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An analytical model for ballistic impacts against plain-woven fabrics with a polymeric matrix

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ABSTRACT

The widespread use of composite materials in load-carrying components leads to the need of studying their behaviour also in extreme situations, like ballistic impacts. At present the design of these structures against ballistic impacts is strongly dependent upon expensive experimental tests. To reduce the costs, numerical and analytical models have been developed in recent years, which allow a preliminary setting of the main parameters in the experiments, without substituting for them completely. With this aim, an investigation on the analytical modelling technique for ballistic impacts of blunt projectiles on composite plain-woven fabrics with a polymeric matrix has been carried out and is presented in this paper. An analytical model has been developed with original contributions and has then been compared with experimental results and data from the literature. The analytical model is based on the wave theory and on the energy balance between the kinetic energy of the projectile and the dissipation modes of the target: the kinetic energy is absorbed by the "V-tent" deformation moving ahead the projectile tip, the deformation energy of primary and secondary yarns, the delamination and matrix cracking energies, the energy associated to the bending of the layers (which has a considerable contribution in thick targets), the dissipation by the compression of the layer, and finally the energy dissipated by the shear plugging of the layers (if it takes place). The energy dissipated by friction between the projectile and the target and between the woven yarns is neglected. In addition, the model reproduces the sequential failure of the layers under the impact of the projectile, allowing the prediction of the impact velocities at which the projectile remains stuck inside without complete perforation. The aim is to provide a reliable tool able to work on a broad range of conditions and target configurations (thick and thin). From the energy balance, the deceleration of the projectile and the velocity at every time step, together with other parameters like contact duration, radius and depth of the conoid can be determined. The quasi-static properties of the materials are employed in the model. Performances and the pros/cons are evaluated.

1. Introduction

Nowadays composites are employed in many applications including protection equipment capable of arresting ballistic impacts; however components may also be designed for multifunctional use, for example capable of protecting against an impact but also able to function as a load-carrying structure. Different applications also lead to different technological processes; body armours need to be resistant to impacts but also flexible, in order to adapt to the body shape: for this reason, they are made of woven fabrics, usually without a matrix. On the other hand, structural components are designed to carry load while absorbing the energy of an impact; therefore, the use of a matrix is fundamental to give the structure the required stiffness. These considerations highlight the need to fit the manufacturing of a composite structure to its end use, especially when an extreme load such as impact is possible. Although experimental tests still play an important role, modelling approaches are increasingly gaining in importance. Numerical models are a powerful tool. However, a reliable analytical methodology can be of interest in a preliminary investigation allowing the fast evaluation of several configurations. The analytical models in the literature adopt different ways of determining and approaching the fracture of the composite but all of them assume the projectile is rigid when it is made of a hard material (e.g. steel, tungsten); this hypothesis is confirmed by several experimental observations [1–3,5]. Furthermore, the analytical models reported in the

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Nomenclature

a	Yarn reference dimension
A	cross sectional area of yarns
A_{ql}	quasi-lemniscate (figure of 8) area reduction factor
a_p	deceleration of the projectile
b	wave transmission factor
C_L	longitudinal wave speed
$C_{L,Th}$	in-thickness longitudinal wave speed
C_t	transversal wave speed
E	Young modulus
$E_{bend,i}$	energy dissipated by bending of the layers
$E_{compr,i}$	energy dissipated by compression of layers
$E_{del,i}$	energy dissipated by delamination
$E_{kp,i}$	kinetic energy of the projectile
$E_{kc,i}$	kinetic energy of the moving conoid deformation
$E_{mat,i}$	energy dissipated by matrix cracking
E_{mt}	energy absorbed by matrix cracking per unit volume
$E_{py,i}$	energy dissipated by primary yarns
$E_{sy,i}$	energy dissipated by secondary yarns
$E_{sp,i}$	energy dissipated by shear plugging
E_{Th}	transversal elastic modulus
F	force on the projectile
G_{II}	critical dynamic strain energy release rate in mode II
h_1	layer thickness
L_1	length of the undeformed yarns
l_{sy}	length of deformed secondary yarns
M	bending moment per unit length
M^*	bending moment
M_c	mass of the conoid deformation
m_p	mass of the projectile
n_{failed}	number of failed layers
$n_{prop,i}$	number of layers passed by the in-thickness longitudinal wave
N_p	total number of primary yarns
n_{shear}	number of layers that undergo shear plugging
R	radius of the conoid
R_1	radius of the projectile
r_d	delamination radius
$r_{l,i}$	distance travelled by the longitudinal wave
$r_{t,i}$	distance travelled by the transversal wave
s	thickness of the deformed layer
S_{sp}	shear plugging strength
V_{mat}	matrix volume fraction
V_p	velocity of the projectile
z	depth of the conoid deformation
$z_{L,Th,i}$	distance travelled by the in-thickness longitudinal wave

