Experimental Investigation and FE Analysis of Fiber Woven Layered Composites under Dynamic Loading

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Abstract

Woven composites are used in a wide range of industrial applications such as development of individual body armor, aviation, astronautics and others . Thus, it is important to learn the mechanical behavior of the composite and to perform it's adequate modeling under dynamic impact loading.

The paper is concerned with modeling of woven fabric composite made of aramid yarns. The experimental investigation including static tests, dynamic tests with the Split Hopkinson Bar and ballistic impact tests was performed.

The full-scale model with yarn-level detalization was constructed using obtained experimental data. The method allows getting qualitative results on the small specimens but realistic analysis of real-size models consisted of billion elements requires huge computational resources. So the paper is focused on the development of the alternative homogenized macro-model of the layered composite.

Introduction

Adequate simulation of woven composites constitutive behavior and failure prediction under complex impact loading is required for a wide range of applications.. Today, many investigations all over the world are concerned with this problem. Generally, they can be divided into two main groups. One is a micro- or full-scale modeling which takes into account a detailed geometrical structure of a composite [1]. Such method requires large computational resources but generally simple material models can be used to describe behavior of individual yarns, forming the composite. Parameters for such models, such as geometry, elastic moduli, failure criterion, etc., can be determined from experiments with the yarns [2]. The other method is so called macro or reduced modeling [3]. The method is based on the homogenization of material properties of the composite and its effective characteristics. So the composite is represented as anisotropic solid media with complex nonlinear mechanical behavior. In this case it is very difficult to obtain the unique composite failure mechanism. Nonlinearity is concerned with the local damage and internal friction. Thus in most cases multilayered shell elements with several through thickness integration points and classical laminate theory is applied [4]. In this work, woven composite is represented as a set of multilayered homogeneous orthotropic shells (Fig. 1) without internal friction. The material was assumed to be linear until failure. The elastic characteristics were defined from the static and dynamic tests in comparison with full-scale model. All data below relate to woven fabric made of Rusar® aramid fibers.

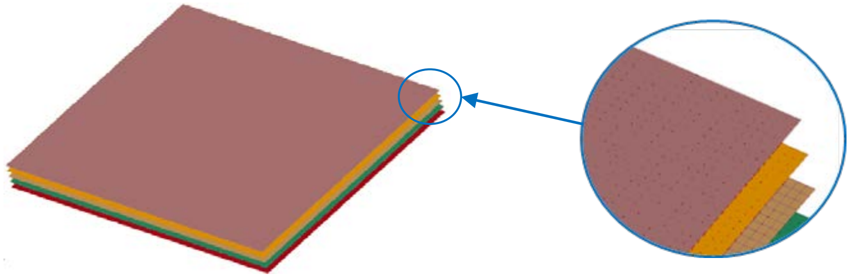

Fig. 1 FE reduced model of a multilayered woven composite.

Full scale model

FE model with detailed representation of each fill and warp yarn was constructed (Fig. 2). It is important to take into account the difference in the geometry of the fill and warp yarns, since it affects the initial elastic characteristic of the layer and failure criterion.

