Dissipation mechanisms and FE-modelling of penetration processes in multilayer aramid barriers of various weaving types

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Abstract. Experimental investigation and computational estimation of the ballistic resistance properties of the multilayer fabric barriers which include layers with various weaving types carried out. Plain and four patterns of twill weave fabrics were concerned. The dynamic interaction of multilayer woven barriers with two forms of impactors is considered, and the processes of energy dissipation are investigated using the FE-modelling of impact processes. Verification of the FE-models is carried out by full-scale ballistic experiments, and the simulation error is estimated. The contribution of various mechanisms to the energy dissipation of the impactor is evaluated. The influence of the placement of layers with different weaving types in the woven barriers on the impactor velocity after the rupture is analyzed numerically. The advantages of some particular combinations of weaving types placement in comparison with the uniform barriers with the same number of layers is shown.

1. Introduction
Textile reinforcements, including woven, braided, knitted, and non-woven fabrics are widely used in aerospace, automotive, civil and other industries. The textile industry offered the large variety of weaving types for the woven fabrics: plain, basket, twill and satin. Some examples of biaxial orthogonal woven fabrics are presented in figure 1. The plain weave remains the most common used and discussed weaving type. Fill (weft) and warp yarns in the plain weave are interlaced in a "one under–one over" pattern. As a result, the plain weave fabrics are highly consolidated, though their draping properties cannot always reproduce complicated mold shapes because of wrinkling. The twill woven pattern is visually characterized by continuous rib diagonals on the faces of the fabric (figure 1). An approach to the geometrical modelling of weaving types with a number of parameters for the further generation of the 3D internal geometry of the woven fabric families is presented, for example, in [1, 2]. Sometimes a special weaving type among twills is defined (basket weave), where fill and warp yarns are interlaced in an "m under–m over" pattern. The twill weave fabrics (as well as even less consolidated satin weaving types) demonstrate improved draping properties.
It can be expected that twill and satin weave fabrics provide worse impact resistance. The yarns in the less consolidated fabrics, indeed, easily slide apart, pull out, enveloping the blunt impactors. Nevertheless, the dissipation in impact problems is governed by the interaction of many simultaneous mechanisms including friction, yarns moving and rupture [3, 4]. The weaving type influences strongly the number of yarns that become involved in the motion and deformation, extending or decreasing the dissipation properties of the barrier. It is observed in experiments that sometimes the fabrics with the looser weaving pattern show better ballistic efficiency [5, 6]. It is shown in that for twill weave fabrics the loss of impactor velocity can be up to 22% higher than for the plain weave fabrics. It should be noted, however, that in all the experiments presented in [5] the satin weave fabrics demonstrate worse impact resistance in comparison with the plain weaving since the yarns slide apart at the impact point.

This work is devoted to the search for the best combination of layers of plain and four types of twill weave from the point of protection from impactors of ogival and spherical forms. For this, FE-models, verified by the results of full-scale ballistic experiments, have been created and the contribution of various mechanisms to the dissipation of the energy of impactors has been estimated.

2. FE-modelling of woven fabrics and the verification of models
The five weaving types which this paper concern with are plain and four patterns of twill weave fabrics (figure 1) made of aramid fibers. The elastic properties and limit characteristics of aramid fibers were obtained in the previous investigations as well as geometry properties [7]. The cross sections of the yarns are ellipses with semiaxes depending on the type of weaving, but with a constant area of 0.033 mm$^2$ and an effective area (in the loaded state) of 0.022 mm$^2$.

Static and dynamic interlayer friction coefficients for fabric samples of different types of weaving were determined in two kinds of experiments 1) pulling out the fabric layer for pulling out from a multilayer structure of fabrics under the conditions of controllable transverse compression loading [8] and 2) sliding one fabric layer against the other under the conditions of transverse compressive load.

