International Journal of Impact Engineering 000 (2017) 1–11

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Ballistic impact of layered and case-hardened steel plates

Jens Kristian Holmen[a,b,*], Jan Ketil Solberg[c], Odd Sture Hopperstad[a,b], Tore Børvik[a,b]

[a] *Structural Impact Laboratory (SIMLab), Department of Structural Engineering, NTNU, Norwegian University of Science and Technology, Trondheim, Norway*
[b] *Centre for Advanced Structural Analysis (CASA), NTNU, Trondheim, Norway*
[c] *Department of Materials Science and Engineering, NTNU, Trondheim, Norway*

ARTICLE INFO

Article History:

Keywords:
Penetration
Structural steel
Node splitting
Laminated plates
Small-arms bullets

ABSTRACT

We investigated the ballistic resistance of hot-rolled structural steel plates with a nominal yield stress of 355 MPa in this study. Ballistic tests were conducted with 7.62 mm armor piercing bullets on monolithic and multi-layered configurations both in the as-received (AR) state and in a case-hardened (CH) state. In the CH state we made the surface stronger while preserving a relatively ductile core. This was done to improve the ballistic properties of the plates. Quasi-static uniaxial tension tests and Vickers hardness tests were conducted to calibrate constitutive models for numerical simulations. The ballistic tests revealed that the capacity was highest for a monolithic CH plate, and that case hardening increased the perforation resistance by more than 20%. Plate layering decreased the capacity of the CH plates, while the capacity of the AR plates did not decrease consistently by increasing the number of layers. Finally, we used the hardness measurements to distribute material properties across the thickness of the CH plates. These distributed material properties were used in numerical models. Finite element simulations gave predominantly conservative results within 11% of the experimental values.

1. Introduction

The perforation resistance of multi-layered plates compared to that of monolithic plates has been a subject of research, and of controversy, for a long time [1,2]. Numerous parameters affect the ballistic capacity of layered plates, e.g., impact velocity, material strength and ductility, target-plate span, spacing and thickness, and also the order of the plates if they are made of dissimilar materials or have different thicknesses. The existing literature contains studies of multi-layered plates with various combinations of the parameters mentioned above. Since lamination might simplify manufacturing, transportation and assembly of protective solutions, the main objectives of these studies were to either improve the design of protective structures, or to determine the gain or loss in capacity by using multi-layered configurations.

More specifically, Marom and Bodner [3] found that layering might be beneficial to resist perforation by round, relatively soft, lead bullets. Corran et al. [4] later saw that multi-layered targets performed better than monolithic targets when the target plates were above 4–6 mm thick. Further, they highlighted that the effect of layering is extremely dependent upon the projectile-nose shape and hardness as well as the impact velocity. The effect of nose shape was exemplified by investigations of sub-ordnance velocity impacts by Dey et al. [5]. Double-layered (2 × 6 mm) steel target plates performed much better than one 12 mm thick plate against a blunt-nosed projectile, whereas the monolithic configuration had a higher capacity against perforation by ogival-nosed projectiles of the same weight (see also Teng et al. [1,6]). In contrast, when thin plates were subjected to impacts at low velocities the ballistic capacity was reduced with layering for both nose shapes [7], but more for ogival than for blunt-nosed impactors. Little, or negative, effect of layering was found by Gupta and Madhu [8], Gupta et al. [9], Iqbal et al. [10], and Iqbal and Gupta [11]. Other studies also highlight the complexity of the problem, see e.g., Refs. [12–15]. Recently, Ben-Dor et al. [2] presented a state-of-the-art review of optimization of multi-layered configurations and concluded that perforation mechanism and velocity regime strongly affect the ballistic capacity.