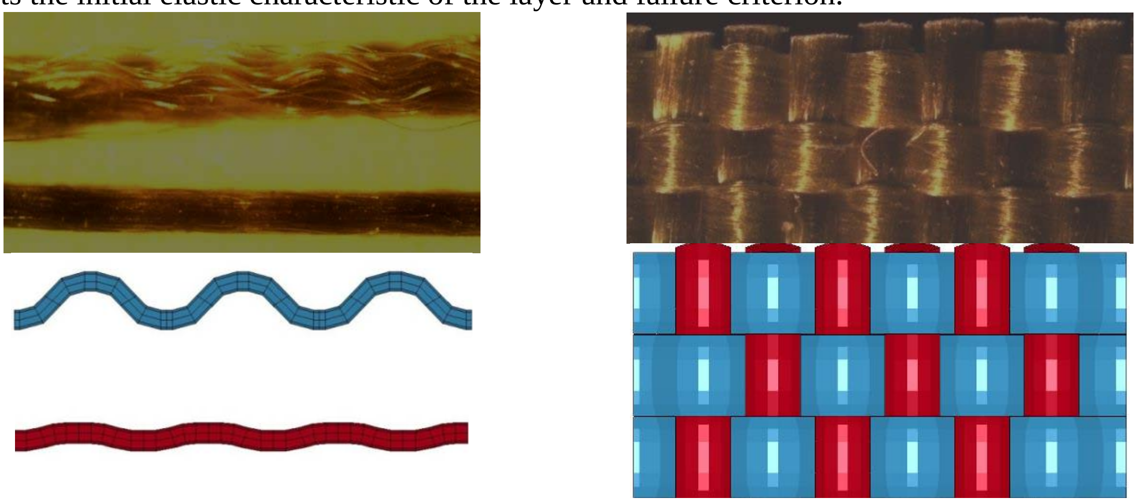

Fig. 2 Fragment of the FE model.

Each yarn was assumed to be a transversally anisotropic body with its c-axis directed along the yarn and the other axes at its cross section (Fig. 3).

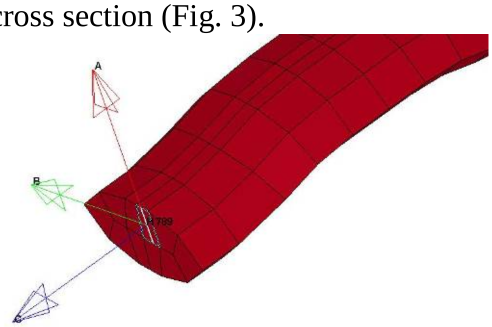

Fig. 3 FE model of an individual yarn.

Stiffness matrix of the material is a symmetric one.

$$C_L^{-1} = \begin{pmatrix} \frac{1}{E_a} & -\frac{\nu_{ba}}{E_b} & -\frac{\nu_{ca}}{E_c} & 0 & 0 & 0 \\ -\frac{\nu_{ab}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{cb}}{E_c} & 0 & 0 & 0 \\ -\frac{\nu_{ac}}{E_a} & -\frac{\nu_{bc}}{E_b} & \frac{1}{E_c} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{ab}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{bc}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{ca}} \end{pmatrix}$$

The yarn is supposed to carry loads only in longitudinal tension, so elastic moduli in transverse direction are small in comparison with longitudinal. Also according to the hypothesis of incompressibility of the yarn section and a form of the first strain tensor invariant

$$\theta = \frac{\sigma_a}{E_a}(1-\nu_{ab}-\nu_{ac}) + \frac{\sigma_b}{E_b}(1-\nu_{ba}-\nu_{bc}) + \frac{\sigma_c}{E_c}(1-\nu_{ca}-\nu_{cb}),$$

we obtain a special condition on the Poisson's ratios:

$$\nu_{ab}+\nu_{ac}=1, \quad \nu_{ba}+\nu_{bc}=1$$

Elastic properties of the yarns are listed in Table 1.

Table 1

	E_a, GPa	E_b, GPa	E_c, GPa	G_{ab}, GPa	G_{bc}, GPa	G_{ca}, GPa	ν_{ba}	ν_{cb}	ν_{ca}
Fill	0.38	0.38	38	0.1	0.1	0.1	0.997	0.3	0.3
Warp	0.42	0.42	42	0.1	0.1	0.1	0.997	0.3	0.3

Stress-strain curves obtained in the single yarn tensile tests are represented in the Fig. 4 (dotted curve is a simulation). Stress-strain curves for the specimen consisted of 8 layers placed in the alternating material directions are shown in the Fig. 5.

