Кудрявцев О.А., Сапожников С.Б. Моделирование на уровне нитей тканых и однонаправленных композитных материалов с термопластичной матрицей при баллистическом нагружении // Вестник Пермского национального исследовательского политехнического университета. Механика. – 2016. – № 3. – С. 108–119. DOI: 10.15593/perm.mech/2016.3.07

Kudryavtsev O.A., Sapozhnikov S.B. Yarn-level modelling of woven and unidirectional thermoplastic composite materials under ballistic impact. *PNRPU Mechanics Bulletin*. 2016. No. 3. Pp. 108-119. DOI: 10.15593/perm.mech/2016.3.07

ВЕСТНИК ПНИПУ. МЕХАНИКА

№ 3, 2016

PNRPU MECHANICS BULLETIN

http://vestnik.pstu.ru/mechanics/about/inf/

DOI 10.15593/perm.mech/2016.3.07

УДК 539.3

МОДЕЛИРОВАНИЕ НА УРОВНЕ НИТЕЙ ТКАНЫХ И ОДНОНАПРАВЛЕННЫХ КОМПОЗИТНЫХ МАТЕРИАЛОВ С ТЕРМОПЛАСТИЧНОЙ МАТРИЦЕЙ ПРИ БАЛЛИСТИЧЕСКОМ НАГРУЖЕНИИ

О.А. Кудрявцев, С.Б. Сапожников

Южно-Уральский государственный университет, Челябинск, Россия

О СТАТЬЕ

Получена: 1 июля 2016 г.
Принята: 20 сентября 2016 г.
Опубликована: 30 сентября 2016 г.

Ключевые слова:

композит, термопластичная матрица, защитная структура, высокоскоростной удар, конечно-элементный анализ, LS-DYNA, малопараметрическая модель, баллистический предел

АННОТАЦИЯ

Композиты с термопластичной матрицей на основе высокопрочных волокон (арамидных или СВМПЭ) широко используются при производстве различных защитных структур (бронежилеты, шлемы, бронепанели), которые могут подвергаться высокоскоростному ударному воздействию. В настоящее время с целью снижения времени и стоимости разработки новых конструкций, повышения их надежности широко используются возможности численного моделирования процессов деформирования и разрушения волокнистых композитных материалов при баллистическом нагружении. Можно выделить несколько основных подходов к моделированию композитного материала. Самым распространенным является подход, в котором композит рассматривается как однородный ортотропный материала. Его несомненным достоинством является высокая скорость решения задачи. В то же время он не позволяет описать все особенности разрушения волокнистых композитов, например расслоение и вытягивание волокон. Возросшая за последние несколько лет вычислительная мощность компьютеров, а также повышение доступности суперкомпьютерных вычислений сделали возможным активную разработку и внедрение многоуровневых и мезоуровневых моделей композитных материалов, непосредственно учитывающих их неоднородную структуру на уровне волокон и матрицы. Применение подобного подхода позволяет использовать более простые модели материалов с меньшим числом параметров.

В данной работе мезо-уровневое моделирование в конечно-элементном пакете LS-DYNA было использовано для описания деформирования и разрушения двух прессованных композитов с термопластичной матрицей при баллистическом ударе имитатором осколка. Первый тип композитной панели был изготовлен из арамидной ткани полотняного переплетения КВ110П с прослойками из полиэтилена низкого давления (ПЭНД). Композитная панель второго типа состояла из материала на основе высокопрочных полиэтиленовых волокон Dyneema® HB80. Для описания поведения данных панелей при ударе были предложены комбинированные конечно-элементные модели, в которых волокна были схематизированы оболочечными элементами, а матрица – твердотельными. Полученные модели позволили получить удовлетворительное соответствие экспериментальным данным, включая остаточную скорость ударника и основные механизмы разрушения (разрыв волокон, расслоение, вытягивание волокон и т.д.). Представленные модели могут быть использованы для детализированных расчетов керамокомпозитных слоистых структур при ударе.

© **Кудрявцев Олег Александрович** – аспирант, e-mail: kudriavtcevoa@susu.ru
Сапожников Сергей Борисович – доктор технических наук, профессор, e-mail: ssb@susu.ru

Oleg A. Kudryavtsev – PhD student, e-mail: kudriavtcevoa@susu.ru
Sergei B. Sapozhnikov – Doctor of Technical Sciences, Professor, e-mail: ssb@susu.ru

YARN-LEVEL MODELLING OF WOVEN AND UNIDIRECTIONAL THERMOPLASTIC COMPOSITE MATERIALS UNDER BALLISTIC IMPACT

O.A. Kudryavtsev, S.B. Sapozhnikov

South Ural State University, Chelyabinsk, Russian Federation

ARTICLE INFO

Received: 1 Jule 2016
Accepted: 20 September 2016
Published: 30 September 2016

Keywords:
composite material, thermoplastic matrix, protective structure, high-velocity impact, FEA, LS-DYNA, mesoscale approach, ballistic limit

ABSTRACT

Composite materials made of high-strength fibres (for example, aramid or UHMWPE) are extensively used in such protective structures as bulletproof vests, helmets, etc. Many researchers have carried out numerical simulations of ballistic impact on composite laminates applying continuum, multiscale and mesoscale approaches. The continuum approach requires a little computational time but cannot catch all features of composite panel or fabric plies behaviour during high-velocity impact. Thus, using the mesoscale and multiscale models has recently been increased.

