Dynamic Tests for Energy Absorption by Selected Auxetic Fabrics

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ABSTRACT

Experimental dynamic tests for energy absorption by four selected auxetic fabrics were conducted and analyzed. An original test stand was designed, manufactured and attached to a Hopkinson's bar. The energy absorbed by an auxetic curtain was expressed in terms of the energy of the maximum elastic deformation of a unit volume along the support line of the witness-plate. A quasi-impulse load was induced using a gas blast under a pressure corresponding to an indoors deflagration explosion of a propane-air mixture in a vented room. The auxetic fabric with the best energy-absorption properties was identified on the basis of the comparative analysis using a reference system with a steel specimen.

Keywords: Auxetic fabric, material properties, gas blast test, energy absorption.

INTRODUCTION

An auxetic fabric, in the form of an auxetic yarn as the weft and ordinary fibers as the warp, is taken into consideration. The fabric is of a plain weave type. The auxetic fiber is wound in a double helix, and contains a thin high-strength spiral wrap and a thick elastomeric core. Under tension in the yarn direction, the spiral wrap tends to straighten, which causes bending of the the core resulting in a negative effective Poisson's ratio. Hence, the elastomeric core absorbs energy by bending itself. Changes in the wrap angle during tension of the auxetic fibers lead to a Young's modulus and Poisson's ratios dependent on strain [1].

The components of an auxetic fabric are well-known materials with positive Poisson's ratios. The effect of a negative effective Poisson's ratio is caused by the geometrical configuration of the components of significantly different mechanical properties.

The results of a tensile test of a single auxetic fiber are presented in Ref. [1]. The yarn was subjected to six load–relief cycles. The best auxetic fiber was identified in the group of fibers under consideration. Static tests on the energy absorption of a fabric strip were conducted using a device for measuring the vertical displacement of the fabric caused by stretching in the weft direction up to failure. The absorbed energy was calculated based on the force – displacement graph.

The auxetic effect is fully revealed in the case of a transverse load on an auxetic fabric, e.g. the blast wave of a gas explosion or explosive charge [1]. Then a displacement surface with a double synclastic curvature appears.

Until now, research on auxetic fabrics of the above-mentioned structure has related to experimental and numerical studies of a single auxetic fiber (micro scale), a cell of the material (meso scale) and a fabric sample (macro scale) [1, 2, 3, 4]. The impact of the geometry and material parameters on the mechanical properties of a single auxetic fiber or an auxetic fabric was investigated. A characteristic feature was observed in the form of a strong non-linear dependence of effective Poisson's ratios on the geometry of an auxetic material, including a sign change. Significantly high negative values of the effective Poisson's ratio up to (–8) can be achieved by changing the fabric geometry.

One of the possible applications of auxetic fabrics is curtains protecting from an indoor gas explosion. An indoor deflagration explosion of propane-air mixtures induces a pressure wave. The vent in a room plays an important role in lowering the pressure, which reduces the pressure of the explosive wave and increases the flame speed. In-room ventilation plays an important role in lowering the pressure, which reduces the pressure of the explosive wave and increases the rate of combustion.

A gas explosion is rapid combustion of a gas-air mixture at a concentration of gas in the room, leading to an explosion. A flame surface is created after igniting at a point in the room and it expands continuously during the chemical reaction process. The discharged gases carry away large amounts of energy after venting. The pressure rise in the room is determined by the difference between the released energy during the combustion and the discharged energy [5].

A propane-air mixture gas explosion in a vented room can be considered under the following assumptions [5]: (1) heat transfer between the gas and the obstacles is ignored; (2) the pressure remains uniform in the whole room during the explosion; (3) the flame surface is spherical.