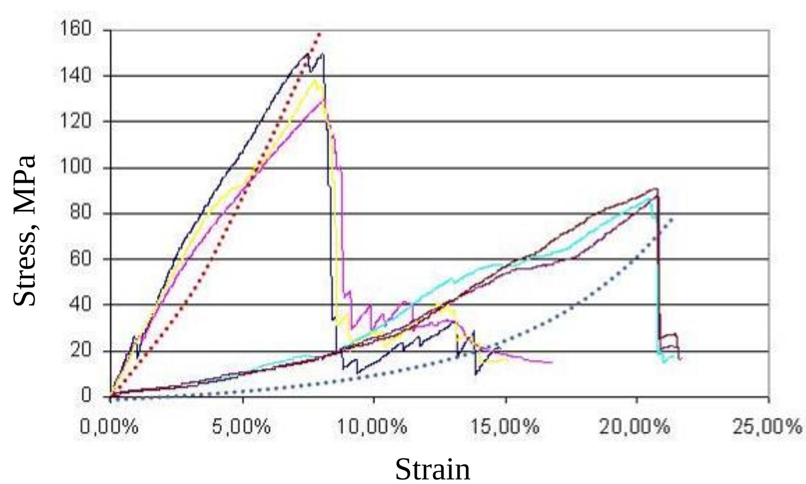

Fig. 4 Stress-strain curve in tensile tests with a single-layer fiber.

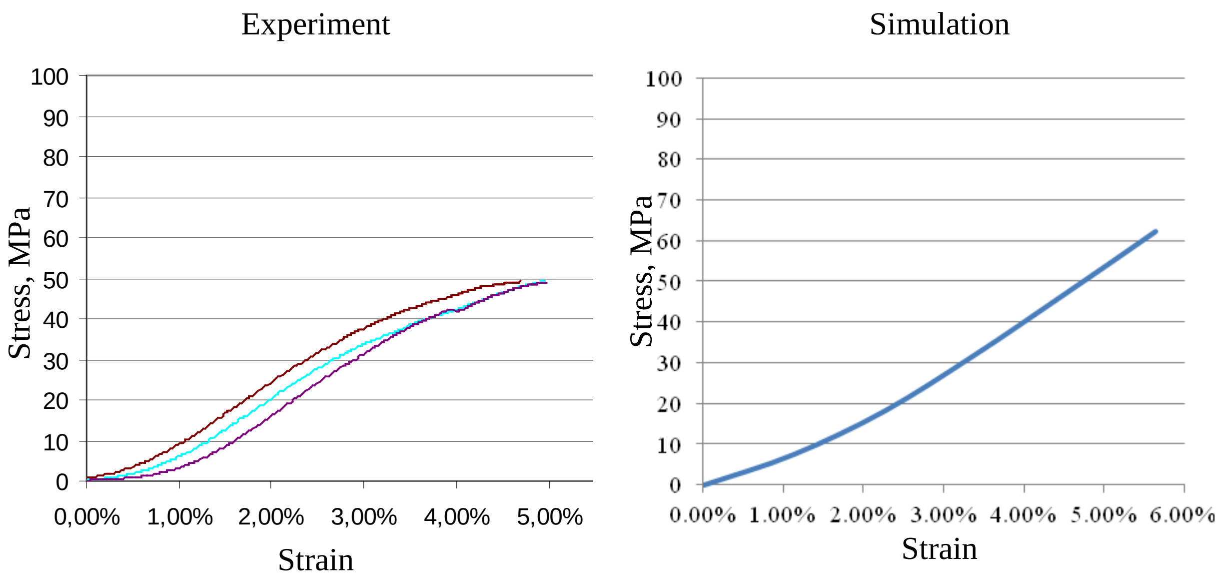

Fig. 5 Stress-strain curves in tensile tests with 8-layer package.

It should be noted that in the simulation as well as in the experiments with multilayered specimens, an initial increase in the specimen thickness was observed, which can be explained by interaction between adjacent layers due to fiber straightening during tension.

Also the yarn pull out tests were conducted to identify the parameters of interior friction. The specimens of 3.56 mm and 3.04 mm length for fill and warp yarns pull out respectively were used. The maximum force values, obtained in experiments were 0.9 N and 1.3 N respectively. Force received during simulation is shown in the Fig. 6.