In this paper, mesoscale approach was used to simulate a 6.35 mm steel ball impact on two types of hot-pressed thermoplastic composites with LS-DYNA finite-element code. The first type of the composite panel is made of aramid fabric KV110P (plane weave structure) with LDPE matrix. The second one was Dyneema® HB80 UD laminate. The proposed models of the real-sized panels were based on the combination of shell (for yarns) and solid (for resin) elements with common nodes to reduce an overall number of contacts and CPU time. The yarn-level modelling allowed using simple material models and fracture criteria. The models reflect the main failure modes in the real panels including the fracture of fibres, delamination, fabric/matrix debonding, yarns pull-out, etc. The experimentally obtained ballistic curves were used to validate results of the numerical simulations.

Introduction

Composite materials made of high-performance fibres are well known for their remarkable strength and low weight. Compliant composites with thermoplastic matrices (resin content does not exceed 20% by weight) are widely used in lightweight structures for ballistic protection [1]. Aramids and UHMWPEs (Ultra-High-Molecular-Weight-Polyethylene) are two most commonly used fibre types for armour applications [2].

Until recently, ballistic tests of real panels have commonly been used for determining their ballistic performance [2-5]. At the same time, such experiments can be very expensive especially when a range of thicknesses, configurations or projectiles is considered. On this reason, various numerical methods along with finite element codes are used to quantify interaction between composite panel and projectile. They allow to perform assessment of panel impact resistance and provide useful information about penetration process.

The numerical simulation of composite materials under impact loading conditions can be performed at different levels. On the macromechanical level, a composite laminate is considered as a continuum orthotropic material with linear or non-linear mechanical behaviour. The main advantage of the modelling on the macromechanical level is a high computational efficiency. On the other hand, the continuum approach does not allow to catch delamination of the panel and fibres-matrix debonding. Nevertheless, such approach was widely implemented both into finite element and into finite difference codes like ABAQUS, LS-DYNA, ANSYS AUTODYN etc. and used by many researchers to simulate ballistic impact onto ceramic/composite [6-9] or fully fibre composite armour [10-16].

On the micromechanical level an explicit modelling of fibres and matrix elements is performed. Constituent modelling could provide great predictive capabilities but even now, computational power of modern supercomputers is not enough for simulating real-size composite target at the fibre scale. It should be noted that this approach might be used for some specific investigations [17] or as a part of multiscale simulations [18, 19].

All the mentioned above reasons are making mesoscale simulations widely used for analysis of composite materials behaviour. In this case, consolidated plies or fibre bundles are considered. Thus, it is possible to use simpler material models and fracture criteria for fibres bundles and a matrix. The interaction between a "failed" composite (which can behave like a dry woven fabric) and a projectile is also much easy to take into account using a mesoscale model. The yarn-level modelling was successfully used to simulate ballistic impact onto high-strength fabrics [20-23]. Among the mesoscale simulations of fibre composite materials, several works should be certainly mentioned. Gopinath et al. [24] investigated deformations of a clamped woven fabric rectangular laminate impacted at normal incidence by a full metal jacket projectile. Kevlar® yarn bundle and polymer matrix were modelled as a 3-D continuum with contact interfaces between the layers. Bresciani et al. [25] used similar approach for simulating ballistic impacts against Kevlar® 29 plain-woven fabrics with an epoxy matrix. Gama and Gillespie Jr. [26] proposed a layered model with tiebreak contacts for assessment of the damage evolution and penetration of thick-section plain weave S-2 glass/SC15 laminates. Chocron et al. [27] developed a numerical model for UHMWPE that captures the essential physics (wave propagation) during the 0.30 cal. FSP impact. The model bundles fibres in a strip as solid elements with orthotropic properties. All the models use different tiebreak contacts which significantly influence on material performance. At the same time, the authors mentioned that it is difficult to determine real properties of the interface between layers at high-strain rates and only approximate assessments are possible.

In our work we developed yarn-level models for two most widely used composite armour-grade materials: aramid fabric with plane weave structure/thermoplastic matrix and Dyneema® HB80 UD laminate. Proposed models have two significant differences from the previous models presented above. Firstly, both models use combination of shell (for yarns) and solid (for resin) elements. Using of shell elements instead of solid elements for the yarns allows to reduce an overall computational cost of the models and realistically catches dynamic processes in fibre bundle [23]. The second feature is using of common nodes between yarns and matrix instead of contact algorithm that decreases an overall amount of contacts and more realistically reflects a material structure. The models successfully reflected the main failure modes in the real panels including the fracture of fibres, delamination, fabric/matrix debonding, yarns pull-out, etc. A reasonable agreement between the numerical and experimental ballistic curves was obtained.

The organization of the paper is as follows: the data about materials and results of ballistic tests are presented in Section 2. The numerical models of the composite materials are described in Section 3. The results of numerical simulations are discussed in Section 4. Section 5 gives a conclusion.

1. Materials and ballistic tests

1.1. Composite laminates

In this work, two types of composite panels were investigated. The first type of panel was made of single layers of Dyneema® HB80 prepreg. Each single layer of Dyneema® HB80 with the areal density of 145 g/m^2 manufactured by DSM (Netherlands) is a $(0/90)_2$ lay-up composed of approximately 84% fibres (in weight) and 16% polyurethane matrix [27]. Ultra-high-molecular-weight polyethylene (UHMWPE) [28] fibres SK76 are used for prepregs [29].

The second type of composite material was an aramid plain weave fabric KV110P/low density polyethylene (LDPE) composite. The aramid fabric with areal density of 110 g/m^2 was produced by JSC «Kamenskvolokno» (Russian Federation) [30]. LDPE films with a thickness of 0.040 mm and areal density of 38 g/m^2 were placed between fabric layers and used as a thermoplastic matrix.

