

Influence of a Woven Fabric Structure on the Propagation Velocity of a Tension Wave

Abstract

This article presents the results of research into the propagation velocity of a tension wave in a woven fabric with dependence on the parameters of its structure, such as the weave and the density of weft insertion. The investigation carried out allowed the selection of woven fabric structures which are characterised by the highest velocity of propagation of a tension wave. This velocity has decisive importance in the case of woven fabrics used as anti-impact barriers in bulletproof vests. Methods of investigation used in this work are presented, as well as a discussion of the results obtained.

Key words: woven fabrics, bulletproof vests, anti-impact properties, geometrical structure, structure parameters, weave, tension wave, propagation velocity.

Introduction

High-tensile strength woven fabrics are one of the elements of individual anti-impact protection systems in the event of the barrier being struck by bullets from different kinds of guns. Very important features of textile fabrics are their high elasticity and low specific mass compared to ceramic and metal barriers. The character of destroying a woven fabric and the amount of energy absorbed by it during the stroke of a missile depends on a number of parameters, such as the material from which the fibres are manufactured, the geometrical structure of the fabric, its surface density, and the number of layers in a multiplayer fabric or fabric packet, among others. Also of great importance are parameters connected with the character of the impact, such as the shape, mass, material, and velocity of the missile, the angle of its stroke, as well as the phenomenon of friction between all elements placed in the field of non-zero tensions during the impact.

During the stroke of a missile onto a flat material in the form of a woven fabric, the energy emitted propagates as a wave with a determined velocity c_f along the weft and warp threads. The wave impedance Z is a quantity characterising the velocity of absorption of the energy emitted by the particular material. The wave impedance is an independent combination of the Young modulus E and density ρ of the material and is described by the formula:

$$Z = \sqrt{E \cdot \rho} \quad (1)$$

On the basis of the material's wave impedance, the factor of ballistic resistance of the particular material is formulated. Faur- Csukat [1] has given the factor of

resistance against a stroke R^2 in the following form:

$$R^2 = w_b \cdot c_f \quad (2)$$

where:

$R = Z$ – is the wave impedance,

w_b – is the energy of breaking of the anti-impact barrier, and

c_f – is the propagation velocity of the tension wave in the anti-impact barrier.

According to this dependency, the efficiency of an anti-impact barrier increases with the increase in its tensile properties and the propagation velocity of the tension wave. In the case of thread used to manufacture ballistic woven fabrics, the propagation velocity of the tension wave is within the range of 6,000 to 10,000 m/s (Table 1) [2].

In the case of an anti-impact barrier manufactured from a woven fabric, the propagation velocity of the tension wave cannot be explicitly assessed in an unlimited direction on the fabric's plane. From the point of view of the penetrator, the normal woven fabric has two dominating directions of tension wave propagation determined by weft and warp threads. Therefore, in principle, in the case of a woven fabric, we may consider only two velocities of tension propagation, this is along the weft and warp. These

velocities may be differentiated even if the woven fabric is manufactured totally from the same raw material. The asymmetry may be caused by the technological process of weaving itself, for example, different tensions of the weft and warp threads during weaving cause their different working-in. In the case of intermediate directions, the tension wave propagates to the subsequent nodes exclusively along weft and warp threads caused by the discrete structure of the woven fabric. As in a given time after the stroke, the way which the tension wave passes in the intermediate directions is longer than that in the two dominating directions. The base of the cone of deformations and the tension distribution in the woven fabric have nearly a square shape with diagonals along the weft and warp threads [3, 4, 11 - 14].

A literature review carried out did not indicate any complex research concerned with the propagation velocity of a tension wave in the directions of weft and warp, as well as the influence on this velocity of such quantities as weave type, weft and warp densities, area mass, etc. Royland [3, 4] in his long-standing investigation concerning the mutual interaction between the penetrator and the anti-impact barrier came to the conclusion that the tension wave propagation velocity in

Table 1. Basic parameters of threads used in ballistic woven fabrics.

