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Effects of curvature on high-velocity impact resistance of thin woven fabric composite targets

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ABSTRACT

As structural elements with shielding requirements often feature nontrivial curvatures, their effective use in many engineering applications must undergo a precise evaluation of the effects of curvature on their resistance to impacts. In this work, an analytic formulation aimed at estimating the effects of curvature on the ballistic limit of thin woven fabric composite targets given their mechanical and geometric properties, as well as the projectile shape and initial velocity, is proposed. The described approach consider two-dimensional woven fabric composites and is based on wave propagation theory. The energy transfer occurring from the projectile to the target encompasses various energy-absorbing mechanisms. The tensile deformation of the yarns beneath the impact area, the tension and bending-induced deformation of the yarns constituting the region surrounding the impacted zone, the delamination onset and propagation and matrix cracking are considered in the model. The conical deformation on the back face of the composite target as result of the impact and the shear-driven generation of a plug are also taken into account. Ballistic limit, damage size and impact duration are then obtained through enforcement of the energy balance, showing that a nontrivial correlation exists between the curvature and the impact resistance of the target.

1. Introduction

Ballistic impacts, generally defined as low-mass high-velocity impacts caused by a propelling source, draw the attention of researchers since decades [1]. While the early studies were concentrated on isotropic and homogeneous metallic materials, more recent efforts have been dedicated to the study of anisotropic and non-homogeneous materials [2–4]. Composite materials have steadily received more attention primarily due to their increased usage over the past twenty years in the aerospace field, mainly for structural and shielding applications. In particular, when survivability of personnel and equipments against penetration by external objects is required, 2D woven fabrics are known to represent the best option in terms of impact performance [5–7]. Due to the large computational costs of numerical simulations and the specific nature of experimental tests, in the last decades research has focused on finding an accurate analytical model to fully understand and predict the behavior for this type of fabric [8–11]. However, theoretical approaches to model the propagation of strain waves on a single fiber subject to transverse impact can be dated back to 1950s [12]. Based on the energy conservation law, many analytical models have been proposed to calculate the decrease of kinetic energy and residual velocity of a projectile penetrating targets manufactured with plain weave fabrics [15–18]. In such formulations, the representation of the impact event is rooted into the dynamic, mechanical and fracture properties of the textile composite, implying the knowledge of its geometrical and constitutive parameters, as well as of the projectile mass, velocity, shape and size to compute the energy absorbed during the impact under different physical mechanisms [13–15]. Layers reciprocal independent behavior and constant absorbed energy with varying impact velocity, when full target perforation occurs, have taken into account as basic assumptions in the modeling process [9,19]. Nonlinear formulations associated to iterative resolution methods aimed at predicting the target response when subject to ballistic impacts have also been proposed [11], with major issues regarding the impossibility of guaranteeing the solution uniqueness.

As shown above, the majority of research on ballistic impact has been conducted on plane targets. Over the past fifteen years, more research efforts have examined the effects of curvature on the impact response of materials, with the focus, however, being mainly kept on low-velocity impact tests. Early findings [20] on the low-velocity impact response of curved composite targets have

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shown (i) an elliptically-shaped area of contact approaching a circular shape with increasing radius of curvature of the cylindrical specimen; (ii) a decreasing value of the area of contact with decreasing cylinder radius; (iii) a decreasing maximum value of the contact force with decreasing cylinder radius; (iv) an increasing maximum surface pressure with decreasing cylinder radius; and (v) an increasing contact duration with decreasing cylinder radius. More recent works on the impact on curved composite targets have focused the attention on the effects of curvature on damage evolution [21–23] and on the dynamic response of the structure [24–26], showing that the main effect of curvature is to increase the damaged area. Comprehensive reviews describing the fundamental parameters which determine the low-velocity impact resistance of continuous fibre-reinforced composite materials can be found elsewhere [27–29].

A common theme in these works is the relatively low value of the impact velocity that has been investigated. While, in fact, a large body of literature has addressed the problem of low-velocity impact characterization for curved composite targets, a relatively small number of works is available when impact velocities capable of penetration are taken into account. Most of the studies in this field are associated with the design of lightweight helmets for military and civil use [30–34]. Such works indicated that reducing the radii of curvature of the target increases its ballistic impact resistance. However, a direct study comparing the ballistic impact resistance of a helmet changing with its radii of curvature has not yet been performed [30].