Aramid fabric composite panels were heated up to 145 °C and conditioned at this temperature for 2 h to minimize the temperature gradient. Then all the panels were pressed using the program: 0 … 13 MPa/1 min; 13 MPa/10 min; 13 MPa … 0/1 min. UHMWPE composite panels were heated only to 125 °C due to low melting temperature of PE fibres and pressed under the same program. All the panels had dimensions of 85×85mm. Table 1 contains a brief information about the manufactured laminates for ballistic tests.

Table 1

Properties of the panels for ballistic tests

Material	Areal density (kg/m^2)	Average thickness of panel (mm)	Number of layers
KV110P/LDPE	4,01	3,72	27
Dyneema® HB80	4,35	4,70	30

1.2. Ballistic testing

Ballistic tests were conducted according to GOST R 50744-95 [31] using ∅6.35 mm tempered steel ball with a mass of 1.05 g. A special gunpowder stand for acceleration of projectiles with terminal velocity up to 900 m/s was used. More details about the experimental setup and testing procedures could be found in [32, 33].

Initial (before an impact) and residual (after a target perforation) velocities of the projectile were measured during the experiments. Then the experimental data were fitted by least-square regression according to the classical Lambert-Jonas equation [34]:

$$V_{\mathrm{r}} = \begin{cases} 0 \; if \; V_{\mathrm{i}} < V_{50} \\ A \cdot (V_{\mathrm{i}}^k - V_{50}^k)^{1/k} \; if \; V_{\mathrm{i}} \geq V_{50} \end{cases}, \tag{1}$$

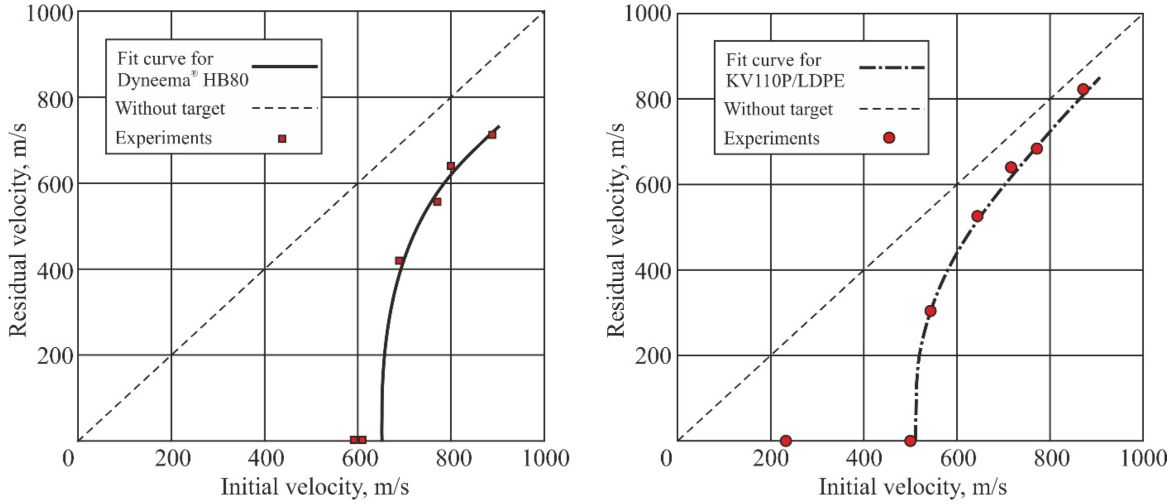
where A, V_{50} and k are three regression parameters. V_{r} and V_{i} are the residual and initial velocities of the projectile, respectively. V_{50} defines incident impact velocity at which there is 50% probability of partial penetration and 50% probability of perforation [4] and it is close to ballistic limit velocity V_{BL} (maximum initial projectile velocity which does not cause full perforation). Therefore, it can be assumed that $V_{\mathrm{BL}} \approx V_{50}$. Table 2 contains the values of the regression parameters for the both types of the tested composite panels.

Table 2

Lambert-Jonas equation parameters for the composite panels

Material	V_{50} (m/s)	A	k
KV110P/LDPE	656	0,87	4,401
Dyneema® HB80	511	1,003	3,089

Fig. 1 shows the residual velocity vs. initial velocity curves according to Lambert-Jonas fits with actual tests measurements.



a *b*

Fig. 1. Ballistic curves for the composite panels: *a* – Dyneema® HB80; *b* – KV110P/LDPE

The panels made of the aramid fabric demonstrated a reducing of back face deflection with the increase of the projectile velocity (Fig. 2).

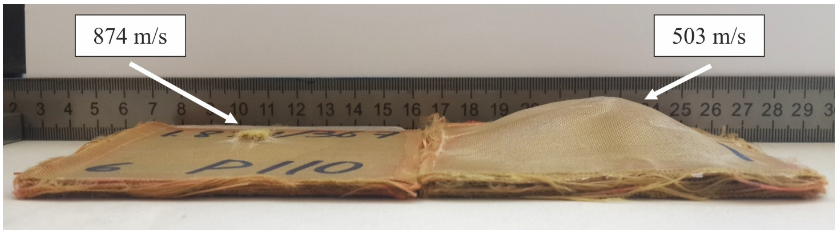


Fig. 2. KV110P/LDPE panels impacted at different velocities

On the front side of all KV110P/LDPE panels, there is a buckling area of front layers with a specific cruciate form (Fig. 3).