Type of tread	Density, kg/m ³	Tensile strength, MPa	Modulus, GPa	Elongation at break, %	Velocity of tension wave, m/s
High Molecular Weight Polyethylene (HMWPE)	970	2400 - 3340	73 - 124	2.8 - 3.5	10000
Ballistic aramid	1390 - 1440	2965 - 3390	70 - 121	2.6 - 4.4	8200
Polybenzobisoxazole (PBO)	1540 - 1560	5800	180 - 270	2.5 - 3.5	8000
Polyamide HT	1140	1500 - 1700	10	20.0	2200

a woven fabric during a stroke is only a fractional part of the propagation velocity of the tension wave in a singular thread from which the fabric is manufactured. According to this theory, the tension propagation velocity c_f in a woven fabric equals:

$$c_f = \frac{c}{\sqrt{\alpha}} \quad (3)$$

where:

- c – tension propagation velocity in a singular thread, and
- α – coefficient compensating the effect of threads interlacing in woven fabric.

Not differentiating the weave type and other structural parameters of woven fabric, as for example the weft and warp densities, Roylance proposed to assume that $\alpha = 2$ as the value of the coefficient. This model of tension wave propagation has been used in many publications concerning modelling the phenomenon of a penetrator striking against a woven anti-impact barrier [5 - 7]. The coefficient 'a' is generally called the Roylance coefficient.

Extensive research has confirmed that the amount of energy absorbed by a woven fabric during the stroke of a penetrator, which moves with a given velocity, depends not only on the strength parameters of the singular thread, but also on the structure of the woven fabric, its preparation, and in the case of a multiplayer fabric and a packet of fabric layers, on the number of layers, the way they are sewn together and stitched. Roylance et al. [8] indicates that during the striking of a woven barrier by the penetrator, we addain a structural answer resulting in the connection of the thread's properties as properties of its material and woven fabric's geometry. Typical geometrical woven fabric systems used in anti-impact barriers are the plain weave 1/1 and the hopsack weave 2/2. Lyons [8] indicated experimentally that the so called 50-percentage boundary value of the piercing velocity (v_{50}) depends on the area mass of the anti-impact barrier. On this basis he developed an empirical equation which determines the boundary velocity v_{50} with dependence on the area mass. He used woven fabrics manufactured from Nylon 66 fibres, with a hopsack weave 2/2, in his investigations. Lyons changed the area mass by a different number of layers in the packets. Hosur et al. [10] in their experimental investigations

compared the properties of anti-impact barriers with insertions of woven fabrics stitched and non-stitched, all manufactured with the use of plain and hopsack weaves. In ballistic tests they indicated that the 50-percent boundary value of the piercing velocity (v_{50}) is greater for the barriers with insertions of fabrics manufactured with the use of hopsack weaves. Faur-Csukat [1] drew similar conclusions on the basis of his investigations. He also used plain and hopsack woven fabric-insertions in anti-impact barriers, but irrespective on the number of layers applied in the packed the amount of energy absorbed was slightly greater if the case when the woven fabric used was manufactured by the hopsack weave. Broad investigations of anti-impact systems have been presented by Cuniff [11]. He used woven fabrics with plain and rep weaves in his research work. Without differentiation of the weave type, he indicated that the amount of the penetrator's energy absorbed depends practically linearly on the area mass of the woven fabric. These examples selected from literature testify that not only the raw material of the thread is decisive on the anti-impact properties of the barrier, but also the geometrical structure of the barrier.

In conjunction with intensive research work into improving the tensile strength properties of threads, investigation projects have been realised with the aim of obtaining optimum structures of textile anti-impact barriers.

■ Aim of investigation

The aim of this research work presented herein was an analysis of the influence of woven fabric structures on the propagation velocity of a tension wave. The investigation results should allow the selecting of woven fabric structures characterised by the greatest velocity of tension wave propagation.

■ Method of estimating the propagation velocity of a tension wave in a woven fabric

The development of the method presented herein has been described in [15 - 17]. The principle of the method of estimating the propagation velocity of a tension wave in woven fabric consists of observing the position change of two points placed along the way of wave propaga-

tion. If we know the distance between the two points observed, and the difference in their times of reaction, it is possible to assess the wave propagation velocity. A block scheme of the measuring stand is presented in Figure 1.