Wang et al. [6] examined numerically, using CFD software AutoReaGas, the effects of ignition location and vent size on the physical processes and the parameters of a propane-air mixture explosion in a vented room of the dimensions 4.6 m × 4.6 m × 3 m. Propane is the main component in liquefied petroleum gas. A vent (a window) was located in one of the walls and in the geometric center of the wall. An unconstrained vent was arranged using a 0.02 mm thin polypropylene sheet over the vent opening. The peak explosion overpressure was measured to be equal to 40 kPa and 12 kPa for back ignition for the vent area ratio (the vent area to the wall area where the vent is located) $\alpha = 0.1$ and 0.2, respectively. For center ignition they obtained 15 kPa and 4 kPa, respectively [6].

Bauwens et al. [8] performed a series of vented explosion tests using stoichiometric propane-air mixtures in a room-size enclosure of 63.7 m^3 in volume. The experimental pressures did not exceed 19 kPa.

The objective of this article is to provide a methodology for estimating energy absorption by auxetic fabrics under a shock pressure wave induced by a vented explosion in a room-size enclosure for stoichiometric propane-air mixtures.

Experimental research on the energy absorption was conducted for four selected auxetic fabrics. An original test stand was developed and assembled with a Hopkinson's bar. The energy absorbed by an auxetic curtain was expressed in terms of the elastic energy of the maximum elastic deformation of a unit volume along the support line of the witness-plate. The quasi-impulse load was executed using a gas blast under a pressure corresponding to a gas explosion in a vented room. The auxetic fabric with the best energy-absorption properties was identified.

SPECIFICATION OF FABRICS AND METHODOLOGY OF EXPERIMENTAL RESEARCH

Four auxetic fabrics, commercially available in England, are considered in this study. Their components are provided in *Table I*. Based on the results of the explosion-proof curtain studies, it was found in Ref. [1] that the AUXFAB2 code material exhibited the best energy-absorption properties. This material has the following components:

- a warp fiber: conex (meta-aramid);
- a spiral wrap: a twisted Dyneema fiber with improved tension control during wrapping;
- an elastomeric core: an elastomeric fiber made of red polyurethane.

The above mentioned components are different from those considered in this study (*Table I*).

The energy absorption research was carried out using specifically designed instrumentation, indicated as AFGB (a stand for Auxetic Fabric under Gas Blast). The concept of the instrumentation is as follows (*Figure 1*):

- The bottom plate of the instrumentation is assembled with the bottom plate of a Hopkinson's bar.
- In the vertical zone of the instrumentation, there is a circular zone of the gas impulse with pressure p acting on a fabric sample stretched in the vertical direction coinciding to the auxetic yarns.
- The circular zone of the gas outlet nozzle has a diameter of 25 mm and is close to the sample (auxetic fabric or a reference plate).
- Auxetic fibers are arranged vertically and fixed in the horizontal blocks.
- Longitudinal strains close to the support line of the witness-plate and the process of stretching and destroying the fabric sample are registered using a high speed camera. The witness-plate is a cantilever.
- A 5 mm thin reference plate made of S235JR steel, replacing an auxetic fabric sample, is applied.

Figure 1 shows a visualization of the designed AFGB instrumentation. The device has a width of 200 mm and height of 320 mm. The witness-plate has a width of 120 mm, height of 65 mm and thickness of 6 mm.

Close to the support line of the witness-plate, a red marker indicates the location of the strain gauge bridge used for measuring the longitudinal strain (in the vertical direction). *Figure 1* also presents a segment of the bottom plate of the Hopkinson's bar, to which the equipment is fixed by means of screws.

TABLE I. Components of auxetic fabrics (AF) selected for experimental tests.

Component		Auxetic fabric			
		AF1	AF2	AF3	AF4
Warp fibers		DuPont Kevlar 29 (3000 den)	glass fiber with stainless steel wire inclusions	Twaron para-aramid Type 2200 (1100 dtex)	ballistic Nylon 6-6 HT (940 dtex)
Auxetic yarns	spiral wrap	DuPont Kevlar 129	DuPont Kevlar (777 dtex)	Twaron Type 2200 (1100 dtex)	Honeywell Spectra 1000 (375 den)
	elastomeric core	0.6 mm diameter, elastomeric polyester monofilament			
Weight per unit area		700 gsm	820 gsm	650 gsm	650 gsm
Properties		—	higher fire resistance	—	resistant to UV radiation

