International Journal of Impact Engineering 85 (2015) 67–82

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

An analytical model of the dynamic response of circular composite plates to high-velocity impact

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ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form
10 May 2015
Accepted 14 June 2015
Available online 22 June 2015

Keywords:
Ballistic limit
Finite element
Wave propagation
Plate theory
Impact damage

ABSTRACT

Analytical models are developed to predict the transient elastic response of fully clamped circular composite plates subject to high-velocity impact by a rigid spherical projectile. The models are based on first-order shear deformation plate theory and account for the effects of large deformations as well as propagation and reflection of flexural waves. Analytical predictions of plate deflection history and peak strain in the plates are found in good agreement with those obtained from detailed explicit FE simulations. The dynamic response is found to be governed by four non-dimensional parameters and two characteristic regimes of behaviour are identified. The models are used to construct maps to design impact-resistant composite plates.

1. Introduction

Fibre-reinforced composite materials are progressively employed as structural materials in light-weight ships, road vehicles, aircraft components and armour systems, due to their low weight, high stiffness and excellent corrosion resistance. The resistance of composite plates to high-velocity impact is a concern in many industrial applications. In the last decades, significant effort has been devoted to foster understanding of the dynamic response of composite laminates consequent to localised impact loading. In composite materials, energy absorption due to plastic deformation is very limited and their response to localised transverse impact leads to deformation modes dictated by propagation of longitudinal, shear and flexural waves travelling in the material at different velocities [1].

The damage and failure modes of composites upon impact depend on the plate geometry, impact velocity as well as on the shape and mass of the projectile. The impact resistance of a structure is often quantified by the limit velocity (or ballistic limit), defined as the velocity required for a projectile to penetrate a given material at least 50% of the time. When laminates are impacted at velocities below the ballistic limit, matrix cracking and delamination have been recognised to be the main energy dissipation mechanisms. Takeda et al. [2] conducted impact tests on glass-fibre/epoxy laminates and used high-speed photography to observe the growth of delamination cracks propagating in the samples, concluding that delamination growth was associated with flexural wave propagation. Post-impact matrix cracks and delaminations were also observed by Heimbs et al. [3], who conducted an experimental and numerical study of the impact behaviour of CFRP composites subject to compressive and tensile preloads, concluding that tensile preloading leads to a reduction in delamination while compressive preloading facilitates delamination. At impact velocities near the ballistic limit, they also observed fibre failure in addition to delaminations and matrix cracks. Other authors [4,5] employed theoretical modelling approaches to study delamination of laminates subject to transverse impact. Some authors have investigated the mechanism of plate spalling induced by reflection of through-thickness stress waves, see e.g. Ref. [6].

Studies investigating the deformation and failure mechanisms of laminates impacted above the ballistic limit are extensively described in the literature and a comprehensive review of existing work on this subject can be found in Abrate [7]. For example, Cantwell and Morton [8] observed the mechanisms of perforation of thin CFRP beams and noted that plate failure involved a shear-off penetration in the upper half of the plate (impact side) and tensile

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http://dx.doi.org/10.1016/j.ijimpeng.2015.06.010
0734-743X/

breakage of plies in the bottom half. The effect of projectile geometry on the perforation resistance of fibre-reinforced composites was investigated by Wen [9], who derived a simple empirical relationship for the ballistic limit by assuming that the resistance provided by the laminate is composed of a static and a dynamic term, with the latter depending on the nose shape of the projectile. Mines et al. [10] conducted ballistic tests on woven, z-stitched and through-thickness reinforced glass/polyester laminates, varying laminate thickness as well as mass and geometry of the projectile. Their results showed only small differences in the impact behaviour of the different composite systems investigated.

While carbon-fibre (CFRP) and glass-fibre reinforced laminates (GFRP) are the most widely used material systems in engineering applications, the recent development of new fibres with extremely high stiffness to weight ratios has greatly improved the ballistic performance of fibre-composites. They include Nylon, aramids (e.g. Kevlar®), ultra-high molecular weight polyethylene (e.g. Spectra®, Dyneema®) and PBO (e.g. Zylon®). Zhu et al. [11] performed dynamic perforation tests on Kevlar/polyester laminates and found that they outperform aluminium plates of equal weight in terms of impact resistance. They also tested laminates with deliberately introduced delaminations and the results showed that the ballistic limit was not greatly affected by such defects.