The woven fabric tested was fastened onto a frame with dimensions 50 cm × 70 cm. Before fastening it to the frame, the fabric was preliminary tensioned along weft and warp by a force evenly distributed, with the value of 50 N/m. The aim of the preliminary tension was to smooth out the fabric, and by stretching it normalise the tensions in weft and warp threads. In order to create a tension wave, which would propagate in the woven fabric, a forced input function was applied in the form of a pneumatic shooting of a missile (6) with a mass of 9.5 g, connected with the weft or warp threads by a pull rod, [16. 17] along which were placed markers (2) and (3) at a mutual distance L . In the pneumatic shooting system applied, the outlet velocity was 120 m/s. The tension wave created in the woven fabric caused a displacement of the markers placed along the way of wave propagation. The presence of the wave front at the position of the marker defines the beginning of the marker's position change in relation to its initial position. A follow-up system developed by the author was used for checking the position change of the markers in relation to the initial position. The system consists of following-up a light beam reflected from the marker being observed [4, 5]. A block scheme of this system is presented in Figure 2.

The fastening body (1) is the base element for fastening the optical sub-system (3), PSD sensor of the light beam position (5), light dividing prism (4), and the CCD camera (6). The light reflected from the marker being observed in the form of a beam is divided with use of a prism, and linked toward the light sensitive surface of the CCD camera and the PSD S1200 sensor, from the Hamamatsu Photonics Company, which serves to detect the light beam position. The task of the optical sub-system is obtaining an appropriate sharpness of the image analysed and selecting the magnification in such a way that maximum changes of the marker's position during propagation of the tension wave would be focussed on the surface of the light beam position sensor. On the other hand, the task of the CCD camera is preliminarily setting the

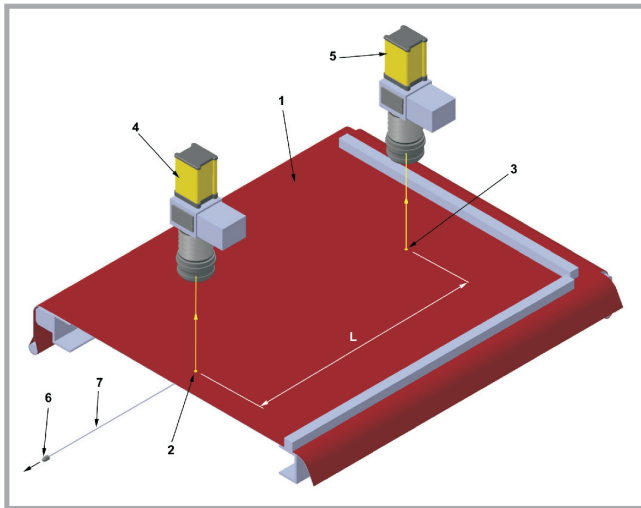


Figure 1. Block scheme of measuring stand for estimating the tension wave in woven fabrics; 1 – woven fabric tested, 2, 3 – markers, 4, 5 – systems recording the markers' positions, 6 – missile (bullet).

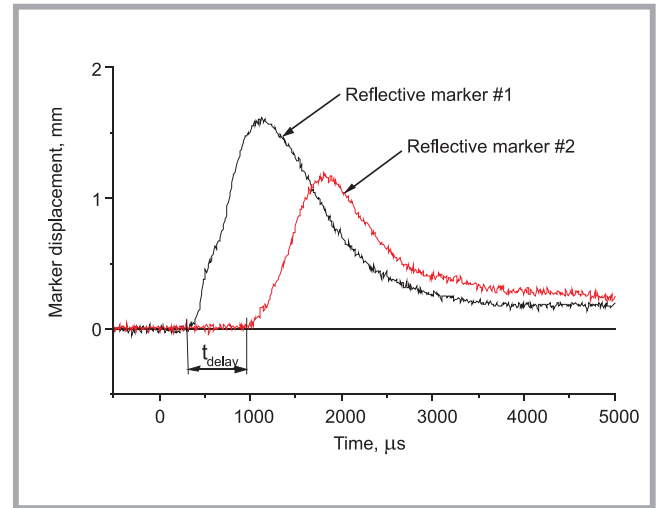


Figure 3. An example of the time-dependencies of the observed markers' position change during propagation of the tension wave in a woven fabric.

