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Two-scale modeling of high-velocity fragment GFRP penetration for assessment of ballistic limit

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ABSTRACT

The present paper deals with the ballistic testing and numerical modeling problems of fragment penetration of glass fabric/epoxy-phenolic (GFRP) laminates. Two laminates of different thickness (1.95 and 3.90 mm) were subjected to ballistic impact of 6.35 mm dia steel sphere as a fragment simulator at different velocities to get ballistic curves. There were developed the continuum-based model (CBM) and the microstructural model (MSM) of GFRP laminates in two finite element codes (AUTODYN-3D and LS-DYNA). The CBM is a model of anisotropic body with the fiber-dominated failure mechanics. The advantages of this model include short CPU time and good prediction of ballistic limit velocity with the use of only two free parameters of failure model to be determined from preliminary dynamic experiments. The MSM has geometrically accurate GFRP structure and assumption of isotropy and simple failure criteria of constituents (fiber bundles and matrix) not only to get the ballistic limits, but also to describe in details the damage mechanisms of GFRP laminates. The numerical simulation results showed a good correlation with the experimental data in terms of ballistic curves and internal material damage.

1. Introduction

The issues of the local contact interaction of low-plastic projectiles and laminates composite are traditionally considered to be the most difficult issues of the mechanics of deformable bodies, in which there occur wave processes, large inelastic deformation, local destruction and delamination [1–3].

In this regard, practically important problems are being solved experimentally and numerically now with the use of software packages and implementation of the finite element method, for example, LS-DYNA, ABACUS, ANSYS et al. [4–6].

It is important to note that the central issue is the correct choice of the material model in the process of practical using of the finite element method, i.e. the model of deformation and failure [7,8], as well as the appointment/definition of the relevant parameters of the selected models. One of the shortcomings of the present material models is a lack of inclusion of the contribution of various phenomena and processes occurring at different length scales to the overall behavior/performance of the material. In the paper [9], a brief overview was provided of the main microstructural scales encountered in the case of armor-grade polymer-matrix fiber-reinforced composite materials.

Correctness of the choice of the material model is traditionally estimated by the value of error in determining the specific performance characteristics: the depth of indentations in a layer of special clay (in the development of body armor) or residual velocities of a bullet after the perforation of laminates (in the development of shield or protective panels).

It is obvious that the calculated ballistic curve (and corresponding ballistic limit – the impact velocity, which is corresponded with perforation) is important during the optimization of composite structures which are capable of stopping a bullet flying at certain velocities, since direct experiments during the optimization of the structure are usually very expensive and prolonged [9,10].

In works [11,12], authors developed a strain rate dependent multiparametric UD-lamina model based on continuum damage accumulation mechanics for simulations of ballistic impact on panels made of S2-Glass/Epoxy and Kevlar fabric's composites. But real strain rate dependence of axial strength is weak enough and might be neglected for engineering applications (axial strength has only 15% increasing with three decimal orders increasing of strain rate). Unfortunately, authors did not include quasi-static data. The very promising offer is finite element excluding from the mesh only after reaching of UD-ply axial stress (in warp and weft directions) of its strength values. There was also declared good agreement between the numerical and experimental results in terms of predicting ballistic limit, delamination and energy absorption of laminates but without tabular or graphical illustrations.

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Currently, there are no such models, which can be applied simultaneously to describe the high-velocity impact (HVI), and a low-velocity impact (LVI). Scientists are mainly engaged in the development of models, which describe penetration of the sample [13,14] or simulate quasi-static processes under low velocity impact. Besides, when the damage has a binary character (penetration or not), and the speed of the impactors is close to the ballistic limit these models are ineffective. Such models are not accurate enough in taking into account the observed failure mechanisms.

There are FE software like Composite Pre/Post, PAM-FORM for a detailed description of the composite structures and for setting the properties of components. In these software packages composite structures can be created, taking into account the different stacking of layers for strength analysis under dynamic loading. This software has the ability to set the anisotropic properties of materials and to choose one in a long line of criteria for strength evaluation. However, a large number of parameters must be specified to construct models in such packages which are a disadvantage due to the lack of standardized methods for determining these parameters [15].

The known studies suggest that the impact of the bullets of light weapons (impact speed less than 1000 m/s) can be considered using the models of deformable bodies, taking into account the elasticity, ductility and fracture of finite elements in the Lagrangian formulation [10,16,17] with a deformable mesh of finite elements. Meshless approach (smooth particle hydrodynamics – SPH) can also be used, but the difference of predicted results between Lagrangian formulation and SPH might be decreased with correct statement of erosion strain [18].

While there exists an extensive literature on ballistic evaluation of E-glass composites with epoxy and phenolic matrices [19,20], glass/epoxy-phenolic laminates have attracted only limited attention. Therefore, in this paper the authors carried out experimental work to determine the mechanical and ballistic properties of glass/epoxy-phenolic composite against a steel ball impact.