In an attempt to relate the ballistic performance of a given laminate to the velocity and geometry of the projectile, Cunniff [12] proposed a set of non-dimensional parameters and argued that the ballistic limit of fibre composites scales with a characteristic velocity determined by the material properties of the fibres. However, for some types of laminate, the characteristic velocity introduced by Cunniff does not accurately capture the experimental data. For example, Karthikeyan et al. [13] recently measured the ballistic performance of Dyneema® plates (ultra-high molecular weight polyethylene fibre composite) and found that the characteristic velocity required to normalise the perforation data cannot be deduced from the fibre properties. Their observations showed that the propagation of flexural wave fronts followed an almost square-like pattern, due to the extremely low shear strength of this type of laminate, whereas those observed on CFRP plates were almost circular.

A considerable body of literature exists on numerical and theoretical predictions of the elastic response of composite plates subject to various dynamic loading conditions. A possible analytical treatment of impact on elastic plates follows that given in Zener [14] who expressed the transient response of thin simply-supported isotropic plates in terms of mode shapes and natural frequencies. A similar approach was used by Olsson [15] who extended the theory of Zener [14] to the case of orthotropic plates. Sun and Chattopadyay [16] employed a similar technique to investigate the central impact of a mass on a simply-supported laminated composite plate under initial stress by employing a plate theory that accounts for transverse shear deformations [17]. They also noted that rotary inertia has only a minor effect on the dynamic response. Dobyns [18] also used plate theory [17] to analyse the dynamic response of composite plates subject to loading by pressure pulses of various shapes, in order to mimic different types of blast loading. Finite strain solutions for the impact behaviour of elastic plates with fully-clamped boundaries are obtained in the published literature via approximate techniques, since closed-form solutions are not available in this case. For example, the Rayleigh-Ritz method was employed by Qian & Swanson [19] for the case of impacted rectangular carbon/epoxy plates. A reduced model for predicting the dynamic deformation modes is presented in Hoo Fatt and Palla [20] for the case of composite sandwich plates subject to loading by a prescribed pressure history. Phoenix and Porwal [21] derived a theoretical model for the 2D response of an initially unloaded elastic membrane impacted transversely by a cylindrical projectile, predicting that the structural response comprised propagation of tensile waves and 'cone waves' emanating from the impact point, with the cone wave travelling at lower speed. The theory was used to predict the ballistic resistance of composite systems and predictions were found in agreement with Cunniff's scaling theory [12].

In this study we derive an analytical model for the dynamic response of a fully-clamped, circular composite plate subject to high velocity impact by a rigid projectile. Effects of transverse shear deformations, large deflections and flexural wave propagation will be taken into account. In addition, the effect of higher order vibrational modes, activated upon reflection of flexural waves at the boundaries, will also be modelled. The model is based on a linear elastic material response but accounts for the geometric non-linearities in the problem and, to some extent, for material anisotropy.

It is clear that the prediction of the ballistic limit of arbitrary composite plates is beyond the scope of the present study, which does not attempt modelling the complex damage mechanisms activated in composite laminates upon impact. On the other hand the model presented here provides, for a certain class of composite plates and for an arbitrary projectile, the critical impact velocity at the onset of tensile ply failure; this information is readily used in the design of components exposed to a substantial threat of impact loading (e.g., impact of runway debris or similar on aircraft structures). The model allows identifying the four main governing non-dimensional groups of the impact problem and predicts two possible, distinctive regimes of behaviour.

The outline of this paper is as follows: in Sections 2 and 3 we derive the analytical models and describe the FE scheme employed; in Section 4 we validate the analytical models by comparing analytical and FE predictions; in Section 5 the validated analytical model is used to compare the damage resistance of glass-fibre and carbon-fibre reinforced composite plates, and non-dimensional design maps are constructed for both types of laminate.

2. Analytical modelling

The elastic response of composite plates to high-velocity impact by rigid projectiles is dictated by propagation of flexural waves, shear waves and extensional waves travelling in the material at different velocities. In fibre-reinforced composites, wave speeds are different when measured along different axes or directions due to the anisotropic behaviour of the material, see e.g. Sierakowski and Chaturvedi [22] for a comprehensive account of the dynamic behaviour of fibre-reinforced composites. Due to the complexity of the problem, exact solutions are restricted to the use of numerical methods which require high computational effort, especially when parametric studies are being conducted.

The objective of this study is to develop an approximate analytical model able to provide, in a computationally efficient way, reliable predictions of plate deformation associated with the dynamic elastic response a circular composite laminate subject to high-velocity impact. In this section, we employ an approach similar to that of Schiffer and Tagarielli [23] to derive the equations of motion in form of non-dimensional ODEs, and to identify the governing non-dimensional parameters; various assumptions concerning plate deformation and material behaviour will be explained and discussed in detail. Finally, we define two characteristic deformation regimes and construct a regime map.

2.1. Governing equations

2.1.1. Material modelling

In this study we consider symmetric composite laminates comprised of a stack of transversely isotropic plies with equally