position of the marker being observed on the light sensitive surface of the PSD sensor. The central points of the light sensitive surface of the CCD camera and that of the PSD beam light position sensor are set in the optical axis of the optical sub-system. Taking this into consideration, the image analysed, divided by the prism, is identical considering the content and displacement in relation to the central points on both light sensitive surfaces. The light beam falling on the light sensitive surface of the PSD sensor

causes generation of two pairs of electric currents, on the basis of which the position co-ordinates of the light beam are calculated from the following equation:

$$x = a \cdot \frac{I_{1x} - I_{2x}}{I_{1x} + I_{2x}} \quad y = a \cdot \frac{I_{1y} - I_{2y}}{I_{1y} + I_{2y}} \quad (4)$$

where:

a – is the width of the light sensitive surface of the PSD sensor,

I_{1x} , I_{2x} – are the pairs of currents determining the marker's position in relation to the x-axis

I_{1y} , I_{2y} – are the pairs of currents determining the marker's position in relation to the y-axis.

From the point of view of analysing the phenomena occurring, the main quality parameter of the light beam position sensor is its response time in answer to the jump position change of the falling light beam. In the case of PSD S1200 sensor used, it equals $1\mu s$, and is insignificantly small in comparison with the delay time between the two signals ($t_{\text{delay}} \approx 600\mu s$).

Figure 3 presents an example of the time-dependencies of the observed markers' position change during propagation of the tension wave in a woven fabric.

On the basis of the determined time t_{delay} (Figure 3) the propagation velocity of the tension wave in the fabric tested was calculated from the following equation:

$$v_{\text{fabric}} = \frac{L}{t_{\text{delay}}} \quad (5)$$

where:

L – distance between the markers (Figure 1).

L was accepted as 500 cm for the investigation carried out.

Test results

Investigations into the propagation velocity of the tension wave in woven fabrics were carried out for structures differentiated by weave type and weft inserting density. Polyester yarn of the type TORLEN TWY 220/48 S300 was selected as the material for weft and warp. For this yarn the tension wave value of velocity propagation was determined experimentally. The velocity was equal to 2500 m/s at a preliminary tension of 20% of the yarn's breaking force. All woven fabrics were manufactured with the same warp density of 32 threads/cm with the use of a Picanol Luna weaving loom. The weft insertion density was changed, and fabrics with 15, 20, 25, and 30 threads/cm were manufactured. The lower boundary of this range was determined as a value near the beginning of the stable structures of the given fabric, which depends not only on the density of weft insertion, but also on weave type. The upper boundary was also the limit value of weft density in the woven fabric at which it was possible to manufacture the fabric. Table 2 presents the types of weaves which were accepted for the fabrics investigated. Special attention was given to the analysis of woven fabrics manufactured with basic weaves. They are commonly used in technical woven fabrics, including ballistic fabrics where the plain weave, the hopsack weave 2/2, and the twill weave dominate.

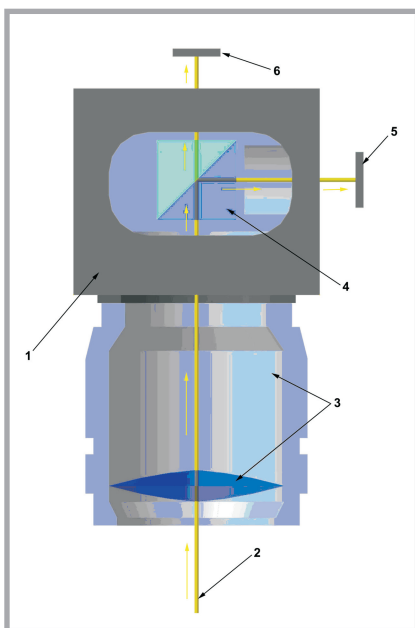


Figure 2. Block scheme of the marker position observation system; 1 – fastening body, 2 – light beam reflected by the marker, 3 – optical sub-system, 4 – prism dividing the light, 5 – PSD sensor of the light beam position, 6 – CCD sensor.

The tension impulse was induced in the warp threads and tested along them in all cases.