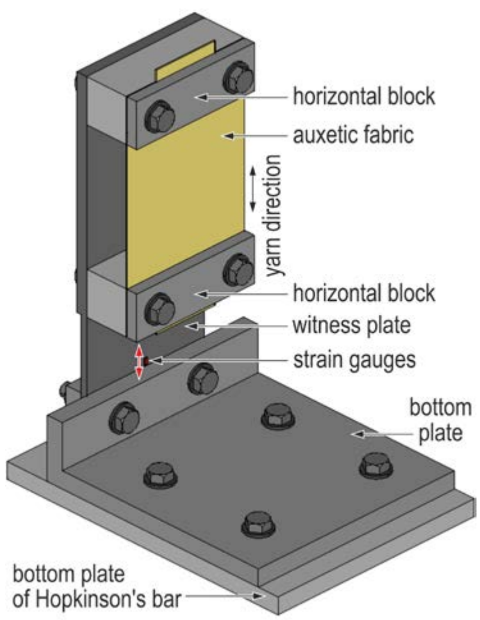

FIGURE 1. Visualization of AFGB instrumentation – isometric view from top.

The executive project of the instrumentation has one simplifying modification, i.e., the horizontal bottom plate of the instrumentation has a constant thickness of 55 mm instead of a thinned plate as proposed in the technological project.

A strip of the auxetic fabric has the dimensions 120 × 140 [mm] between the horizontal blocks and is fixed on the horizontal edges. The method of fixing the fabric provides tension of the auxetic fibers.

The peak gas outlet pressure from a nozzle of a Hopkinson's bar was assumed to be equal to 0.8 MPa. The maximum resultant force of the pressure is equal to:

$$P = pA\varphi = 0.8 \times 0.0004906 \times 2 = \\ = 0.000785 \text{ MN} = 785 \text{ N} \quad (1)$$

where $p = 0.8$ MPa is the peak gas outlet pressure, $A = 0.0004906 \text{ m}^2$ is the cross sectional area of the outlet nozzle, $\varphi = 2$ is the approximate value the dynamic coefficient (a value corresponding to a single-degree-of-freedom system under a Heaviside-type load was assumed).

The pressure of 0.8 MPa = 800 kPa, distributed over a small circular cross-sectional area of the nozzle at the center of the specimen, is equivalent to the pressure of 23 kPa spread over the entire surface of an auxetic fabric specimen. The value of 23 kPa is close to the average value, 26 kPa, of peak gas explosion overpressures derived by Wang et al. [6].

The maximum bending moment in the support cross-section of the witness-plate is:

$$M = P\,L = 785 \times 0.165 = 129 \text{ Nm} \quad (2)$$

where L is the arm of the resultant force of the pressure distributed over a small circular cross-sectional area of the nozzle. After calculating the bending index of the witness-plate treated as a cantilever bar, the maximum normal stress $\sigma = 181$ MPa in the support cross-section is obtained. The yield strength R_e of the steel is equal to 372 MPa. The values of σ and R_e ensure working of the witness-plate in the elastic range.

The tests on the energy absorption by selected auxetic fabrics were conducted in the Laboratory of Strength of Materials and Structures, Department of Mechanics & Applied Computer Science, Faculty of Mechanical Engineering, Military University of Technology, Warsaw, Poland. The research stand is shown in *Figure 2*.