Dyneema® HB80 laminates were deformed significantly after the ballistic tests. Fig. 4 shows the back and the front sides of the panel impacted at a velocity of 771 m/s. It is clearly seen that the impact caused extensive delamination of the panel and fibres pull-out (Fig. 4, *b*) as well as buckling and fibre-matrix debonding of the front side layers (Fig. 4, *a*, dashed lines) and fibres fracture.

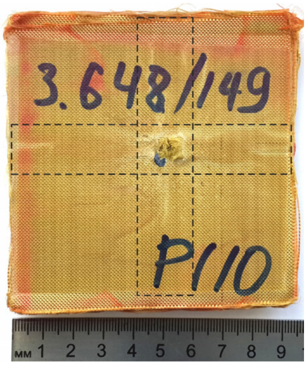
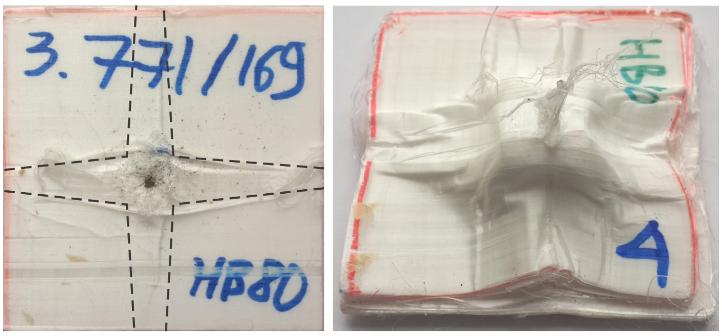


Fig. 3. Buckling area (limited by dashed lines) on impacted side of KV110P/LDPE panel



a *b*

Fig. 4. Dyneema® HB80 laminate impacted at a velocity of 771 m/s: *a* – the front side; *b* – the back side

The experiments showed that during ballistic impact there were several fracture modes in thermoplastic composites. It is difficult to reproduce all the observed deformation and failure mechanisms using continuum approach, and mesoscale models seem to be promising in this case.

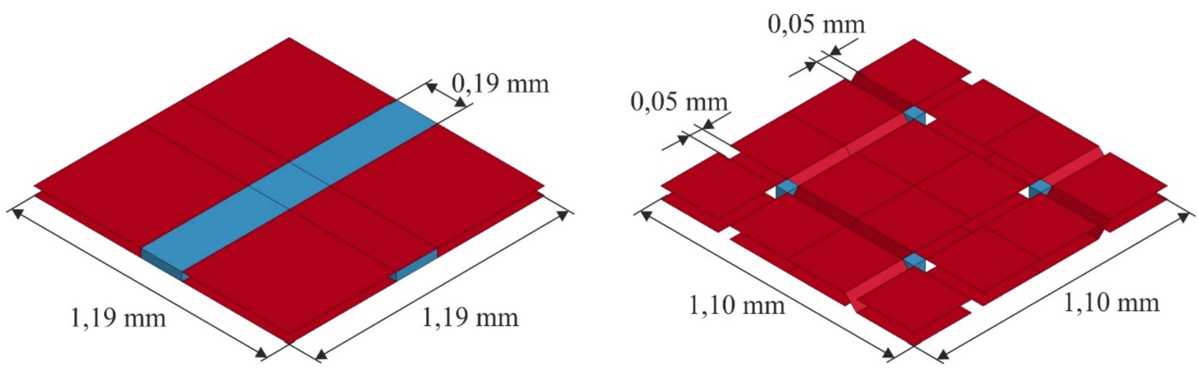
2. Descriptions of mesoscale models

The mesoscale models for both (plain weave and cross-plied) architectures of the ballistic composites were created using commercial finite-element package ANSYS and LS-PrePost. All the computations were performed with LS-DYNA finite element code using the supercomputer «RSC Tornado SUSU» [35].

2.1. Geometry

The first step to create the geometry of the models was to determine fibres and matrix content by weight. It was mentioned that the Dyneema® HB80 single layer (i.e. four plies) had an areal density of 145 g/m^2. Densities of UHMWPE fibres and Polyurethane matrix were assumed equal to 970 kg/m^3 [27, 28]. A simple estimation provides a layer thickness of 0,157 mm. KV110P/LDPE panels had 74% aramid fibres by weight and a layer thickness of 0,138 mm. Areal density of a layer was 148 g/m^2. It was assumed that densities of an aramid fibres and LDPE matrix were 1440 kg/m^3 [4] and 937 kg/m^3.

Representative volume elements (RVE) were used to construct the composite architectures. Both architectures were meshed using square shell elements (ELFORM = 10) to represent the yarns and 8-nodes solid elements (ELFORM = –1) for the matrices. The RVE for the Dyneema® HB80 single layer consists of bundling fibres into strips with width of 1 mm (Fig 5, *a*) and gap between the strips of 0,19 mm filling with a matrix. As in the previous paper [35] four plies were consolidated into two because of computational reasons so the strip thickness was 0,0784 mm. The RVE for KV110P/LDPE lamina (Fig 5, *b*) was a bit more complicated due to a plain weave structure of the aramid fabric. According to the manufacturer data [30], KV110P aramid fabric with an areal density of 110 g/m^2 has about ~170–180 strands in the warp and weft directions on each 100 mm. In this regard, the width of the yarn bundle was equal to 0.5 mm.



a *b*

Fig. 5. Representative volume elements: *a* – for Dyneema® HB80; *b* – for KV110P/LDPE

A yarn thickness was 0,08 mm: each two layers were consolidated into one in order to reduce a computational cost of the model. This approach was successfully used for the modelling of aramid fabric [37]. The gap between adjacent yarns was 0,05 mm. KV110P has enough dense weave structure and it was assumed that LDPE matrix fills only pores between yarns and does not impregnate fibre bundles. Thus LDPE matrix between aramid strands was not explicitly modelled and taken into account using special option MAREA in card *SECTION_SHELL (MAREA is a non-structural mass per unit area). For the RVE presented in this paper MAREA was 18,9 g/m^2.