Figure 4 presents the results of measuring the propagation velocity of the tension wave with dependence on the density of weft insertion for the woven fabrics analysed. Each result is the average value of five measurements. The test results for the particular fabrics were approximated by linear continuous functions. In the case of the fabrics with plain and twill weaves, fabrics with the weft insertion of 30 threads/cm were not manufactured. For these woven fabrics the maximum weft density was lower than 30 threads/cm.

Discussion of the test results

From the point of view of the woven fabric's stability resulting from the density of weft insertion, the fabrics may be theoretically divided (Figure 5) into the following three types:

- fabrics with unstable structure,
- fabrics with stable structure, and
- fabrics with structure impossible to manufacture.

Designations in the Figure 5:

- $g_{\text{weft_min}}$ – minimum weft density securing a stable structure of woven fabric,
- $g_{\text{weft_max}}$ – maximum weft density possible to be obtained,
- $c_{\text{fabric_max}}$ – maximum propagation velocity of a tension wave in warp direction for fabrics of stable structure,
- c_{yarn} – velocity of tension wave propagation in yarn (thread),
- $g_{\text{weft}} = 0$ means that we have not got a fabric, but only a singular thread (yarn).

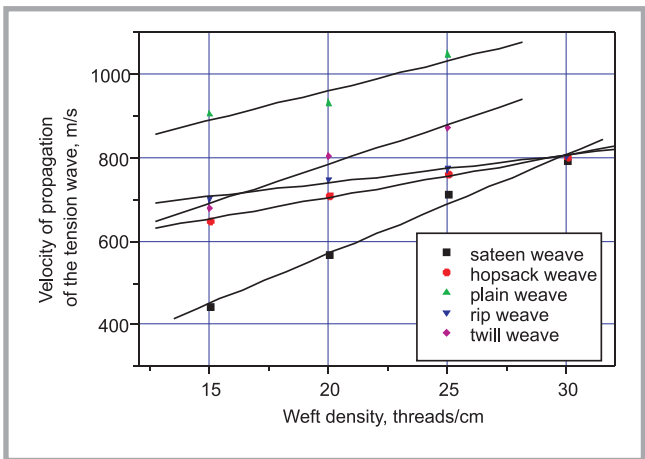


Figure 4. Dependencies of propagation velocity of the tension impulse on the weft density for different woven structures.

Table 2. Weaves applied in woven fabrics tested.

Weave description	Type of weave				
	plain	twill	sateen	hopsack	rip
Graphical					
Symbolic	1/1	1/2	1/4	2/2	3/3

On the basis of the tests carried out, it is possible to indicate that in a woven fabric with stable structure the propagation velocity of a tension wave in warp direction depends linearly on weft insertion density and changes within the range of $c_{\text{fabric_max}}$ to $c_{\text{fabric_min}}$. The greater the weft inserting density, the greater the propagation velocity of the tension wave is. In the case of ballistic woven fabrics, the propagation velocity should be the greatest. However, for the weaves in this research, the velocity is limited by the boundary weft insertion density $g_{\text{weft_max}}$ above which the woven fabric cannot be obtained. In the range of weft insertion densities which was investigated by the author, and in which the fabric was characterised by a stable structure, the greatest velocity of tension wave propagation occurred for woven fabrics with plain and sateen weaves.

In the case of woven fabrics with unstable structure, with the weft insertion density equalling zero, the tension wave would propagate only into a single system of parallelly placed threads. In such a case the interlacing effect does not occur and it can be assumed that the velocity of the tension wave propagation will be the same as for a single thread ($c_{\text{fabric}} = c_{\text{yarn}}$). From comparison of the

propagation velocities of tension waves tested in experiments involving threads and woven fabrics in warp direction, it concludes that the wave velocity in a single thread is at least twice as great as the maximum velocity occurring in woven fabrics. Therefore, in fabrics with unstable structure, with an increase in the weft insertion density beginning with the value zero, a drop in the tension wave propagation velocity will occur down to the minimum value, and next an increase to the value $c_{\text{fabric_max}}$ related to the minimum velocity of the tension wave propagation in warp direction for the woven fabric with a stable structure.

It may be assumed that the propagation velocity of the tension wave along the weft threads should be ruled by the same dependencies as in the case of propagation along the warp. Future tests should confirm this assumption.