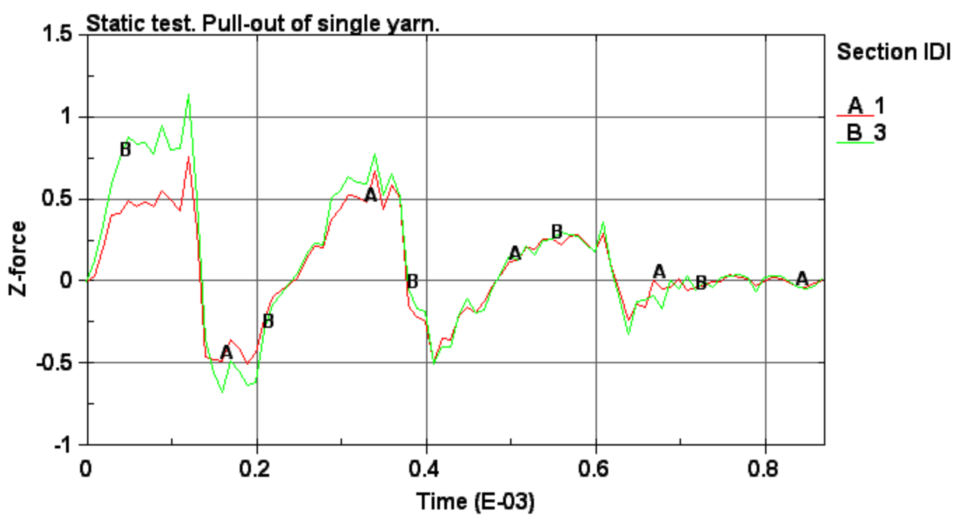

Fig. 6 Friction curve obtained in the simulation of the pull out tests.

As a result of pull out test the following parameters of the friction model was defined:

$$\begin{cases} \dfrac{\overline{\tau}_n}{\tau_n} = \dfrac{\overline{v}_{ab}}{v_{ab}} \\ \tau_n = \min\{\mu_c p_n, VC\} \end{cases}, \quad \mu_c = FD + (FS - FD)\exp(-v_{ab} DC),$$

where v_{ab} is a relative sliding velocity of the contact pair; τ_n and p_n - tangential and normal component of the contact force; FS = 0.3 and FD = 0.3 – static and dynamic friction coefficients; VC = 0.22 MPa – coefficient for viscous friction.

Finally, a set of ballistic test including different types of specimens with from 1 to 100 layers of fabric with alternating packing of adjacent layers were performed. Experiments on normal and angular impact were conducted. The virtual model is shown in Fig. 7.

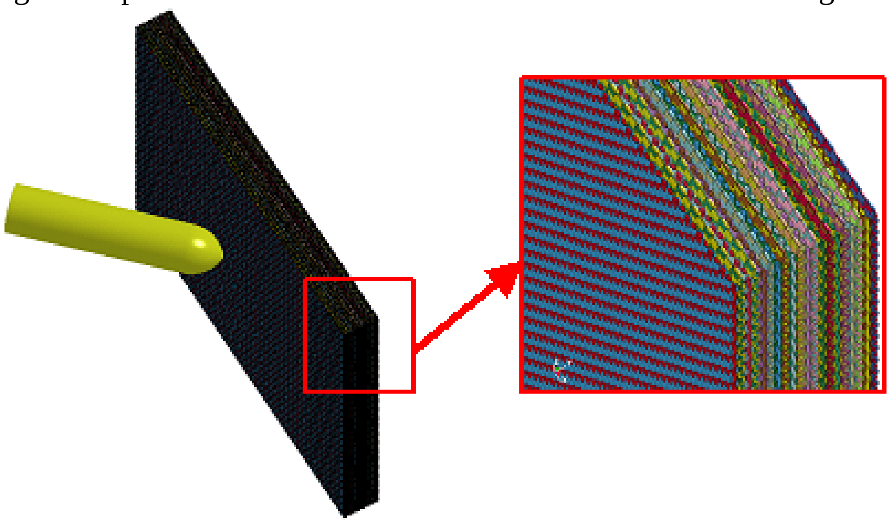

Fig. 7 Full-scale FE model for ballistic angular test with 20-layer package.

