Materials and Design 58 (2014) 252–264

Contents lists available at ScienceDirect

Materials and Design

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

Multi-hit ballistic damage characterisation of 304 stainless steel plates with finite elements

B.P. Russell *

Engineering Department, University of Cambridge, Trumpington Street, Cambridge CB1 1PZ, UK

ARTICLE INFO

Article history:
Received 26 November 2013
Accepted 30 January 2014
Available online 7 February 2014

Keywords:
Multi-impact
Ballistic loading
Damage
Finite elements
Stainless steel

ABSTRACT

Multi-impact of projectiles on thin 304 stainless steel plates is investigated to assess the degradation of ballistic performance, and to characterise the inherent mechanisms. Assessment of ballistic degradation is by means of a double-impact of rigid spheres at the same site on a circular clamped plate. The limiting velocity of the second impact, will be altered by the velocity of the antecedent impact. Finite element analyses were used to elucidate experimental results and understand the underlying mechanisms that give rise to the performance degradation. The effect of strength and ductility on the single and multi-impact performance was also considered. The model captured the experimental results with excellent agreement. Moreover, the material parameters used within the model were exclusively obtained from published works with no fitting or calibration required. An attempt is made to quantify the elevation of the ballistic limit of thin plates by the dynamic mechanism of travelling hinges. Key conclusions: The multi-hit performance scales linearly with the single-hit performance; and strength is a significantly greater effector of increased ballistic limit than ductility, even at the expense of toughness.

1. Introduction

Multi-hit performance of structures by fragments is of broad interest to both the transportation industry and the military. Rarely is it adequate to design components to mitigate the effects of a single impact event. An understanding is required of how damage, resultant from an initial impact, might cause reduction to the protective capacity of an armour system subject to further impact. Karthikeyan et al. [1] propose a method by which an armour system might be characterised for multi-hit performance, and the present study aims to recapture this using a numerical approach.

A wealth of literature exists on the characterisation of impact of metal plates. The focus is primarily on penetration and its mechanisms (for example, the reviews of [2–4]), although some consider the non-penetrating mechanisms that give rise to dishing (Liu and Jones [5] report and comment on a number of other works). However, little is reported on the direct measurement and analysis of multi-hit loading scenarios, although several authors allude to its importance [6–10].

Karthikeyan et al. [1] introduce the idea that the interaction of two sequential impacts (denoted V_I and V_{II}) can be mapped out in V_I—V_{II} space, Fig. 1a. The initial impact V_I modifies the plate and the resultant degradation is interrogated by the second impact V_{II}. A combination of V_I and V_{II} will result in either the survival or failure of a plate. Thus regions pertaining to survival and failure are mapped out in V_I—V_{II} space by testing combinations of V_I and V_{II}. The shape of the boundary between these regions, is shown to be a function of the material properties. Boundaries were obtained for monolithic carbon fibre composite and 304 stainless steel plates (Fig. 2) as well as hybridised composite/304 stainless plates. What is striking are the distinct boundaries that the material properties give rise to: the composite shows little interaction at low velocity impacts resulting in a square-looking boundary, whereas the steel shows degradation in its ballistic resistance even at low velocities.

The present study seeks to recapture this boundary in V_I—V_{II} space for the 304 stainless steel by simulating the experiments through finite element modelling. Such a model exhibiting high fidelity, will facilitate understanding of the mechanisms that give rise to the boundary shape. A second objective is to determine the effects of manipulating the material properties. In traditional engineering materials, there is often a trade-off between strength and ductility. One advantage of recreating the experiments of Karthikeyan et al. [1] *in silico* is that we can now explore how this trade-off may best be made, particulary with regard to optimising for multi-hit capability.

---

* Tel.: +44 (0)1223 748541.
E-mail address: bpr23@eng.cam.ac.uk

http://dx.doi.org/10.1016/j.matdes.2014.01.074

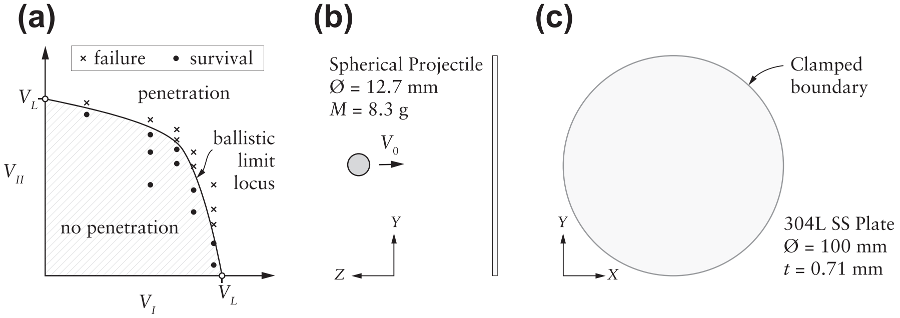

Fig. 1. (a) Illustration of the construction of the ballistic limit boundary in V_I–V_{II} space. The (b) side and (c) muzzle views of the experimental set-up as used by Karthikeyan et al. [1].