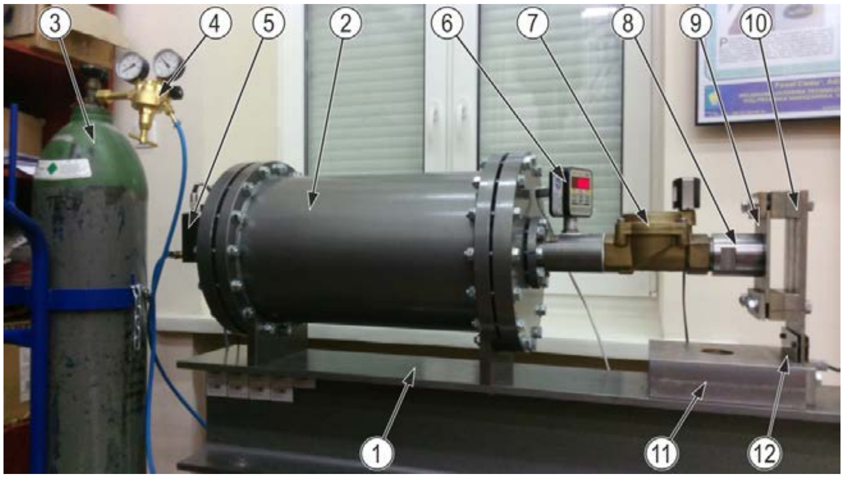

FIGURE 2. Experimental stand for testing auxetic fabrics under pressure impulse.

Compressed gas was used to form a pressure impulse. The pressure vessel (2) was filled with argon taken from the bottle (3) through the pressure reducer (4) and proportional filling valve (5). The test manometer (6) was used to control the pressure in the vessel. The sample (9) (a fabric or a reference plate) was attached to the support structure (10), whereupon the bottom plate of the support structure (11) was attached to the bottom plate of the Hopkinson's bar (1). The test was performed by opening the drain valve (7). Compressed gas hit the sample (9) via the nozzle (8).

The strains were recorded and archived using a specialized computer program. The recording time of 200 ms of the pressure impulse action was assumed.

The measuring system of longitudinal strain (12) close to the witness-plate rigid support line allows qualitative and quantitative assessment of the effect of the gas pressure impulse on the tested materials. An electrical scheme of the system for the strain measurement is depicted in *Figure 3*. A full strain gauge bridge sensitive to bending was used.

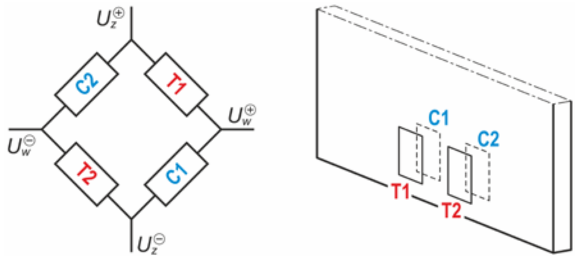

FIGURE 3. Scheme of strain measurement system.

The output signal from the strain gauge bridge was determined as follows:

$$U_w = 0.25 U_z \, N \, k \, \varepsilon \tag{3}$$

where U_w [V] is the output voltage, U_z [V] is the power supply voltage ($U_z = 5$ V), N is the configuration constant ($N = 4$), k is the strain gauge constant ($k = 2.09$), ε is the longitudinal strain. Scaling of the strain measurement system was carried out by shunting one branch of the bridge by a resistance of 100 kΩ. The response of the system to the gas pressure impulse was recorded using a Phantom v12 high speed camera (producer: Vision Research, USA).

Let us denote:

$\varepsilon_1(t)$ – longitudinal strain vs. time, close to the witness-plate rigid support line of the AFGB instrumentation with an auxetic fabric specimen,

$\varepsilon_{1,\max}(t)$ – maximum value of $\varepsilon_1(t)$,

$\varepsilon_{1,\mathrm{ref}}(t)$ – longitudinal strain vs. time, close to the witness-plate rigid support line of the AFGB instrumentation with the reference steel plate,

$\varepsilon_{1,\mathrm{ref,max}}(t)$ – maximum value of $\varepsilon_{1,\mathrm{ref}}(t)$,

E_1 – Young's modulus of S235JR steel.