The values of the static friction coefficients for all possible combinations of weaving types under consideration are given in table 1. The dynamic coefficients vary little and are obtained to be equal 0.2. The comparative mass of samples of different types of weaving is presented in table 2. As it can be seen from the table 2, the less consolidated twill fabrics are, indeed, appreciably lighter than the plain fabric: the difference in the weight can exceed 20%.

| Type of weaving | Plain | Twill 3/3 | Twill 1/2 | Twill 1/4/4/1 | Twill 2111/2111 |
|-----------------|-------|-----------|-----------|---------------|-----------------|
| Plain           | 0.3   | 0.24      | 0.24      | 0.27          | 0.26            |
| Twill 3/3       | 0.24  | 0.26      | 0.21      | 0.25          | 0.31            |
| Twill 1/2       | 0.24  | 0.21      | 0.26      | 0.27          | 0.3             |
| Twill 1/4/4/1   | 0.27  | 0.25      | 0.27      | 0.3           | 0.29            |
| Twill 2111/2111 | 0.26  | 0.31      | 0.3       | 0.29          | 0.3             |

Table 1. Static interlayer friction coefficients for fabrics of different weaving types.
Figure 1. Types of weaving at the magnification and corresponding FE-models on the base of cable beam elements.

Table 2. Comparison of masses for fabrics of different weaving types.

| Type of weaving    | Sample 150x150 mm weight (g) | Weight relative to the plain (%) |
|--------------------|-------------------------------|---------------------------------|
| Plain              | 3.8                           | 100                             |
| Twill 3/3          | 3.3                           | 86.8                            |
| Twill 1/2          | 2.7                           | 71.1                            |
| Twill 1/4/4/1      | 3                             | 78.9                            |
| Twill 2111/2111    | 3                             | 78.9                            |

Based on these characteristics, the corresponding computer models were created in the FE-program LS-Dyna using elastic beam elements (material model 071_Cable_Discrete_Beam). This models reproduce the effective cross-sectional area of yarns, the geometry of various types of weaving, the elastic properties of fill and warp yarns. The fracture criterion for yarns is the attainment of ultimate tensile deformation. The specific values of the axial modulus of elasticity and the limiting value of deformation are given in the table 3. All the examined fabrics were woven from the same yarns, however, during the weaving process, the yarns are damaged in various ways, which causes a dispersion of properties.
Table 3. Elastic modulus and limiting deformation for yarn from different types of weaving.

| Type of weaving      | E (GPa) | Limit stress (GPa) | Limit deformation |
|----------------------|---------|--------------------|-------------------|
| Plain fill           | 64      | 3.2                | 0.05              |
| Plain warp           | 57.5    | 2.3                | 0.04              |
| Twill 3/3 fill       | 55.1    | 2.15               | 0.039             |
| Twill 1/2 warp       | 60.4    | 3.2                | 0.053             |
| Twill 1/2 fill       | 75      | 3.3                | 0.044             |
| Twill 1/4/4/1 warp   | 76.8    | 1.92               | 0.025             |
| Twill 1/4/4/1 fill   | 69.5    | 2.78               | 0.04              |
| Twill 2111/2111 warp | 62.7    | 2.07               | 0.033             |
| Twill 2111/2111 fill | 81.3    | 3.09               | 0.038             |

FE-modelling of penetration of four- and ten-layer protective barriers of plain weaving with an ogival-shape impactor (weighing 8.2 grams) were verified according to the full-scale experiment results which were carried out using the ballistic test equipment of the Institute of Mechanics of the Lobachevsky State University of Nizhni Novgorod (figures 2, 3). The full-scale experiment error can be estimated on the base of the linear approximation of the dependence of the post-impact indenter velocity on its initial velocity. This estimation is calculated as

\[ \delta = \frac{|v_r - v_{th}|}{v_r}, \]

where \( v_r \) is the experimental post-impact velocity, and \( v_{th} \) is the value of the post-impact velocity obtained from the linear approximation of experimental data. The maximum experiment error is 3.4% for four-layer samples and 2.3% for ten-layer samples. The upper and lower linear estimates of the dependence of the post-impact velocity on the initial impactor speed is determined on the base of these values and, as it is shown in figures 2 and 3, all the experimental points lay within this interval. The results of numerical modeling for the plain fabric barriers are located within the error estimates of 7.8% and 9.8% respectively. At the same time, the values of the post-impact velocities obtained in numerical modeling in all the calculations performed turned out to exceed the experimental values (therefore, only the upper bound is shown in the graphics). Thus, the numerical modeling error in our case can be consider as an additional safety factor. In this paper, it is considered that the order of the modeling error remains the same for models with other types of weaving.

