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Development of an experimental set-up for dynamic force measurements during impact and perforation, coupling to numerical simulations

W.Z. Zhong [a], I.A. Mbarek [b], A. Rusinek [b,*], R. Bernier [b], T. Jankowiak [c], G. Sutter [d]

[a] Institute of Systems Engineering, China Academy of Engineering Physics, 621999 Mianyang, China
[b] Laboratory of Mechanics, Biomechanics, Polymers and Structures, Lorraine University, National Engineering School of Metz (ENIM), 1 Route d'Ars Laquenexy, 57078 Metz, France
[c] Institute of Structural Engineering, Poznan University of Technology, Piotrowo 5, 60-965 Poznań, Poland
[d] LEM3, UMR 7239, Lorraine University, Ile du Saulcy, 57045 Metz Cedex 1, France

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ABSTRACT

Quasi-static tension and dynamic compression experiments on S235JR mild steel were performed using a screw-driven machine and a split Hopkinson pressure bar (SHPB) device. A wide range of strain rates from 10^{-4} to 2500 s^{-1} has been covered during experiments. The Johnson–Cook constitutive relation was adopted to describe the material visco-plastic behaviour. Ballistic impact experiments on S235JR plates with conical-nose shaped projectile were carried out using pneumatic gas gun having different impact velocities varying from 49 to 181 m/s. A new experimental set-up allowing resistance force measurement during impact and perforation was developed. Different impact velocities and thicknesses were evaluated during ballistic experiments. All the projectiles are 12.8 mm in diameter and 28g in weight. The ballistic impact device is equipped with laser sensors for velocities measurements and piezoelectric sensors for dynamic force measurement. Based on numerical and experimental investigations, the ballistic properties and failure modes of the material have been studied. The finite element code ABAQUS/Explicit was used to simulate the perforation process but also to have a better understanding of the measurement. A good agreement between experiments and numerical results has been observed in terms of ballistic curves, failure patterns, resistance force as well as the energy balance.

1. Introduction

Ballistic behaviour of thin metal plates is paid close attention in military and civil protection fields recently [1–3]. The ballistic impact problems were mainly focused on military interest. The perforation and penetration of thin plate structures have become more interesting in transport and aerospace fields. For instance, the automobile manufacturing industry, the ship hull manufacturing, aviation and spacecraft designing [4–6]. The ballistic properties are strongly related to the material behaviour under dynamic loading and to the interaction between the projectile and the thin steel target during perforation process. Thus, in order to improve ballistic curves prediction, many dynamic constitutive relations have been improved and modified by several researchers [7–13]. For instance, Johnson and Cook [7] proposed a dynamic constitutive relation based on a phenomenological approach. The model has been frequently used in impact and perforation problems analysis, thanks to its simplicity, namely its five parameters to describe the thermo-viscoplastic behaviour of the material. Verleysen et al. [8] investigated the effect of strain rate on the forming behaviour of sheet metals and described the materials' stress–strain curves using Johnson–Cook model. Erice et al. [9] presented a coupled elastoplastic-damage constitutive model to simulate failure behaviour of Inconel plates. Rusinek and Rodríguez-Martínez [10] provided two extensions of the Rusinek–Klepaczko constitutive relation in order to define the behaviour of aluminium alloys at wide ranges of strain rate and temperature. Dey et al. [11] and Børvik et al. [12] studied the influence of a modified Johnson–Cook constitutive relation using numerical simulations of the perforation of steel plates. The thermoelastic–thermoviscoplastic constitutive models used in the simulation of the penetration and perforation process are discussed by Kane et al. [13] and Voyiadjis [14].

In ballistic impact experiments, the projectile nose shape and its diameter, the impact conditions, the projectile velocity, the thickness of the target and the boundary conditions are very important

* Corresponding author. Laboratory of Mechanics, Biomechanics, Polymers and Structures, Lorraine University, National Engineering School of Metz (ENIM), 1 Route d'Ars Laquenexy, 57078 Metz, France. Tel.: +33 387346930; Fax: +33 3 87 34 69 35.
E-mail address: alexis.rusinek@univ-lorraine.fr (A. Rusinek).

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parameters that are mainly taken into account to analyse the resistance of the target against impact and perforation as well as the fracture behaviour [15–17]. Chen et al. [18] studied the oblique perforation of thick metallic plates with rigid projectiles having different nose shapes. Kpenyigba et al. [19] and Rusinek et al. [20] studied the influence of the projectile nose shape (conical, blunt and hemispherical nose-shaped projectiles) and its diameter on the ballistic properties and the failure modes of thin steel targets. Many advanced optical measuring facilities and precise instruments are usually used to measure the initial and residual velocities of the projectile and to better analyse the target failure mechanisms [21–23]. Grytten and Fagerholt [21] developed a new optical system using structured light for full-field continuous measurements of the out-of-plane deformation during perforation experiments. To analyse the mechanical behaviour of tempered bainitic steel, microstructural and fractographical examinations were carried out on small samples taken from the perforated region by Atapek and Karagoz [22]. Some multi-layered plates were also considered to investigate about the resistance of the targets against perforation as well as the energy absorbed by the target during the perforation process. Dey et al. [24] studied the resistance against ballistic perforation of double-layered steel plates impacted by blunt and ogival nose-shaped projectiles. Flores-Johnson et al. [25] investigated about the ballistic performance of monolithic, double- and triple-layered metallic plates. It was found that monolithic plates have a better ballistic performance than that of multi-layered plates.