Børvik et al. [16] and Holmen et al. [17] reported that material strength is the most important parameter for perforation resistance, but if the local ductility is not sufficient to prevent fragmentation, the ballistic limit velocity can actually decrease with increasing strength [18]. Surface strengthening of relatively weak and ductile steel plates can in theory increase the material strength while preserving the ductility. Lou et al. [19] conducted an experimental study on ballistic perforation of surface strengthened steel plates and found that the ballistic limit velocity increased significantly after the surface-strengthening procedure. The main focus of that study was not, however, the ballistic perforation, but the metallurgical aspects of the procedure also known as case hardening.

---

[*] Corresponding author at: Structural Impact Laboratory (SIMLab), Department of Structural Engineering, NTNU, Norwegian University of Science and Technology, Trondheim, Norway.
E-mail address: jens.k.holmen@ntnu.no (J.K. Holmen).

http://dx.doi.org/10.1016/j.ijimpeng.2017.02.001
0734-743X/© 2017 Elsevier Ltd. All rights reserved.

Please cite this article as: J.K. Holmen et al., Ballistic impact of layered and case-hardened steel plates, International Journal of Impact Engineering (2017), http://dx.doi.org/10.1016/j.ijimpeng.2017.02.001

Case hardening is a manufacturing process commonly used to obtain a hard and durable outer surface and a ductile inner core of for instance screws, bolts, nuts, gears, lock shackles, and agricultural equipment. Steels with 0.13–0.20% carbon and a ferrite/pearlite structure can be carburized by placing the specimen in a carbon-rich environment at a temperature between 850 °C and 950 °C. At this elevated temperature, the steel transforms into an austenite structure that can contain more carbon than the initial structure leading to diffusion of carbon atoms into the surface of the specimen. After cooling, we get a coarse martensitic structure that can be refined by subsequent heat treatment. Tempering usually takes place at the end of the process to alleviate the internal stresses. Depending on the details of the heat treatment a martensitic surface with a ferritic or a martensitic core is obtained [20,21].

The experimental objectives of this study are to investigate how the capacity of multi-layered target plates compare to monolithic targets of the same total thickness, and to compare the performance of case-hardened plates to plates in the as-received state. We present ballistic limit velocities resulting from numerous impacts by 7.62 mm armor piercing bullets together with uniaxial tension and Vickers hardness tests. Constitutive and failure models were calibrated from these material tests. In the numerical part of the paper, the predictive capability of finite element simulations employing node splitting was evaluated against the experimental results.

The variation of material properties across the thickness of the plates resulting from the case-hardening procedure was included in the finite element models. We present, in the paper, a method that scales the initial yield stress in the constitutive model as a function of Vickers hardness, effectively taking into account this variation. The method assumes proportionality between the Vickers hardness and the ultimate engineering tensile stress (UTS).

Since case hardening makes the surface of the steel plates less ductile than the core, we used node splitting in an attempt to simulate the resulting quasi-ductile perforation mechanisms seen in the impact tests. Node splitting is an alternative to element erosion for introducing fracture into a finite element model. It has received some attention in the past, specifically for two-dimensional problems [22–24]. In this study we used a general three-dimensional formulation that is available in the IMPETUS Afea Solver [25] which has formerly been applied by for instance Holmen et al. [18], Ruggiero et al. [26] and Olovsson et al. [27]. Advantages of node splitting are that failure does not imply removal of an element meaning that mass and energy loss can be reduced compared to element erosion, and that fragmentation can be captured due to the explicit modeling of crack growth. However, studies employing node splitting are still rare and further assessment of the method applied in structural impact analysis is definitely needed.

2. Materials

2.1. NVE 36 steel plates

NVE 36 is a structural steel with a carbon content of 0.15 wt.-% and nominal yield stress of 355 MPa (designated S355J according to the European standard (EN)). Its intended applications are in maritime structural components. This study considers hot-rolled plates with in-plane dimensions 300 mm × 300 mm and three different thicknesses: 12 mm, 6 mm, and 4 mm in either a monolithic configuration (1 × 12 mm) or laminated configurations (2 × 6 mm and 3 × 4 mm). Table 1 shows the complete chemical composition of the steel. Some plates were tested in the as-received (AR) condition and some plates were case hardened (CH) before testing, meaning that they were kept in a carbon-rich environment at elevated temperatures to increase the surface strength while keeping the core relatively unchanged.