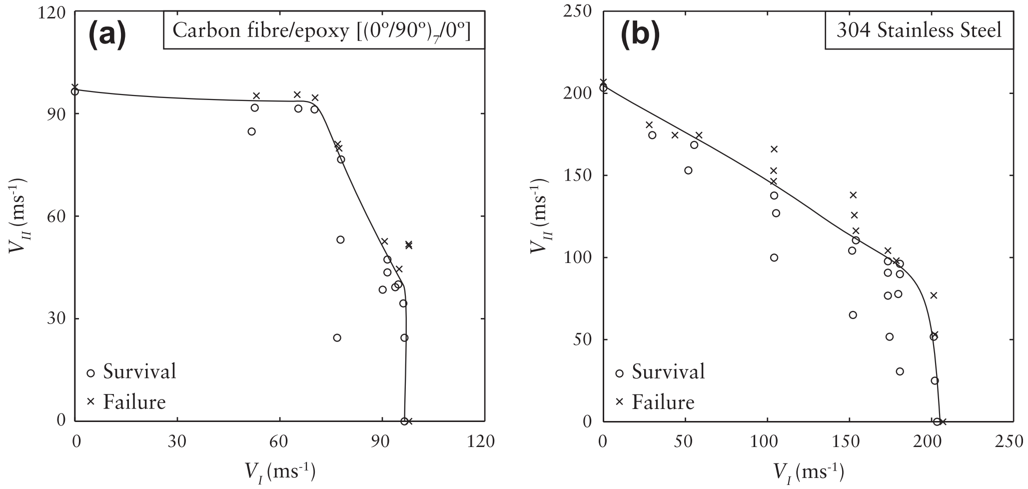

Fig. 2. The measured ballistic limit surfaces in V_I–V_{II} space for monolithic (a) carbon fibre/epoxy laminate, (b) 304 stainless steel; reproduced from Karthikeyan et al. [1].

2. Materials and methods

2.1. Methodology

The test procedure follows that of the experiments conducted by Karthikeyan et al. [1]. A spherical hardened-steel[1] projectile impacts a circularly clamped plate normally and concentrically at a velocity, V_I, Fig. 1b and c. The second impactor is identical to the first, and follows the same trajectory, the only difference being its impact velocity, V_{II}. The two velocities V_I and V_{II} together make a co-ordinate, defining a point of survival or failure in V_I–V_{II} space, Fig. 1a. Successive tests refine the region of uncertainty between survival and failure until sufficient accuracy is acquired, and such point is then considered a ballistic limit point. At this point it is worth highlighting the distinction between a second hit of arbitrary velocity denoted V_{II}, and that of a second hit located at the limit boundary and notated V_{II}^*. For each value of V_I a unique V_{II}^* exists. Interpolation between these co-ordinates (V_I, V_{II}^*) provides the ballistic limit locus (boundary).

2.2. Notation

The *ballistic limit velocity* of an undamaged plate is notated V_L. Karthikeyan et al. [1] also introduce a second parameter, the so-called *equivelocity ballistic limit* for a double-impact and denoted V_{2L}. This simply corresponds to a point on the limit boundary where both velocities are equal (i.e. $V_I = V_{II}^*$), and is a convenient proxy as a measure of the multi-hit capability.

In the experiments of Karthikeyan et al. [1], survival or failure of the plate was ascertained by a witness plate, placed behind the target, by which the occurrence of a penetration event could be clearly established. In the numerical study, penetration is defined by the residual velocity of the sphere.

Throughout the text, a number of velocity parameters are more conveniently expressed non-dimensionally. Here:

$$\overline{V}_i = \frac{V_i}{V_L} \tag{1}$$

where V_i represents parameters such as V_I, V_{II}, V_{II}^* and V_{2L}.

2.3. Finite element model

Numerical simulations were performed using the finite element package ABAQUS explicit, version 6.11. Fig. 3 shows the meshed geometry of the double-impact simulation. In the regime of interest where (i) the plate is thin, (ii) the impact velocities are relatively low, and (iii) the projectile geometry is rounded (i.e. no sharp edges), the problem can be appropriately modelled with shell elements. Under these conditions failure of the plate is governed by tensile failure. Thickening the plate, increasing the impact velocity or using a projectile with sharp edges, may result in localised shearing [11]. The experiments of Karthikeyan et al. [1] indicate failure is by tension. In order to verify that the geometry of the set-up was in the tension failure regime, preliminary 2D axisymmetric simulations were conducted to investigate the local

---

[1] Chrome steel, AISI 52100. Obtained from Atlas Ball and Bearing Company Ltd., Leamore Lane, Walsall, England, WS2 7DE, UK.