During the tests, the witness-plate cantilever works in the elastic range. Close to the witness-plate rigid support line, the gas pressure impulse induces only longitudinal normal stresses calculated from the classic formula for bent bars

$$\sigma_1 = E_1\,\varepsilon_1 \tag{4}$$

The elastic deformation energy of a unit volume located close to the witness-plate rigid support line is calculated from the second classic formula for bent bars, taking into account Eq. (4), i.e.

$$E(\varepsilon_1) = \frac{1}{2}\sigma_1\,\varepsilon_1 = \frac{1}{2}E_1\,\varepsilon_1^2 \tag{5}$$

The relative energy absorbed by an auxetic curtain in the AFGB instrumentation, expressed in terms of the energy of the maximum elastic deformation of a unit volume along the support line of the witness-plate, from Eq. (5), is equal to

$$\begin{aligned}\overline{E}_a &= \frac{E(\varepsilon_{1,\mathrm{ref,max}}) - E(\varepsilon_{1,\max})}{E(\varepsilon_{1,\mathrm{ref,max}})}\times 100\% = \\ &= \left(1 - \frac{\varepsilon_{1.\max}^2}{\varepsilon_{1,\mathrm{ref,max}}^2}\right)\times 100\%\end{aligned} \tag{6}$$

RESULTS OF EXPERIMENTAL RESEARCH AND THEIR ANALYSIS

On the basis of the recorded signals, the time histories of the longitudinal strain close to the witness-plate rigid support line were prepared, both for the reference plate and the selected auxetic fabrics. Each test was performed twice for individual samples. The $\varepsilon(t)$ graphs are presented in *Figures 4–8*. The values of the maximum strain for each test are summarized in *Table II* along with the relative energy absorbed by each auxetic curtain. In the reference system, slight vibration amplification for time $t > 400$ ms is observed, probably caused by vibration superposition in the AFGB instrumentation – the Hopkinson's bar system.

The dynamic response of the reference plate is shown in *Figure 9*, whereas the responses of the AF1–AF4 fabrics are presented in *Figures 10–13*, respectively. The photographs illustrate the geometry of the system from the side view at the three main time points, i.e. before the test (a), during the test at the maximum strain (b) and after the test (c).

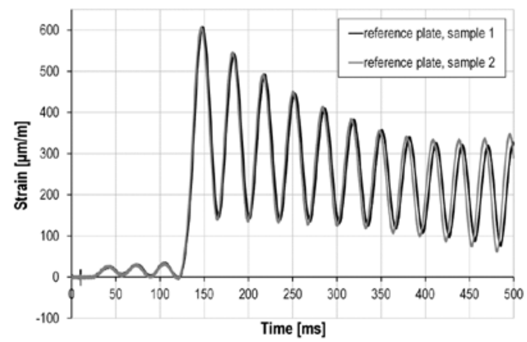

FIGURE 4. Longitudinal strain vs. time, close to witness-plate rigid support line, for reference plate.

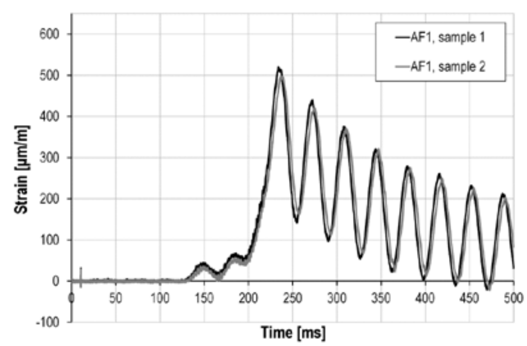

FIGURE 5. Longitudinal strain vs. time, close to witness-plate rigid support line, for AF1 fabric.

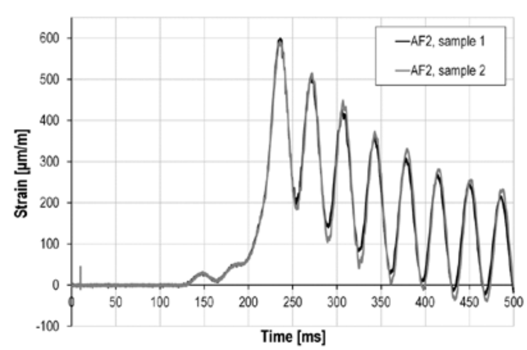

FIGURE 6. Longitudinal strain vs. time, close to witness-plate rigid support line, for AF2 fabric.