The geometry of the representative volume elements allows to perform not only full scale simulations of a target but also to use symmetry properties and consider only a ¼ part of a model. Shell and solid elements in both RVE had common nodes.

In addition, RVE for Dyneema® HB80 with an increased width of strips (2 mm) was also created to determine sensitivity of the model on the mesh size.

2.2 Material models and contacts

The main advantage of mesoscale models is a possibility to use simple constitutive models of materials.

Simulations of the ballistic impact onto Dyneema® HB80 were performed with resin properties taken from [27]: the material was assumed to be a homogenous isotropic and perfectly elastic plastic (*MAT_PLASTIC_KINEMATIC). Young modulus of matrix was 70 MPa, Poisson ratio of 0.45, yield strength of 3.5 MPa and failure at an effective plastic strain of 10%. The material of the fibres was linear elastic up to failure (*MAT_LINEAR_ELASTIC).

In previous paper [35], the UHMWPE Young modulus of 200 GPa was used according to Utomo [38]. Recent research [39] showed that a value of 120-130 GPa is more realistic. On this reason, the simulations of Dyneema® HB80 were performed with a fibre Young modulus of 132 GPa and fibre failure stress of 3,8 GPa (Chocron et al. [27]).

The polymer matrix in KV110P/LDPE composite was also modelled using perfectly elastic plastic material model with Young modulus of 400 MPa, Poisson ratio of 0.45, a yield strength of 12 MPa and failure at an effective plastic strain of 10%. An aramid yarn's modulus of elasticity was equal to 130 GPa [32]. A failure stress was increased to 4,5 GPa (on ~30% more than the static value [32]) because in paper [40] it was shown that fibres strength increased at high strain rates.

The projectile material being considered was a steel with a linear elastic behaviour, elastic modulus of 200 GPa and Poisson ratio of 0.3.

Two contact algorithms were used. The first type being specified for projectile-composite interaction was *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. The second contact type was *CONTACT_AUTOMATIC_SINGLE_SURFACE to define fibre-fibre interaction. Values of friction coefficient being used for the all simulations are presented in Table 3.

Table 3

Values of friction coefficients used in the simulations

Material	Friction coefficient	
	Projectile-Composite	Fibre-Fibre
Dyneema® HB80	0,02 [27]	0,02 [27]
KV110P/LDPE	0,2 [24]	0,2 [21]

Contacts between fibres and matrices were not specified. Fibre-matrix interaction was realised through common nodes in RVE.

3. Results of numerical simulations and discussion

Transverse impact simulations on the both types of the composite laminates were performed at different velocities of the projectile. Lambert-Jonas fit curves of the experimental data with actual computational results are shown on Fig. 6.

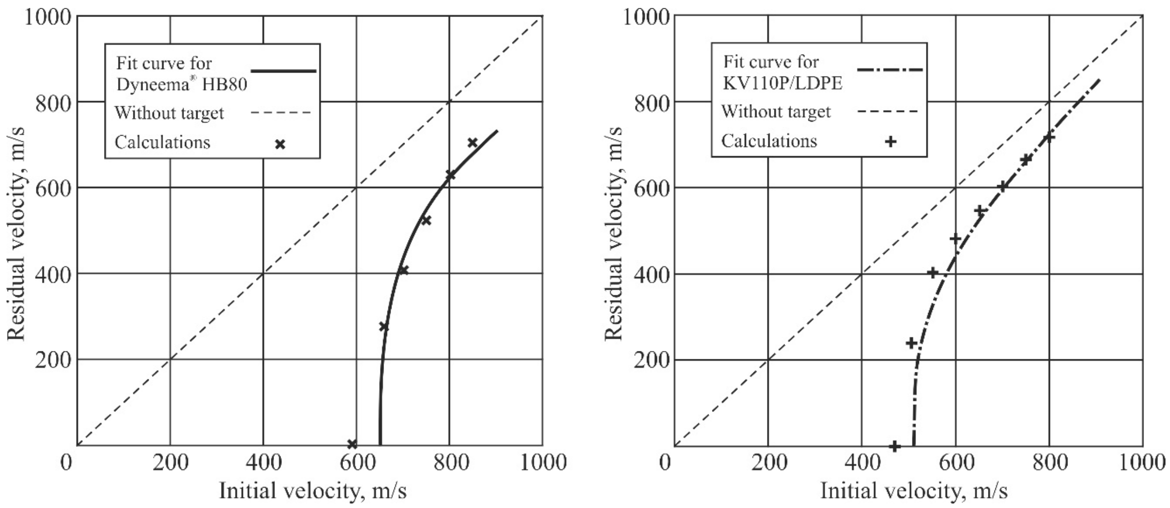


Fig.6. Lambert-Jonas fit curves of the experimental data with actual computational results for *a* – Dyneema® HB80; *b* – KV110P/LDPE