The comparison of full-scale and virtual test on normal impact on 4-layered target is shown in Fig. 8. Fig. 9 illustrates the comparison for angular impact on 20-layered composite.

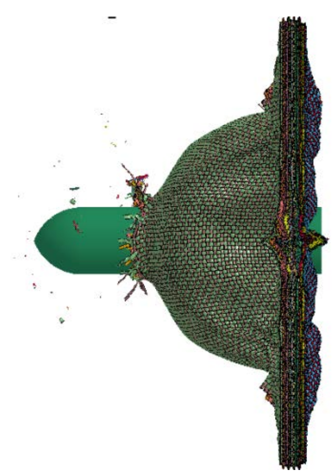

Fig. 8 Results of a ballistic test with 4-layered composite.

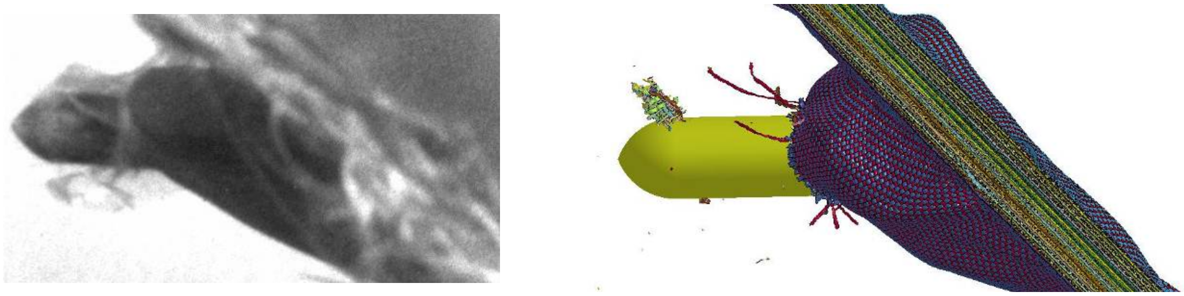

Fig. 9 Results of a ballistic angular test with 20-layered composite.

Macro model of a woven layered composite

The most realistic description of the woven composite behavior under dynamic loading is obtained by the full-scale simulation of material with the individual warp and fill yarns detailization as shown on Fig. 8-9. However, such an approach is possible only for small size specimens. For example, FE model of a single-layer of 50×50 mm size consists of approximately 1 million elements. Thus, even with modern facilities, the simulation of a real full-scale test like a blade-out test is impossible.
In this study, a computational model of a single-layer woven composite proposed is an orthotropic elastic media with material axes a and b directed respectively along the fill and warp directions (Fig. 10). The 8-node shell elements with 3 through thickness integration points were used.

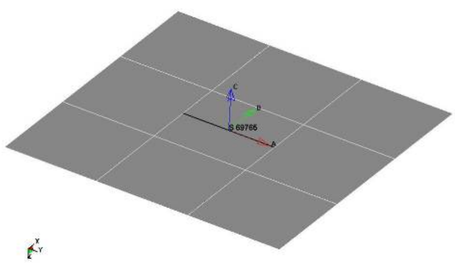

Fig. 10 Fragment of a FE macro model of a layer.

The elastic properties of proposed model were calculated according to the full-scale model and are listed in Table 2.

Table 2

E_a, GPa	E_b, GPa	E_c, GPa	G_{ab}, GPa	G_{bc}, GPa	G_{ca}, GPa	ν_{ba}	ν_{cb}	ν_{ca}
42	38	5	0.1	0.1	0.1	0.32	0.02	0.05

The failure criterion was defined by *MAT_ADD_EROSION card with two parameters

MXEPS = 8 %, SIGP1 = 700 MPa.