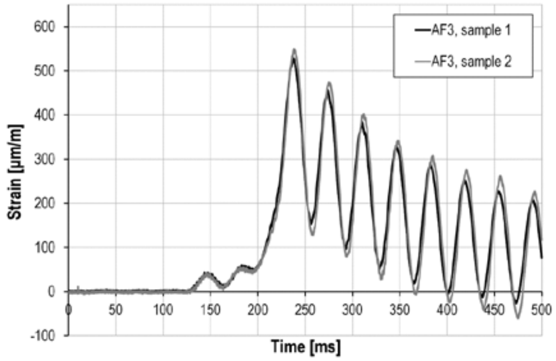

FIGURE 7. Longitudinal strain vs. time, close to witness-plate rigid support line, for AF3 fabric.

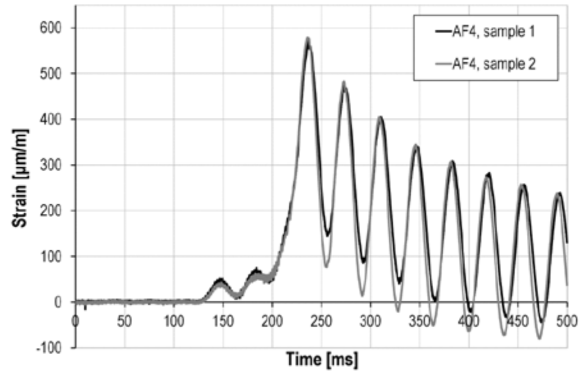

FIGURE 8. Longitudinal strain vs. time, close to witness-plate rigid support line, for AF4 fabric.

TABLE II. Maximum values of longitudinal strain and relative energy absorbed by auxetic curtains.

Specimen	Longitudinal strain [µm/m]			Relative energy absorption [%]
	Sample 1	Sample 2	Average	
Reference plate	608	607	608	–
AF1 fabric	520	498	509	29.9
AF2 fabric	600	593	597	3.6
AF3 fabric	529	550	539	21.4
AF4 fabric	572	580	576	10.2

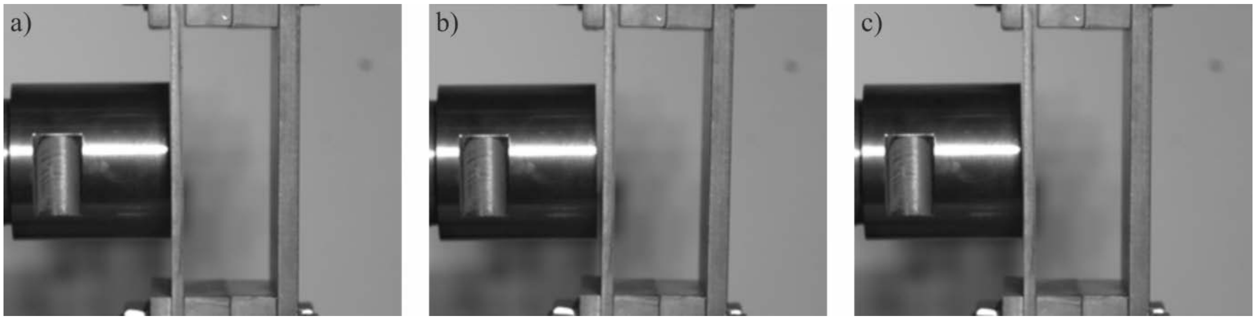

FIGURE 9. Response of reference plate to pressure impulse at selected time points: before test (a), during test at maximum strain (b) and after test (c).