3.1. Mesoscale modelling of Dyneema® HB80 panel

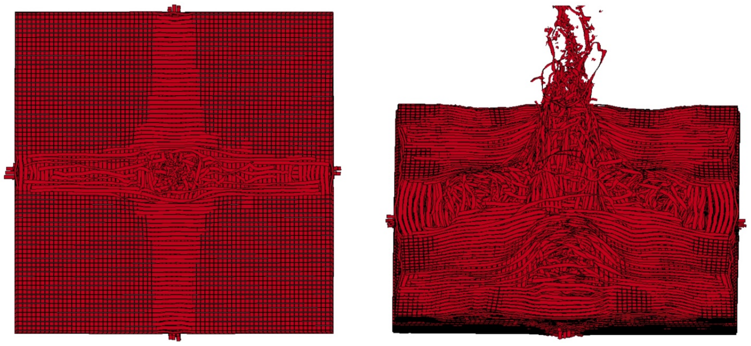
The model with fibres properties taken from the paper of Chocron et al. [27] predicted a stopping of projectile at a velocity of 590 m/s. Thus, the ballistic limit value being obtained was about 590-610 m/s. It should be pointed out that bundling fibres into the strips is only a rough approximation to the real material structure. This fact can explain disagreement between calculated residual velocities and experimental ones. To study the influence of strip width on a projectile residual velocity two runs were performed. Strip widths were 1 mm and 2 mm respectively. The initial projectile velocity was 700 m/s. Fig. 8 compares the velocity vs. time history for the projectile for both computations. It is clear that model with narrow strips demonstrated better performance. Numerical model is sure to be overpredicted with further reducing of strip width. Such a behaviour is a result of simple fibre and matrix material model without thermal effects. They influence greatly on the panel behaviour during impact [41] as UHMWPE fibres have a low melting temperature (about 150 °C) [28]. Thus, it is meaningless to decrease strip width without taking into account thermal softening of the material. Furthermore, computational cost of such model will be enormous. The model with the strip width of 1 mm allows to obtain a realistic panel behaviour, reasonable agreement with the experiments and acceptable computational time.

The model predicted formation of buckling area on the front side of the panel (Fig. 7, *a*) as well as significant deflection of the back side and the delamination on the edges (Fig. 7, *b*) that agree well with the experimental results (see Fig. 4).

3.2. Mesoscale modelling of KV110P/LDPE panel

The proposed mesoscale model of KV110P/LDPE panel also demonstrated both qualitative and quantitative agreement with the experiments. For example, an experimentally obtained ballistic limit velocity for the composite was about 510 m/s (see Fig. 6, *b*). The models give a value of 480 m/s. Moreover, because of a high melting temperature of aramid fibres (about

550 °C) [39] there is no such a significant influence of thermal effects on the ballistic performance of the panel in comparison with Dyneema® HB80 laminate. In this case, the assumption that a fibre bundle is linear elastic up to failure seems to be realistic.



a *b*

Fig. 7. An example of a numerical simulation of Dyneema® HB80 laminate impacted at a velocity of 770 m/s: *a* – front side; *b* – back side

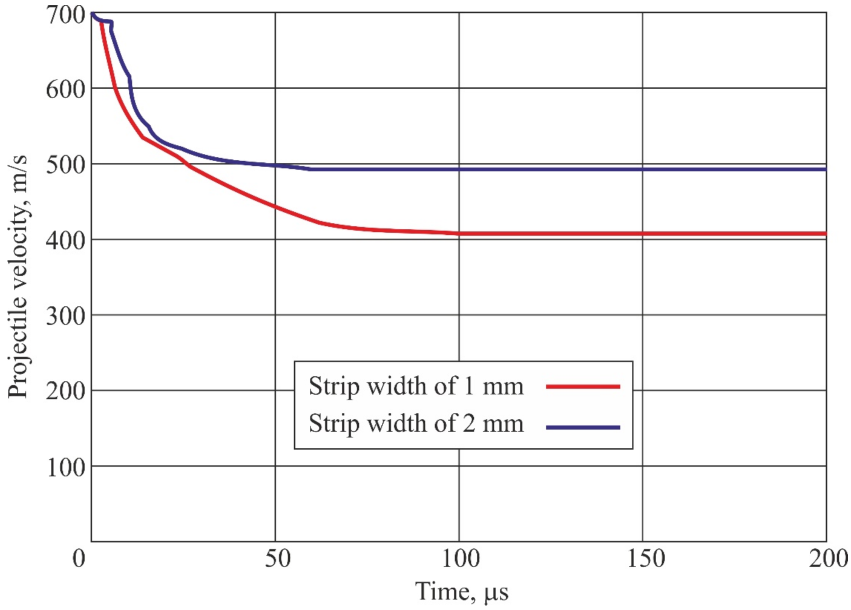


Fig. 8. Relations between the projectile velocity and time history for the models with different strip widths

An example of numerically obtained deformed shape of the panel impacted at a velocity of 550 m/s is shown on Fig. 9.

a *b*

Fig. 9. An example of a numerical simulation of KV110P/LDPE laminate impacted at a velocity of 550 m/s: *a* – front side; *b* –sectional view

A velocity reduction leads to the increase of the back face bulging (Fig. 10) and the area of delamination. It is also seen that the amount of fires subjected to pull-out is negligible even at velocities close to the ballistic limit. This is in a good agreement with experimental data (see Fig. 2).

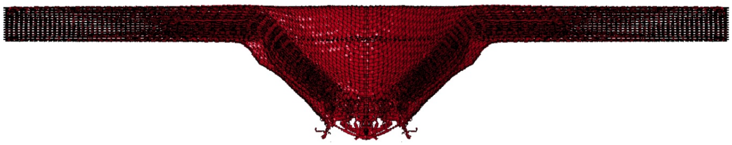


Fig. 10. Sectional view of KV110P/LDPE laminate impacted at a velocity of 500 m/s

Conclusion

In this paper, mesoscale models of two common compliant armour-grade composites for ballistic impact simulations were developed. RVE approach for constructing composite architecture was used in the models. The models were validated by comparing experimental ballistic curves with experimental ones.

