with spacing.

The effect of projectile shape, impact velocity and target configuration on the perforation behavior of thin aluminum plates was studied by Gupta et al. [7]. They found that the plates resisted impacts by hemispherical projectiles better than they resisted impacts from blunt and ogival-shaped projectiles. The double-layered plates performed equally well as the monolithic plates, but a further increase in layers impaired the total capacity. The same authors published another paper where the results from numerical simulations were shown to be sensitive to the mesh refinement [8]. The ballistic properties of blunt and hemispherical projectiles were also studied. Similar to Ref. [7] the plates' capacity against hemispherical projectile impact was found to be the highest.

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Table 1
Nominal chemical composition of Docol 600DL steel in wt-% [17].

C	Si	Mn	P	S	Al_{tot}	Fe
0.10	0.40	1.50	0.010	0.002	0.040	Balance

Work conducted by Woodward and Cimpoeru [9] on the high-velocity perforation processes in monolithic and layered aluminum plates revealed that the ballistic limit of plates struck by conical-shaped projectiles is higher than that of plates struck by flat-ended projectiles. This was found to be independent of the target configuration. The transition from ejection of a target plug for a thick plate to dishing and stretching dominated energy absorption for thinner plates was discussed.

Dey et al. [10] conducted a large experimental and numerical study on the ballistic perforation resistance of monolithic and double-layered Weldox 700E steel plates. Blunt-ended and ogival-ended projectiles were considered. They found that for blunt-ended projectiles a double-layered configuration of 2 × 6 mm performed much better than a monolithic 12 mm configuration. The opposite was found for ogival-ended projectiles, where the monolithic plates performed slightly better than the double-layered configuration. However, the overall protection level increased for layered targets, since the plates' initial perforation capacity using ogival-ended projectiles was considerably higher than the capacity for blunt-ended projectile impact.

Ben-Dor et al. [11] published a review paper in 2012 that gave an overview of some of the most important work regarding layering of target plates in impact engineering. They stated that layering of plates commonly leads to a degradation of ballistic properties and that increasing the velocity reduces the effect of layering. Conclusions from the study highlight the complexity of the problem and that more research is needed to improve our understanding of how target configuration affects the penetration and perforation behavior of protective structures. Further studies concerning low and medium velocity impact are available in the literature (e.g. Refs. [12–16]), however, relatively few systematic studies of the effect of projectile shape and layering of thin plates exist. In general, the large number of parameters involved in the penetration and perforation process of layered plates makes it hard to draw definitive conclusions. Varying the span, projectile shape, projectile weight, impact velocity, target material, angle of incidence etc., will inevitably affect the result. It is thus important to establish reliable and validated numerical models in order to study this problem in a systematic way.

In this study, the response of monolithic and multi-layered steel plates subjected to projectile impact in the low-velocity regime is investigated. Configurations consisting of up to four target plates are considered. No adhesives are applied prior to testing, but the plates are in physical contact at the beginning of each test. A dropped-objects-rig is used to strike the targets using blunt-ended and ogival-ended cylindrical impactors. To assess the accuracy of subsequent finite element simulations and to get a better physical understanding of the impact process, digital image correlation (DIC) is used in most of the experiments. Ballistic limit velocities are reported for all configurations.

2. Target and impactor materials

Thin plates made of the medium-strength, high-hardening steel Docol 600DL were chosen for this study. The nominal chemical composition of the material can be found in Table 1. The steel has been heat treated to obtain a dual-phase structure of ductile ferrite and strong martensite where the content of martensite determines the strength of the material. All the plates were produced and delivered by Swedish Steel Ltd. (SSAB). Nominal mechanical properties for the direction transverse to the rolling direction are provided: the yield strength is reported to be between 280 MPa and 360 MPa, while the tensile strength is reported to be between 600 MPa and 700 MPa [17]. Plates of thicknesses 0.8 mm and 1.8 mm are used in the experimental program described in Section 3. In this study, the tensile testing and subsequent material characterization are only performed for the 0.8 mm thick plates.

Tensile tests were conducted at angles 0°, 45° and 90° with respect to the rolling direction of the plate using both an extensometer and DIC functionality [18]. Standard dog-bone specimens with a 70 mm gauge area were used, see Ref. [19] for the geometry. To ensure repeatability, three specimens were tested in each direction. All tests were carried out with a cross-head velocity of 2.0 mm/min which corresponds to an approximate initial strain rate of 5×10^{-4} s^{-1}. Fig. 1a shows that the material is nearly isotropic with respect to flow stress, but with slight variations in elongation at failure, which is further highlighted in Fig. 2a where the strain at incipient fracture based on DIC measurements is shown as a function of test orientation. As seen, some variation of fracture strain is observed, especially in the 45° direction. Grytten et al. [20] showed that plastic anisotropy is practically insignificant for low-velocity perforation problems. Thus, the limited plastic anisotropy found from the material tests in this study can be

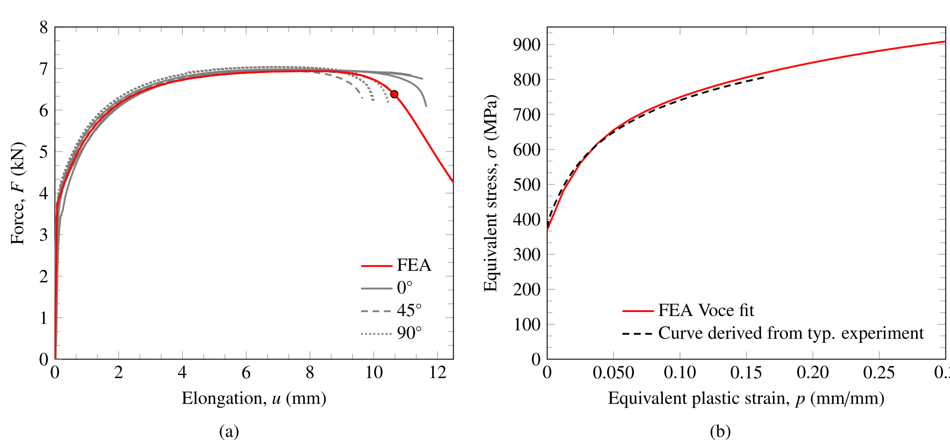

Fig. 1. (a) Force-elongation curves from DIC-measurements with 40 initial gauge-length and the corresponding finite element solution. The circle denotes the assumed point of fracture in the calculation of W_{cr}. (b) Equivalent stress-equivalent plastic strain curves for the representative uniaxial tensile test (until necking), and the optimized extended Voce hardening rule with parameters shown in Table 5.