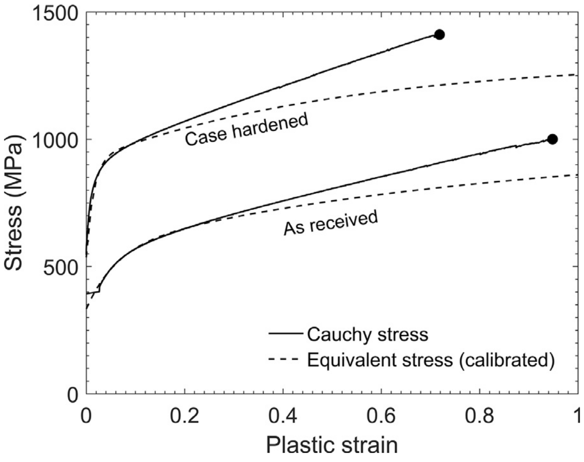

Fig. 1. Cauchy (true) stress plotted against the plastic strain to failure in the tension tests, and the equivalent stress plotted against the equivalent plastic strain from the calibrated Voce hardening rule with values from Table 3.

The case-hardening procedure was based on a series of previously conducted experimental studies (e.g., Ref. [28]). It started by subjecting the plates to carburization in a pit furnace at 920 °C for 4 h for the 4 mm thick plates, and 6 h for the 6 mm and 12 mm plates before air cooling back to room temperature. They were then reheated to 920 °C for a shorter time-period, where precautions were taken to ensure that the plates were hot through the entire thickness for at least 10 min before they were quenched in a 10% NaOH solution. Lastly, all the plates were tempered at 245 °C for 2 h.

2.2. Material testing

We conducted two types of material tests: quasi-static uniaxial tension tests and Vickers hardness tests. Tension testing was done on specimens extracted from the core of the 12 mm AR and CH plates while every plate in both conditions were subjected to Vickers hardness testing.

Cylindrical specimens were machined in the rolling direction of the plate and used in the tension testing (see e.g., Ref. [17] for the geometry). The nominal diameter of the 40 mm gauge section was 6 mm and the cross-bar velocity during testing was 1.2 mm/min, giving an initial strain rate of 5.0×10^{-4} s^{-1}. A calibrated load cell recorded the force F, while a laser-scan micrometer placed on a moving frame continuously measured the minimum diameter in two perpendicular directions all the way to fracture. Fig. 1 presents the average true stress σ_t as a function of the plastic strain ε^p from representative tests. These quantities were calculated as

$$A = \frac{\pi}{4} D_z D_\perp, \qquad \sigma_t = \frac{F}{A}, \qquad \varepsilon^p = \varepsilon - \varepsilon^e = \ln\left(\frac{A_0}{A}\right) - \frac{\sigma_t}{E} \tag{1}$$

Table 1
Chemical composition of the as-received NVE 36 steel plates based on the material certificates.

	C	Si	Mn	S	P	Al	Nb	Cr	Ni	Cu	Mo	V	Ti
12 mm	0.15	0.35	1.50	0.010	0.007	0.044	0.037	0.019	0.019	0.044	0.001	0.002	0.002
6 mm	0.15	0.26	1.48	0.006	0.018	0.036	0.023	0.03	0.01	0.04	0.004	0.003	0.015
4 mm	0.15	0.26	1.48	0.006	0.018	0.036	0.023	0.03	0.01	0.04	0.004	0.003	0.015

Please cite this article as: J.K. Holmen et al., Ballistic impact of layered and case-hardened steel plates, International Journal of Impact Engineering (2017), http://dx.doi.org/10.1016/j.ijimpeng.2017.02.001