Yarn-level modelling of KV110P/LDPE gave a good agreement with experimental data even with consolidated layers. Mesoscale modelling of UHMWPE composite with UD structure is also possible but including thermal effects into calculations can increase their possibilities. Nevertheless, both models can predict the main fracture mechanisms in composite panels and allow to define projectile residual velocities with reasonable accuracy.

…………………..

This work was carried out in South Ural State University (National Research University) with a financial support of Russian Science Foundation (project No. 14-19-00327).

References

1. Cheeseman B.A., Bogetti T.A. Ballistic impact into fabric and compliant composite laminates. *Composite Structures*. 2003, vol. 61, pp. 161-173. DOI: 10.1016/S0263-8223(03)00029-1

2. Kharchenko E.F., Ermolenko A.F. Composite, textile and combined armor materials. Moscow: Publ. of TsNIISM, 2014, 332 p.

3. Grigorian V.A., Kobylkin I.F., Mirinin V.M., Chistyakov E.N. Materialy i zashchitnye struktury dlya lokal'nogo i individual'nogo bronirovaniya. Moscow: RadioSoft, 2008, 406 p.

4. Bhatnagar A. Lightweight ballistic composites – military and law-enforcement applications. Cambridge: Woodhead Publishing Ltd., 2006, 482 p.

5. Abrate S. Impact Engineering of Composite Structures. 2011, Springer. 403 p. DOI: 10.1007/978-3-7091-0523-8

6. Krishnan K., Sockalingam S., Bansal S., Rajan S.D. Numerical simulation of ceramic composite armor subjected to ballistic impact. *Composites: Part B*. 2010, vol. 41, pp. 583-593. DOI: 10.1016/j.compositesb.2010.10.001

7. Bürger D., Alfredo Rocha de Faria, Sérgio F.M. de Almeida, Francisco C.L. de Melo, Maurício V. Donadon. Ballistic impact simulation of an armour-piercing projectile on hybrid ceramic/fiber reinforced composite armours. *International Journal of Impact Engineering*. 2012, vol. 43, pp. 63-77. DOI: 10.1016/j.ijimpeng.2011.12.001

8. Tan P. Numerical simulation of the ballistic protection performance of a laminated armor system with pre-existing debonding/delamination. *Composites: Part B*. 2014, vol. 59, pp. 50-59. DOI: 10.1016/j.compositesb.2013.10.080

9. Tasdemirci A., Tunusoglu G., Güden M. The effect of the interlayer on the ballistic performance of ceramic/composite armors: Experimental and numerical study. *International Journal of Impact Engineering*, 2012, vol. 44, pp. 1-9. DOI: 10.1016/j.ijimpeng.2011.12.005

10. Iannucci L., Pope D. High velocity impact and armour design. *eXPRESS. Polym Lett*, 2011, vol. 5(3), pp. 262-272. DOI: 10.3144/expresspolymlett.2011.26

11. Soykasap O., Colakoglu M. Ballistic performance of a Kevlar-29 woven fiber composite under varied temperatures. *Mechanics of Composite Materials*. 2010, vol. 46 (1), pp. 35-42. DOI: 10.1007/s11029-010-9124-3

12. Dimitrienko Yu.I., Belenovskaya Yu.V., Aniskovich V.A. Numerical simulation of shock-wave deformation of flexible armored composite materials. *Science and Education*. 2013, vol. 12, pp. 471-490. DOI: 10.7463/1213.0665297

13. Grujicic M, Pandurangan B., Koudela K.L., Cheeseman B. A computational analysis of the ballistic performance of light-weight hybrid composite armors. *Applied Surface Science*. 2006, vol. 253, pp. 730-745. DOI: 10.1016/j.apsusc.2006.01.016

14. Nguyen L.H., Lässig T.R, Ryan S., Riedel W., Mouritz A.P., Orifici A.C. A methodology for hydrocode analysis of ultra-high molecular weight polyethylene composite under ballistic impact. *Composites: Part A*, 2016, vol. 84, pp. 224-235. DOI: 10.1016/j.compositesa.2016.01.014

15. Lässig T., Nguyen L., May M., Riedel W., Heisserer U., H. van der Werff, Hiermaier S. Non-linear orthotropic hydrocode model for ultra-high molecular weight polyethylene in impact simulations. *International Journal of Impact Engineering*. 2015, vol. 75, pp. 110–122. DOI: 10.1016/j.ijimpeng.2014.07.004

16. Bandaru A.K., Chavan V.V., Ahmad S., Alagirusamy R., Bhatnagar N. Ballistic impact response of Kevlar® reinforced thermoplastic composite armors. *International Journal of Impact Engine ering*, 2016, vol. 89, pp. 1-13. DOI: 10.1016/j.ijimpeng.2015.10.014.

17. Segala D.B., Cavallaro P.V. Numerical investigation of energy absorption mechanisms in unidirectional composites subjected to dynamic loading events. *Computational Materials Science*, 2014, vol. 81, pp. 303-312. DOI: 10.1016/j.commatsci.2013.08.039.

18. Grujicic M., Arakere G., He T., Bell W.C., Cheeseman B.A., Yen C.-F., Scott B. A ballistic material model for cross-plied unidirectional ultra-high molecular-weight polyethylene fiber-reinforced armor-grade composites. *Materials Science and Engineering: A*. 2008, vol. 498 (1-2), pp. 231-241. DOI: 10.1016/j.msea.2008.07.056.