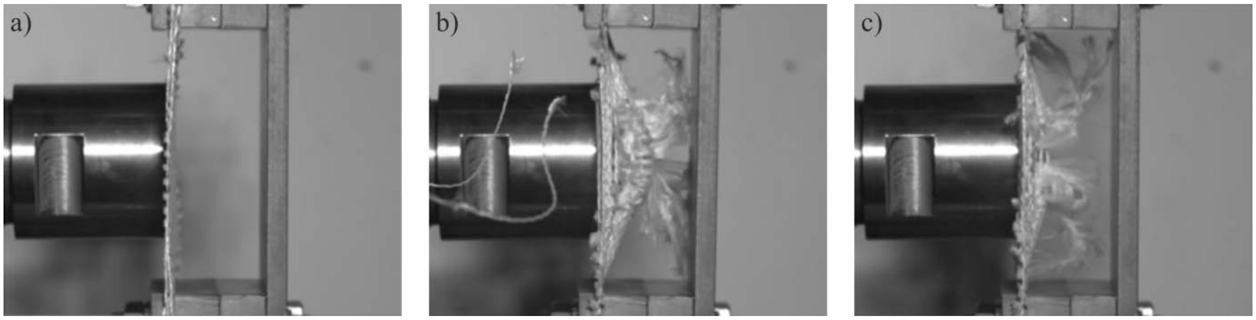

FIGURE 10. Response of AF1 fabric to pressure impulse at selected time points: before test (a), during test at maximum strain (b) and after test (c).

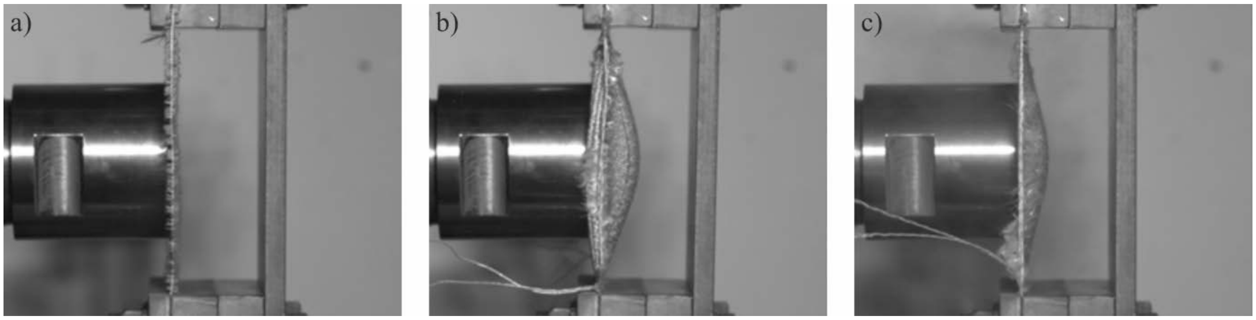

FIGURE 11. Response of AF2 fabric to pressure impulse at selected time points: before test (a), during test at maximum strain (b) and after test (c).

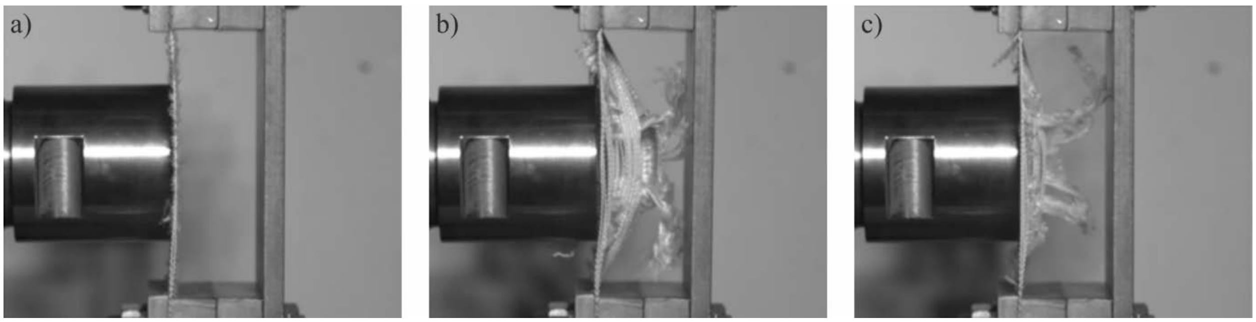

FIGURE 12. Response of AF3 fabric to pressure impulse at selected time points: before test (a), during test at maximum strain (b) and after test (c).