Greek letters

α	angle of the conoid deformation
Δt	time step
$\varepsilon_{0,ij}$	maximum strain of the primary yarns
ε_A	compression strain of zone A
ε_B	compression strain of zone B
ρ	density
$\hat{\rho}$	radius of camber of the deformed plate in orthogonal direction
ν	Poisson coefficient
τ_{shear}	shear stress in the target

literature employ different techniques and formulations to predict the various required ballistic parameters, including the most important, namely the residual velocity of the projectile. One of the first works on composite plates is the one of Vinson & Zukas [4], in which the analytical model is based on the propagation of longitudinal and transversal waves after the impact that generate a "V-shaped" deformation: after reaching a threshold strain value, the composite is considered broken. The velocity is not derived from the energy balance of the several dissipation modes but from calculation of the resistance force of the plate. Roylance [7] and Field & Sun [8], exploited, the longitudinal and transversal wave propagation theory to obtain the strain in the fibres and hence a relationship with the impact velocity, to define a design optimization methodology. In Ref. [6] the calculation of the velocity of the projectile is based on momentum equations that link the strain along the yarns with the velocity itself, basing the model on previous studies on single yarn impacts [8]; furthermore, it considers combined failure criteria depending on the tensile and shear stress and it reproduces multi-layers targets without a matrix. The analytical models based on the energy balance to derive the deceleration of the projectile give an accurate understanding of how the kinetic energy of the projectile is dissipated and which dissipation mode prevails over the others, thus pointing the focus of the design on the relevant parameters. In Ref. [2] three major components i.e. the tensile failure of the composite, the elastic deformation and the kinetic energy of the moving conoid of the composite were identified to contribute to the energy lost by the projectile during the ballistic impact. The most dominant energy absorbing mechanism was found to be the kinetic energy of the deforming composite. In Ref. [1] further components were added to the energy balance: deformation of the primary and secondary yarns, delamination, matrix cracking and shear plugging. The strain in the composite is hypothesized to decrease linearly through the thickness, but how the gradient of the slope is identified is not explained; also, shear plugging is reproduced assuming that the whole force to which the projectile is subjected acts on the cylindrical surface of the target around the tip of the blunt projectile. In the present work, the analytical model adopts an energy balance to derive the velocity and the wave propagation theory studied in earlier works [1,2,7,9,10] forms the base. This choice was made to develop an accurate model capable of working correctly over a wide range of conditions, from the thickness of the target and its materials, to the variation of the impact velocity, the mass and dimensions of the projectile, which is however constrained to be a rigid body with a cylindrical blunt shape (BSP). To achieve this, the reference models cited above were studied and changes made, especially broadening the working range of the model. The main parameter of interest remains the residual velocity, to provide the ballistic limit of the projectile-target couple, because this limit is the ultimate indicator of the effectiveness of ballistic protection. In Section 2, the formulation of the model is presented. In each paragraph the different dissipation modes are described: the kinetic energy of the "V-tent" deformation, the energy of the yarns under tensile strain, the energy required to bend the composite plate, the compression of the layers, the delamination and the matrix cracking and finally shear plugging. In Section 3, the analytical model is compared and validated with experimental data obtained by the authors [5] along with other data from the literature; in particular, the residual velocity and the ballistic limit for different target materials and thickness are analysed, but also the energy trend in time and the morphological features are investigated.