Maximum effective strain at failure corresponds to fiber failure in tension. The second condition on principal stress was introduced to exclude material failure due to large shear strains.

The parameters of friction model between fiber and the striker are listed in the Table 3.

Table 3

FS	*FD*	*VC. МПа*
0.5	0.5	0.22

This approach gives a serious savings in computational resources: a single-layer specimen of 50 × 50 mm size contains approximately 10,000 elements. But still, real structures can consist of more than ten million elements. In this paper, it is proposed to simulate multilayer woven packages with multilayer shell elements, which include multiple fabric layers with alternating directions of the material axes using *INTEGRATION SHELL card. The results of comparison of some ballistic tests and simulation are shown in Fig. 11-13.

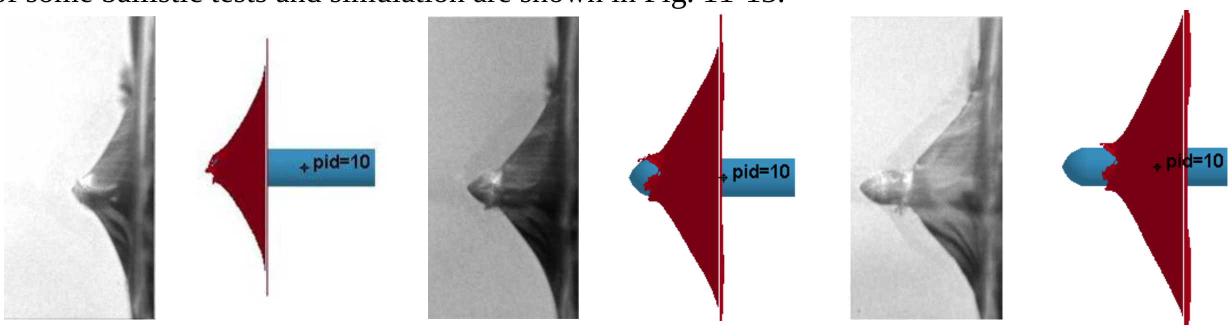

Fig. 11. 4-layer composite. Initial velocity is 266 mps.

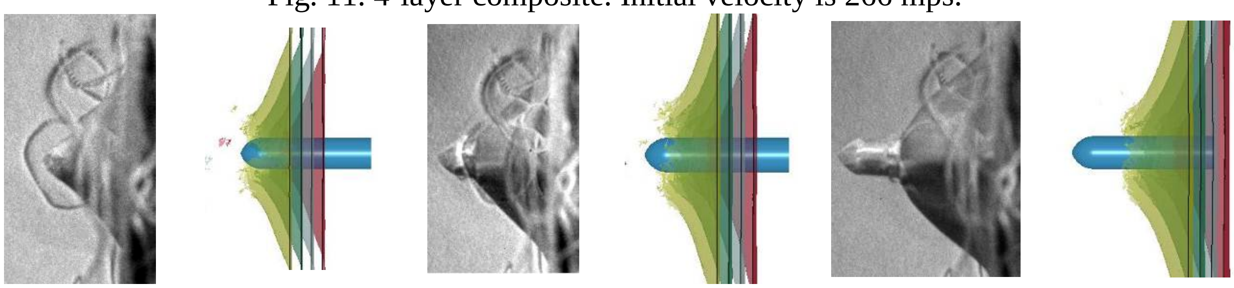

Fig. 12. 40-layer composite. Impact velocity is 380 mps.

This approach also has some negative aspects. First, increasing number of integration points in the shell causes an increase in bending stiffness of the material in the transverse direction, which leads to necessity in a new failure criteria and qualitative mismatch of full-scale and virtual ballistic tests. Secondary, the FE model should include 5 to 10 layers to simulate delamination of the composite and the layers interaction. It can be concluded that each layer in FE model should contain 4 to 10 physical layers optimal.

References

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