The results of penetration process modeling for four-layer samples are presented in table 4 and in figure 4. Though the post-impact impactor velocities are close enough to the initial, and the protective properties of the four-layer fabric barriers are not very high for the initial velocity interval considered, nevertheless, the samples made of twill 1/2 fabric are not completely penetrated. The post-impact velocities in table 4 and in figure 4 are therefore compared at time 1e-4 sec. The best protective behaviour is shown by four-layer samples of twill 3/3 and twill 1/2 and it will be further shown that the result remains the same even for models with more number of layers.
Figure 2. FE-modelling results for impactor velocity in penetration process and the comparison with the obtained experimental data. Four-layer fabric samples.

Figure 3. FE-modelling results for impactor velocity in penetration process and the comparison with the obtained experimental data. Ten-layer fabric samples.
Table 4. FE-modelling results for penetration of 4-layers fabric samples. Initial velocity of impactor is 294 m/s.

| Type of weaving | Impactor velocity at 1e-4 s (m/s) | Decreasing of speed (m/s) |
|-----------------|----------------------------------|--------------------------|
| Plain           | 286.8                            | 7.2                      |
| Twill 3/3       | 284.7                            | 9.3                      |
| Twill 1/2       | 273.2                            | 20.8                     |
|                 |                                  | (no complete penetration)|
| Twill 1/4/4/1   | 289.4                            | 4.6                      |
| Twill 2111/2111 | 287.8                            | 6.2                      |

Figure 4. FE-modelling results for penetration of 4-layers fabric samples.
3. Ballistic resistance of the multilayer woven barriers and its optimization using various weaving style combinations

The fabrics with the looser weaving pattern, such as twills, as it seems in the experiments and in our FE-simulations, can reveal better ballistic efficiency. At the impact, yarns in these fabrics are not predominantly torn but often slide apart, enveloping the impactor. Similarly, fabrics with 3D weaving types do not always provide the expected high dissipation properties, because the constraints of the relative yarn motion can lead to premature yarn rupture [6]. Therefore, it is possible under certain loading conditions that the application of non-plain weaving type fabrics as a structural part of the ballistic barriers can provide an improvement in common dissipation properties.

The combined multilayer samples, including fabrics with plain and twill 3/3 type of weaving were first consider as the most promising from the point of view of the final manufacturer. The results of the FE-modelling for penetration of this combined samples by the ogival-shape impactor are shown in table 5. In the following, to identify the combinations of fabric alphanumeric abbreviations will be used in which the letter "P" means a layer of a plain weave, the letter "S" - twill 3/3, the letter "T" - twill 1/2, and the number after the letter means the total number of layers of such a weaving type laid in a row. The designation "S/P10" assumes an interchange of layers of twill 3/3 and plain weave for ten layers (one layer of plain, then one layer of twill 3/3, and so on). Despite the fact that the results of penetration of four-layer samples differ slightly, the observed effects are observed and grow for ten-layer samples. For the uniform samples consisting of only one type of fabric, post-impact velocities differ slightly (the speed drop of impactor is 15.8 m/s for P10, and 16.5 m/s for S10 (table 5)), but the use of combined protective barriers can result in increasing or in decreasing of post-impact indenter speed. As it can be noted, the barrier properties deteriorate when the frequent alternation of plain and twill layers exists, e.g., for the sample S/P10 impactor speed drop is only 9.5 m/s (table 5). At the same time, the combination of layers S3P5S2 (a rare alternation) improves the protective properties (the impactor speed drop is 31.5 m/s (table 5)).

