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A new analytical model for the low-velocity perforation of thin steel plates by hemispherical-nosed projectiles

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ABSTRACT

Ballistic experiments were conducted on thin steel plates that are normally impacted by hemispherical-nosed projectiles at velocities higher than their ballistic limits. The deformation and failure modes of the thin steel plates were analyzed. A new method was proposed according to the experimental results and the perforation phenomenon of the thin steel plates to determine the radius of the bulging region. In establishing this new method, a dynamic method combined with the plastic wave propagation concept based on the rigid plastic assumption was adopted. The whole perforation process was divided into four consecutive stages, namely, bulging deformation, dishing deformation, ductile hole enlargement, and projectile exit. On the basis of the energy conservation principle, a new model was developed to predict the residual velocities of hemispherical-nosed projectiles that perforate thin steel plates at low velocities. The results obtained from the theoretical calculations by the present model were compared with the experimental results. Theoretical predictions were in good agreement with the experimental results in terms of both the radius of the bulging region and the residual velocity of the projectile when the strain rate effects of the target material during each stage were considered.

1. Introduction

The penetration and perforation of thin metallic plates by projectiles have long been an interesting research topic and have been the subject of numerous studies over the past several decades. Comprehensive reviews on this subject are available in many published works [1–4]. This problem is complex for it involves many factors, such as the impact velocities and nose shapes of projectiles, non-linearities of target materials and geometries, and strain rate sensitivity during the impact process. Therefore, earlier studies mostly focus on plates that are within a particular range of thickness and are impacted by projectiles with a special nose shape in a certain velocity range. However, extensive research indicates that the deformation and failure modes of metallic plates vary with the impact velocity and nose shape of projectiles, as well as the ratio of projectile diameter to plate thickness. In the case of the perforation of thin metallic plates in a sub-ordnance range, blunt-nosed projectiles tend to cause failure by plugging [3,5], whereas conical projectiles are likely to cause failure through the petalling of the target material [3,6].

Given the complexity of the perforation of thin plates, previous analytical models of the deformation and perforation of plates usually consider only one type of perforation mechanism, and some of these models neglect the local plate deformation in the contact area. In Refs. [7–9], all models were produced with a bending-only method, whereas in Refs. [10,11,13], the interaction of the projectile and the plate following a membrane-only assumption was considered. In the theoretical analyses conducted in Refs. [14–16], both bending and membrane stretching, as well as the local deformation of the target plate, were considered [14]. Accordingly, a good agreement was obtained between the theoretical predictions and experimental results. Another aspect of the complexity of the perforation problem mainly involves the influence of the structural response of the surrounding plate on the deformation and failure modes of the plate. Thus, in numerous actual impact situations, the deformation and failure modes of plates mostly involve various types and combinations of perforation mechanisms [17,18]. As plate thickness and impact velocity of a projectile increase, a change in the failure modes from tensile failure to shear

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failure occurs in thin plates [11,12] and intermediate plates [20] impacted by blunt-nosed projectiles. Thus, the selection of failure criteria in analytical models exerts a significant influence on the applicability of models and the accuracy of predictions. A criterion of tensile failure was proposed in Refs. [11,13] for membrane or thin plate perforation, whereas a shear failure criterion was employed in Refs. [21,22]. Thus, the applications of these analytical models were all restricted to particular ranges of plate thickness. In the analytical models presented in Refs. [15,16], an equivalent strain failure criterion was used. This criterion incorporated both the effect of membrane forces and the local shear effect. Although extensive studies have been conducted, they mostly focus on the problem of penetration or perforation of thin plates by blunt-nosed [8,13,16,21,22] or pointed-nosed [7,10,14,17–19] projectiles, and studies on the penetration or perforation of thin plates by hemispherical-nosed projectiles remain relatively scanty. Levy and Goldsmith [23,24] analytically and experimentally investigated the normal impact and perforation of thin metallic plates by hemispherical-nosed projectiles. On the basis of a lumped parameter system, an expression was derived for the force–time history involved in thin plates that are normally impacted by hemispherical-nosed projectiles; this expression is totally predictive below the ballistic limit. However, slightly large deviations above the ballistic limit were obtained for mild steel plates. Moreover, the strain rate effects and the influence of various failure mechanisms were neglected in their analytical model. In recent years, a large number of experimental [25–27] and numerical [26–29] studies have been conducted on the perforation of thin plates by hemispherical-nosed projectiles, whereas theoretical analyses of this subject are rare. In Ref. [30], the dynamic plastic response of thin steel plates impacted by hemispherical-nosed projectiles at low velocities was theoretically analyzed, and the effects of shear, bending, and membrane stretching were considered. The perforation process was divided into three stages, namely, bulging deformation, dishing deformation, and perforation.