The finite element method with explicit time integration procedure is an effective technique to predict the ballistic response of a target impacted by a projectile [26,27]. It is an economic and convenient approach which is commonly used to analyse well the impact process and to improve the researches about perforation issues. Numerical simulations are also an effective supplement for theoretical and experimental investigations which were carried out to analyse the dynamic behaviour of impacted structures [28–31]. Recently, finite element analysis has been used by many researchers to simulate perforation problems. Rodríguez-Martínez et al. [32,33] carried out a numerical study on the perforation of thin steel plates impacted by projectiles having different nose shapes. The predicted ballistic limit and the failure time were in agreement with experimental results. Swaddiwudhipong et al. [34] adopted coupled SPH-FEM to simulate the high velocity perforation of steel and aluminium plates. Rosenberg and Dekel [35] simulated numerically the perforation of ductile plates by sharp-nosed rigid projectiles, and distinguished between dishing and hole enlargement processes which are the main perforation mechanisms for thin and thick plates, respectively. Deb et al. [36] described the impact behaviour of jacketed projectiles on steel armour plates and pointed that the proper choice of the contact algorithm, the element size as well as the strain rate-dependent material properties are very important to predict precisely the residual velocity of the projectile.

Although more and more researches are focused on the ballistic impact field, several publications are discussing the high strength material penetration problems at high impact velocities. Less attention is paid to the measurement of the global force induced by the projectile on the target during impact and perforation. Several relatively low strength materials, such as low carbon steel and aluminium alloys, etc, are widely applied in automobile manufacturing industry and in aeronautic industry. For instance, non-alloyed structural steel S235JR has a low strength but a good ductility, thanks to which, the S235JR is widely applied in engineering structures nowadays.

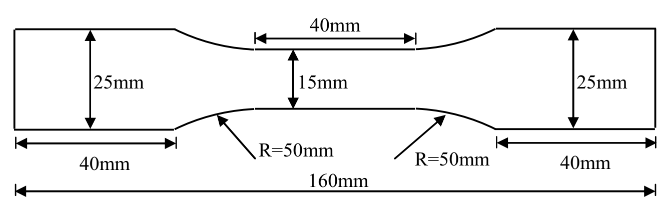
This paper presents quasi-static and dynamic experimental analysis of the mechanical properties of the S235JR mild steel. The mechanical behaviour of the target is described by the Johnson–Cook constitutive model. Ballistic impact experiments on S235JR plates subjected to perforation with a conical nose-shaped projectile are carried out using a pneumatic gas gun. The target thicknesses are 1.5 and 2.0 mm and the impact velocities are varying from 49 m/s to 181 m/s. The experimental protocol allows us to measure the initial and residual velocities as well as the resistance forces of the target. The energy absorbed by the S235JR plates at a wide range of impact velocities is discussed. Moreover, a model of a S235JR target with a conical nose-shaped projectile is established using the finite element code ABAQUS/Explicit and allowed to simulate the perforation process. The predicted values in terms of residual velocities and resistance forces are compared to experimental results and a good agreement is found between the numerical and the experimental investigations.

2. S235JR steel mechanical properties

2.1. Quasi-static tension experiment

Quasi-static uniaxial tension tests of S235JR steel were performed using a conventional screw-driven machine. The dimensions of the flat dumbbell-shaped specimen are shown in Fig. 1a. The thickness is 1.5 mm with an active length of 40 mm. All tests were conducted at room temperature, 293 K, for a constant loading velocity.

During the tests, an inclined fracture plane occurs along the thickness of the specimens and a necking zone is found along the oblique direction as Fig. 1b. It shows that shear fracture and necking are the main failure modes for S235JR steel subjected to quasi-static tension. The load and deformation displacement are recorded during the tests for an imposed velocity. All true stress–strain curves are well consistent and the mean tension strain–stress curve, for 10^{-4} s^{-1} strain rate, is presented in Fig. 2. It shows that the average yield strength of the S235JR steel is close to 252 MPa.



(a) Dimensions of S235JR sheet specimen

(b) Tension fracture of the specimens

Fig. 1. Tension specimen dimensions and fracture mode.
(a) Dimensions of S235JR sheet specimen. (b) Tension fracture of the specimens.