**Table 5.** FE-modelling results for penetration of combined plain/twill 3/3 samples. Initial velocity is 294 m/s.

| Four-layer package | Post-impact indenter speed (m/s) | Ten-layer package | Post-impact indenter speed (m/s) |
|--------------------|----------------------------------|-------------------|----------------------------------|
| P4                 | 287                              | P10               | 278.2                            |
| S4                 | 285.7                            | S10               | 277.8                            |
| P2S2               | 285                              | P5S5              | 271.9                            |
| S2P2               | 286                              | S5P5              | 271.9                            |
| P/S4               | 288.2                            | P/S10             | 283.7                            |
| S/P4               | 289.3                            | S/P10             | 284                              |
| PS2P               | 286                              | P3S5P2            | 277.3                            |
| SP2S               | 287.9                            | S3P5S2            | 269.1                            |
A number of FE-simulations were also made to penetrate the combined obstacles with a spherical impactor of 1 gram in weight with an initial velocity of 842 m/s. The speed value was chosen to retain the total kinetic energy for both forms of impactors. As it can be seen from the results presented in table 6, a rare alternation of layers still leads to the best results, however, frequent alternation (layer through a layer) also leads to improved protective properties, as compared to "pure" combinations P10 and S10.

According to the FE-simulations for penetration processes of uniform barriers, consisting of the layers with the same type of weaving, the best results are shown by twill 1/2 and 3/3 (table 4).

**Table 6.** FE-modelling results for the penetration of combined plain/twill 3/3 ten-layer samples by the spherical impactor. Initial impactor velocity is 842 m/s.

| Ten-layer package | Post-impact speed (m/s) |
|-------------------|-------------------------|
| P10               | 822.5                   |
| S10               | 826.5                   |
| S/P10             | 820                     |
| S3P5S2            | 819                     |

We consider therefore the penetration processes in combined ten-layer barriers of fabrics with these types of weaving (table 5 and figure 4) and a uniform plain fabric barriers. The initial velocity of the impactor is accepted to be 350 m/s, because at a velocity of 294 m/s, the samples containing a 1/2 twill are not completely penetrated, which made a comparison uneasy. As it can be seen in table 7, the best results are demonstrated by the sample T3S5T2 - a speed drop of 21 m/s - which is 2.5 times greater than that of P10 (8.5 m/s). Figure 5 shows computer models for punching samples P10 and T3S5T2. According to the energy dissipation graphs (figures 6, 7), a more loose weave allows the barrier to dissipate more of the impactor energy through the increasing of the kinetic energy of yarns. Dissipation of energy due to friction is constantly growing, dissipation due to kinetic energy has a maximum at the moment of penetration and then decreases (the yarns tend to stop). For plain fabric, this rise and fall of the kinetic energy occurs quickly: the yarns began to move, cling on each other, stopped and this mechanism ceases work. For twill fabrics the yarns are stopping slower because they have more freedom in motion, more fibers are involved in the process, so they accept more total kinetic energy than plain. As a result, the dissipation mechanism, based on the kinetic energy of the yarns, lasts longer for twill fabrics and results in large losses in the speed of the impactor. Moreover, the mass of barriers consisting of different twill weaves is 21% less on average than plain weaves (table 2), therefore, with the same mass, the twill barrier can consist more layers than the plain one.
Figure 5. Computer models of penetration of P10 and T3S5T2 samples. Initial impactor velocity 350 m/s.
Figure 6. Energy dissipation for P10 sample.

Figure 7. Energy dissipation for T3S5T2 sample.
Table 7. FE-modelling results for penetration of combined twill 3/3 / twill 1/2 ten layer fabric samples. Initial impactor velocity is 350 m/s.

| Ten-layer package | Post-impact indenter speed (m/s) |
|-------------------|----------------------------------|
| P10               | 341.5                            |
| S10               | 340.8                            |
| T10               | 337.2                            |
| S3T5S2            | 334                              |
| T3S5T2            | 329                              |

4. Conclusions
In this work, computer models were created for penetration of multilayer aramid fabric protective barriers of five different types of weaving and their combinations by impactors of the ogival and spherical forms. For this purpose, the geometry of the yarns in fabrics was determined, experiments were conducted to determine their elastic and limiting properties, as well as to determine the coefficients of interlayer friction. The obtained models are verified by full-scale ballistic experiments, the error is estimated. The calculations of penetration of four- and ten-layer protective barriers with a combined type of weaving have been carried out. It has been shown that the best results are shown by the sample T3S5T2 (three layers of twill 1/2, five layers of twill 3/3, two layers of twill 1/2) with a more loose weave allowing to absorb more of the energy of the impactor due to the kinetic energy of the yarns. An additional advantage of such samples is a smaller weight relative to the plain weaving.

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