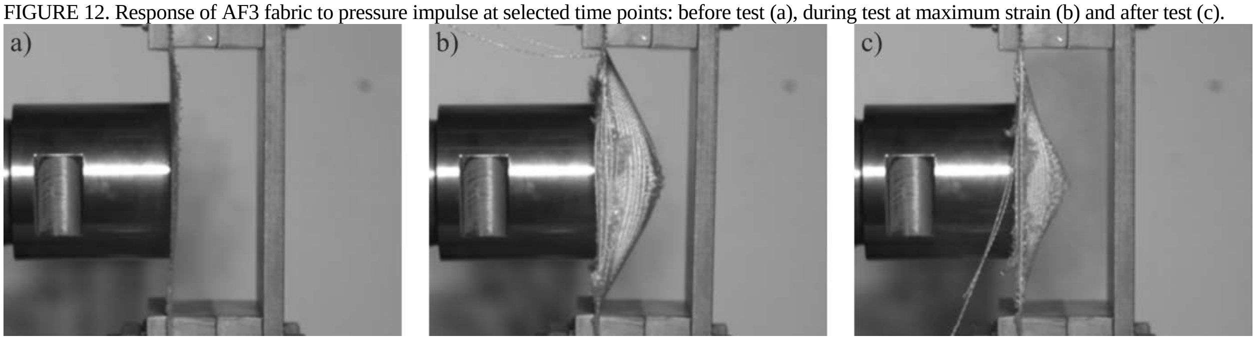

FIGURE 13. Response of AF4 fabric to pressure impulse at selected time points: before test (a), during test at maximum strain (b) and after test (c).

Based on the results of the energy absorption by four selected auxetic fabrics, the following conclusions have been formulated:

1) The pressure impulse causes maximum deflection of the system, which is subsequently reduced to zero in an oscillating manner. The oscillation frequency is 31.4 Hz for the AFGB system with the reference plate, and 26.9 Hz for the AFGB system with a fabric curtain. The deflection decays to zero for the fabrics faster than for the reference plate.
2) Time histories $\varepsilon(t)$ for both samples of each curtain are qualitatively consistent. The repeatability of the impulse and the measurements is very good.
3) The responses of the cantilever system with energy-absorbing elements to the gas pressure impulse are qualitatively consistent. There is an 80 ms delay of the response to the impulse for fabrics AF1–AF4 stretched in the auxetic fiber direction only, which results from the nonlinear elastic characteristics of these fabrics (the initial elasticity is relatively very low).
4) The AF1 fabric with the components specified in *Table I* has the best properties in terms of energy absorption by four selected auxetic curtains. In reference to the AFGB instrumentation, the energy absorption by the AF1 curtain is the highest and equals ~30% (*Table II*).
5) The energy absorption is correlated with the fabric sample destruction level (*Figures 10–13*). The largest destruction is exhibited by the AF1 fabric, lower destruction is by fabrics AF3 and AF4, and the smallest destruction is observed in the AF2 fabric.

CONCLUSION

The study presents an original methodology of measuring the energy absorption by auxetic fabric curtains. The auxetic fibers were stretched, whereas the warp fibers were left free. A transverse load in the form of a gas pressure impulse was applied.

The general conclusions formulated based on the energy absorption by selected auxetic fabric curtains are as follows:

1) The nonlinear elastic characteristics of the tested auxetic fabrics lead to an 80 ms delay in the response to a gas pressure impulse.
2) The AF1 fabric specified in *Table I* is preferable in terms of energy absorption. The reduction of the elastic deformation energy of a unit volume close to the rigid support line of the witness-plate is ~30%.

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