Investigating the ballistic penetration and perforation of thin steel plates by low-velocity hemispherical-nosed projectiles is interesting and remains relevant. Many theoretical studies on this subject are available, as reviewed above. However, the experimental results in Refs. [26,27] and those in the present study indicate that early analytical models are incomplete and perhaps oversimplified in terms of the following important points:

(1) First, no analytical attention is given to the fact that the radius of the bulging region changes along with the impact velocity of the projectile. In early models, the change relation between the radius of the bulging region and the impact velocity of the projectile is obtained experimentally or empirically.
(2) Most early models neglect the strain rate effects and energy dissipation during the impact process resulting from the further deformation of the dishing region after plate dishing.
(3) In most early models, the plastic deformation energy of the dishing region and the energy dissipated by a thin plate during ductile hole enlargement, including the energy required for the propagation of radial cracks, are incomprehensively or unreasonably considered.

To overcome the limitations of early models, the present study conducts ballistic impact tests on mild steel plates measuring 1.36, 1.90, and 2.86 mm thick and impacted normally by hemispherical-nosed projectiles at velocities ranging from 200 m/s to 400 m/s. The deformation and failure modes of thin steel plates are analyzed. On the basis of the experimental results, a new method is presented to calculate the radius of the bulging region of thin steel plates that are normally impacted by hemispherical-nosed projectiles. In establishing this new method, a dynamic method and plastic wave propagation concept based on rigid plastic assumption are adopted. According to the experimental results and the analysis of the perforation process, a new model is developed to predict the residual velocities of thin steel plates that are normally perforated by hemispherical-nosed projectiles on the basis of the energy conservation principle. Theoretical predictions are compared with experimental results in terms of both the radius of the bulging region and the residual velocity of the projectile. Finally, the range of the applicability of the present model is discussed.

2. Experimental procedure

A smoothbore 15 mm caliber powder gun of a fixed barrel was fired at the projectiles at velocities ranging from 200 m/s to 400 m/s, which is a range that generally exceeds the ballistic limit of the target. The initial and residual velocities of the projectiles were measured through the oscilloscopically recorded (Hitachi VC7104 with the highest frequency of 100 MHz) voltage changes produced in two sets of 6 μm-thick aluminum foil screens only before and behind the target plate. The schematic of the experimental setup is shown in Fig. 1.

The projectiles used in the present tests showed a hemispherical nose, a diameter of 14.9 mm, and a length of 21.4 mm. The nominal mass of the projectiles was 25.8 g. The schematic and photograph of the projectile are presented in Fig. 2. The material of the projectiles consisted of quenched 45 steel, which is a type of hardened tool steel with a yield strength of 355 MPa and ultimate tensile strength ranging from 450 MPa to 685 MPa; it was used in as-received condition.

The target plates were fully clamped by steel strips along their four edges, and all of these plates had square dimensions of 350 mm × 350 mm. The plates employed were cut out of commercial Q235 mild steel sheets with thicknesses of 1.36, 1.90, and 2.86 mm. The square targets were made from these plates and were used in as-received condition. The strength and other mechanical parameters of the target materials obtained from the quasi-static uniaxial tests are listed in Table 1.

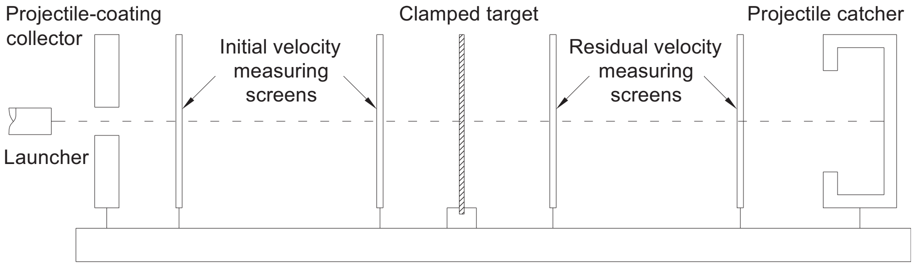

Fig. 1. Schematic of the experimental arrangement.