19. Nilakantan G. Filament-level modeling of Kevlar KM2yarns for ballistic impact studies. *Composite Structures*. 2013, vol. 104, pp. 1-13. DOI: 10.1016/j.compstruct.2013.04.001.

20. Tan V.B.C., Ching T.W. Computational simulation of fabric armour subjected to ballistic impacts. *International Journal of Impact Engineering*. 2006, vol. 32, pp. 1737-1751. DOI: 10.1016/j.ijimpeng.2005.05.006.

21. Chocron S., Figueroa E., King N., Kirchdoerfer T., Nicholls A.E., Sagebiel E., Weiss C., Freitas C.J. Modeling and validation of full fabric targets under ballistic impact. *Composites Science and Technology*. 2010, vol.70, pp. 2012-2022. DOI: 10.1016/j.compscitech.2010.07.025.

22. Nilakantan G., Gillespie Jr. J.W. Ballistic impact modeling of woven fabrics considering yarn strength, friction, projectile impact location, and fabric boundary condition effects. *Composite Structures*. 2012, vol. 94, pp. 3624-3634. DOI: 10.1016/j.compstruct.2012.05.030.

23. Dolganina N.Yu., Sapozhnikov S.B. Study of the influence of type weave for strength of the textile armor panel at the local impact. *Bulletin of the South Ural State University Series "Mechanical Engineering Industry"*. 2013, vol. 13 (2), pp. 95-104.

24. Gopinath G., Zheng J.Q., Batra R.C. Effect of matrix on ballistic performance of soft body armor. *Composite Structures*. 2012, vol. 94, pp. 2690-2696. DOI:10.1016/j.compstruct.2012.03.038.

25. Bresciani L.M., Manes A., Ruggiero A., Iannitti G., Giglio M. Experimental tests and numerical modelling of ballistic impacts against Kevlar 29 plain-woven fabrics with an epoxy matrix: Macro-homogeneous and Meso-heterogeneous approaches. *Composites Part B*. 2016, vol. 88, pp. 114-130. DOI: 10.1016/j.compositesb.2015.10.039.

26. Gama B.A., Gillespie Jr. J.W. Finite element modeling of impact, damage evolution and penetration of thick-section composites. *International Journal of Impact Engineering*. 2011, vol. 38, pp. 181-197. DOI: 10.1016/j.ijimpeng.2010.11.001

27. Chocron S., Nicholls A.E., Brill A., Malka A., Namir T., Havazelet D., H. van der Werff, Heisserer U., Walker J.D. Modeling unidirectional composites by bundling fibers into strips with experimental determination of shear and compression properties at high pressures. *Composites Science and Technology*. 2014, vol. 101, pp. 32-40. DOI:10.1016/j.compscitech.2014.06.016

28. Bunsell A.R. Handbook of Tensile Properties of Textile and Technical Fibres. Cambridge: Woodhead Publishing Ltd, 2009. 696 p.

29. Chocron S., King N., Bigger R., Walker J.D., Heisserer U., H. van der Werff. Impacts and waves in Dyneema® HB80 strips and laminates. *Journal of Applied Mechanics*. 2013, vol. 80 (3), pp. 472-481. DOI: 10.1115/1.4023349

30. http://www.aramid.net/products/kv110p

31. GOST R 50744-95. Armor Clothes. Classification and general technical requirements. Moscow: State Standartization Committe of Russian Federation; September 2013. p. 11.

32. Sapozhnikov S.B., Kudryavtsev O.A., Zhikharev M.V. Fragment ballistic performance of homogenous and hybrid thermoplastic composites. *International Journal of Impact Engineering*, 2015, vol. 81, pp. 8-16. DOI: 10.1016/j.ijimpeng.2015.03.004.

33. Sapozhnikov S.B., Kudryavtsev O.A. Compact accelerator for ballistic testing. *Bulletin of the South Ural State University Series "Mechanical Engineering Industry"*. 2012, vol. 20 (33), pp. 139-143.

34. Lambert J.P., Jonas G.H. Towards standardization in terminal ballistics testing: velocity representation. BRL Report No. 1852. Aberdeen Proving Ground, MD: U.S. Army Ballistic Research Laboratories; 1976. p. 51.

35. http://supercomputer.susu.ru/en/computers/tornado/

36. Sapozhnikov S., Kudryavtsev O. Modeling of thermoplastic composites used in protective structures. *Mechanics of Composite Materials*. 2015, vol. 51(4), pp. 419-426. DOI: 10.1007/s11029-015-9513-8.

37. Dolganina N.Yu., Sapozhnikov S.B. Design of new constructions of textile armor panel using supercomputing. *Bulletin of the South Ural State University Series "Mechanical Engineering Industry"*. 2011, vol. 254 (37), pp. 71-81.

38. Utomo B.D. High-Speed Impact Modeling and Testing of Dyneema Composite, PhD thesis, Delft (2011).

39. Chen X. Advanced Fibrous Composite Materials for Ballistic Protection, 1st Edition. Cambridge: Woodhead Publishing Ltd, 2016. 548 p.

40. Tan V.B.C., Zeng X.S., Shim V.P.W. Characterization and constitutive modeling of aramid fibers at high strain rates. *International Journal of Impact Engineering*. 2008, vol. 35, pp. 1303-1313. DOI: 10.1016/j.ijimpeng.2007.07.010

41. Greenhalgh E.S., Bloodworth V.M., Iannucci L., Pope D. Fractographic observations on Dyneema® composites under ballistic impact. *Composites: Part A*. 2013, vol. 44, pp. 51-62. DOI: 10.1016/j.compositesa.2012.08.012