Ballistic curves obtained under the ballistic loading by the 6.35 mm of dia steel sphere [21] are proposed to serve as an experimental base (dependence of the residual velocity of the projectile V_r after the penetration of laminates from its initial velocity V_i). Thus, any target of reasonable thickness can be investigated to obtain ballistic curves, which give the most valuable information about penetration process. By the way, Larsson and Svensson [22] conducted ballistic tests of various composites and it was found that ballistic limits of the 5.46 mm FSP and the 6.00 mm steel ball were just about the same, despite the ball being 21% lighter. It is known [23] that, for multilayer packages, with increasing number of layers the influence of projectile's geometry on ballistic performance was less noticeable. This suggests that for multilayer armor-grade composites results obtained at 5.56 mm FSP and 6.35 mm steel ball will be close.

Very well known fact is that ballistic impact in normal to surface direction is the mostly dangerous case to estimate ballistic performance of solid targets [24]. Incline shots have the penetration possibility only to soft fabric-based targets. So in this work we used only shots in normal to surface direction.

Besides, two different scale models of GFRP panels impacted by steel sphere were developed. The first, continuum-based model (CBM) created in ANSYS Workbench (AUTODYN-3D), is an extremely simple low-parametric model of composites failure (on the example of plane weave GFRP). The advantages of this model include fast calculation time and satisfactory prediction of ballistic limit even for using of typical table-top PC. This model is required for the optimization of composite structures at the initial stage, when the choice of thickness and properties of material are actual. The second model is a microstructural model (MSM), it suggests a geometrically accurate definition of GFRP structure not only to obtain ballistic limit, but also to describe in-plane and out-of-plane failure mechanisms (delamination areas after impact). This model gives a potential possibility of the analysis of how the weave structures of fabric influence the ballistic properties of the composite. It is required on the final stage of the structure design for the verification of the results obtained by the first CBM model. MSM is much heavier than CBM, so in the second case it needs to use high performance cluster and LS-DYNA software installed (not ANSYS AUTODYN-3D on PC).

Thus, the models presented in this paper are the various length scales and according to References [9,12] may be defined in the groups: “Stacked-lamina length-scale” (CBM) and “Fabric unit-cell length-scale” (MSM).

The organization of the paper is as follows: materials, static and dynamic properties of the GFRP STEF are presented in Section 2. Ballistic test results of composites and a short description of the impact facilities are described in Section 3. Section 4 is devoted to the different scale numerical modeling and Section 5 gives the analysis of the results and comparison with the experiments.

2. Materials and properties

2.1. Specimens

The GFRP plates were made of STEF (1.95 mm and 3.9 mm of thickness) manufactured according to GOST 12652-74. This material consists of plain weave glass fabric (6 and 12 plies) and hot curing epoxy-phenolic matrix. Density of STEF is 1.98 g/cm^3.

2.2. Static properties

To investigate the static properties of the present panels, a series of tensile tests were performed. The tests conducted at the INSTRON 5882 (with clip-on Instron extensometers) testing machine on tensile of rectangular specimens, which were cut out in the direction of warp or weft and in a diagonal direction (45°), showed the values of elastic modulus $E_x \approx E_y \approx 28 \pm 1$ GPa, Poisson's ratio – $\nu_{xy} \approx 0.18 \pm 0{,}01$ and shear modulus – $G_{xy} \approx 6.2 \pm 0.2$ GPa. Other elastic constants were obtained by calculation using the orthotropy of composites structure and recommendations [25]: $E_z \approx 8.0$ GPa, $\nu_{xz} \approx 0.40$, $\nu_{yz} \approx 0.40$, $G_{xz} \approx G_{yz} \approx 3.0$ GPa.

The strength tests under quasi-static tensile (strain rate $d\varepsilon/dt \approx 10^{-3}\,s^{-1}$) were conducted with the specimen's dimensions of $1.95 \times 10 \times 150$ mm until the failure. The tensile strength along the warp/weft fibers was equal to ~395 ± 30 MPa, but the tensile strength in a diagonal direction was equal to ~200 ± 15 MPa. At the transversal quasi-static tensile, the tensile strength of composites was difficult to determine, so, in this research we use a value of ~50 MPa taken from Reference [25] for typical fiberglass.

2.3. Dynamic properties

The strength tests under dynamic tensile (strain rate $d\varepsilon/dt = 80$ s^{-1} and 200 s^{-1}) on the vertical drop tower system (Instron CEAST 9350) were conducted with the specimen dimensions of $1.95 \times 10 \times 150$ mm (working zone of 15 mm long). The tensile strength along the warp/weft fibers was equal to 730 ± 30 MPa and 750 ± 30 MPa respectively. Extrapolation on the average ballistic impact fiber tensile strain rate (10^3–$10^4\,s^{-1}$) showed the tensile strength of about 900 MPa (Fig. 1, line 1).

The strength tests of specimens, which were cut out in diagonal direction (45°) under dynamic tensile at the same condition, showed the tensile strength equal to 250 ± 15 и 280 ± 15 MPa, respectively. Extrapolation on the average ballistic impact fiber tensile strain rate (10^3–$10^4\,s^{-1}$) showed the tensile strength of about 300 MPa (Fig. 1, line 2).