The objective of the present work is to present an analytic formulation to analyze the effects of curvature on high-velocity impact resistance of thin woven fabric composite targets, relying on the geometric and the elastodynamic characteristics of the target [35–37], with particular reference to the properties defining the damage mechanisms onset and propagation, extending the results of the study carried out in [15] for plane targets. The case of thin fiber reinforced composite targets possessing high specific stiffness is considered: despite their thin nature, in fact, for such specimens (which are representative of a large body of engineering applications, above all in the lightweight armor systems field [5,6]), the effects associated to impact-induced shear stresses are nontrivial, making the description of shear wave propagation in the target through-the-thickness direction a necessary step. Using the proposed formulation, the energy absorbed by different damage and energy absorbing mechanisms, the ballistic limit, the contact duration and the damage size are estimated. A parametric study of the target impact performance with varying values of the radius of curvature for cylindrical and spherical specimens is carried out. Numerical predictions are finally discussed and compared with numerical and experimental literature results.

2. Mathematical model

A ballistic impact is usually a low-mass, high-velocity impact of a projectile onto a target. Given the high velocities involved in the event, the effects on the target remain confined to the region of impact, with an energy transfer taking place from the projectile to the target. The physical principles together with the modeling assumptions considered in the analytical description of high-velocity impacts on composite curved targets carried out in this work are presented the following.

2.1. Impact scenarios and modeling assumptions

Depending on the mechanical and kinematic parameters characterizing the projectile-target pair, a ballistic impact can result into three different scenarios: (i) the projectile completely perforates the target and exits with non-null residual velocity; (ii) the projectile partially penetrates the target, either remaining stuck within it or rebounding; (iii) the projectile completely perforates the target with zero exit velocity. In case (i) the projectile initial (kinetic) energy is larger than the energy the target can either absorb or dissipate: the opposite occurs in (ii). In the last scenario, instead, all the kinetic energy possessed by the impactor is transferred to the target, matching with the largest amount of energy the target can receive and absorb/dissipate. In such condition, the initial velocity of the projectile of a given mass is termed as ballistic limit.

The energy transfer characterizing cases (i)–(iii) is defined by different energy absorbing/dissipating mechanisms occurring in the target. Possible energy absorbing mechanisms are: cone formation, tension and fracture of primary yarns, deformation of secondary yarns, delamination onset and propagation, matrix cracking, shear plugging and friction between the projectile and the target [13–15] (see Fig. 1). Given the inner complexity of such mechanisms, some physical assumptions have to be made to enable a simplified and yet accurate modeling. In the present mathematical formulation.

(a) the projectile is assumed to be undeformable, cylindrical, with a flat end;
(b) during the impact event, the projectile is assumed to be always in contact with the target, implying that the zone of primary yarns is constant and limited by the diameter of the projectile;
(c) the projectile-target motion is considered uniform in each time interval of the contact period;
(d) the principal curvatures of the target are assumed to be either identical or with at least one of them having null value: this means that only the cases of cylindrical or spherical targets are investigated (with the case of plane targets falling in the former group for reasons concerning their metric, as will be shown in the following);
(e) the warp and weft yarns of each layer are assumed to coincide with the lines of curvature of the target surface, implying that the target layers share the same stacking angle;
(f) the interactions among layers, among yarns and between yarns and the projectile are assumed to be negligible and are therefore neglected, so that each layer and yarn are considered to act independently;
(g) the projectile trajectory is orthogonal to the target;
(h) longitudinal and transverse waves originate from the edge of the projectile.

Additional assumptions are associated to the specific nature of the target to be investigated and directly affect the balance of the energy transferred from the impactor to the laminate.

2.2. Projectile-target energy transfer

For different materials like carbon, glass or Kevlar, different energy absorbing/damage mechanisms can prevail. One additional parameter governing the behavior of the target is its stiffness. It has been assessed that for thin and/or low-Young's modulus plane specimens, yarns deformation and fracture generally represents the dominant energy absorbing mechanism [38]. No through-the-thickness propagation of elastic waves is usually taken into account in this case. Thick targets, instead, are characterized by the onset of compression waves propagating in the target thickness direction, with the formation of a plug beneath the projectile due to shear stresses which moves through the target [39]. The elastic waves propagation along the target thickness direction must be considered in such scenario.