On the basis of the investigations carried out and assuming that in the case of technical woven fabrics dedicated for use as an anti-impact barrier, the following conditions would be fulfilled:

- the same material has been used for weft and warp threads,
- the woven fabrics have been manufactured with basic weaves,

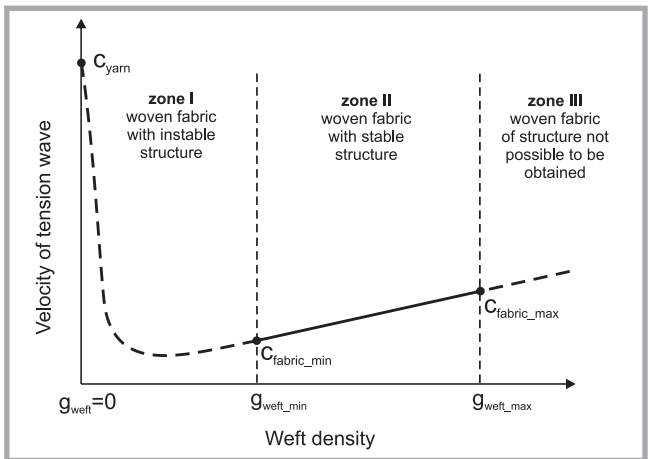


Figure 5. Dependency of the tension wave velocity in a woven fabric along the warp threads vs. weft density and structure stability.

- the warp threads do not significantly change their strength properties during cyclic stretching of about 2,000 cycles during the weaving process, and
- the geometrical structures of the medium in which the tension wave propagates are comparable by changing the weft- into the warp systems.

We can state that the propagation velocity of tension waves in a woven fabric depends not only on the propagation velocity in the yarn used to manufacture the fabric, but also on the fabric's structure parameters such as weave type, weft and warp density. Therefore, in the case of determining the propagation velocity of a tension wave in a woven fabric on the basis of this velocity in yarn, a proposition is given to modify the dependency (3) by accepting a coefficient β as a function of the woven fabric's structure:

$$c_f = \frac{c}{\beta(s, g_{warp}, g_{weft})} \quad (6)$$

where:

β – function which determines the multiplication factor of decreasing the wave velocity in the woven fabric in relation to the wave velocity in yarn used to manufacture the fabric,

s – type of weave,

g_{warp} – warp density,

g_{weft} – weft density.

In Table 3, examples are presented of function β values and propagation velocity values of tension waves in the warp direction for the investigated woven fabrics manufactured with different types of weave, assuming a constant warp density of $g_{warp} = 32$ threads/cm and density of weft insertion of $g_{weft} = 25$ threads/cm.

The differentiated values of the coefficient β indicate that it is not possible to determine the propagation velocity of a tension wave in each woven fabric on the basis of the propagation velocity of the tension wave in the yarn used for manufacturing the woven fabric by using the same value of the coefficient. It is clearly visible that the structural parameters of the fabric should be considered.

Summary

The investigations carried out allow the formulation of the following statements:

- The propagation velocity of a tension wave in a woven fabric depends not

Table 3. Values of function β and propagation velocities of tension waves for woven fabrics tested.

Quantity, parameter	Type of weave				
	plain	twill	sateen	hopsack	rip
Value of function β	2,2	2,8	3,6	3,3	3,2
Velocity of tension wave, m/s	1132	887	688	755	774

only on the propagation velocity in yarn, but also on the parameters of the woven fabric structure, such as the weave, and weft & warp densities.

- With dependence on the weave and density of weft insertion for the woven fabrics tested, the propagation velocity was from twice to six times smaller in relation to the tension wave velocity in the yarn used to manufacture the fabric.
- In woven fabrics with stable structure the propagation velocity increases linearly as a function of the weft insertion density.
- Maximum propagation velocity of the tension wave occurs in woven fabrics with plain weave.
- Accepting the propagation velocity of the tension wave in woven fabrics as a criterion of the efficiency of an anti-impact barrier, on the basis of dependency (2), ballistic woven fabrics should be manufactured with plain weave and maximum weft and warp insertion density.
- Ballistic investigations should be carried out to determine the influence of the woven fabric structure and propagation velocity of the tension wave on the amount of missile energy absorbed and on the parameters of the deformation cone.

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