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New Technological Concept of Textile Highly-Flexible Road Barriers

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Abstract
The main element of road safety is the use of protective barriers. Among all barriers can be distinguished non-deformable solid concrete, steel and deformable rope barriers. A new solution proposed in this publication are highly flexible and strength knitted barriers. Through analysis of the barriers' nature, simulations of typical vehicle collision processes with barriers were carried out. For this purpose, calculations of G-forces which a human experiences during a vehicle collision with the barrier were conducted, and values of human pressure forces on the seat belt, created as a result the vehicle collision, were determined. There were also appointed values of impact energy created at the contact moment of the vehicle with the barrier. It was proved that textile knitted barriers cause a 30-fold decrease in the negative g-forces of the driver and passengers and 12-fold reduction in the pressure force of seat belts on the human body, providing the ability to absorb the impact energy of both cars and trucks, including buses, moving with a speed of 100 to 160 km/h. The publication presents a summary of preliminary research that justifies the desirability of textile barrier use in road engineering.

Key words: *road safety, road barriers, non-deformable barriers, flexible barriers, textile barriers, impact energy, safety belt pressure.*

Introduction

One of the main purposes of protective barrier use in the broad sense of road engineering is to increase the safety of road users. Road barriers occur most often in dangerous locations for vehicles, ie. those in which there is a high probability of leaving the car outside the designated edge of the road or a high probability of exceeding a designated traffic lane. A significant problem that will be especially articulated in considerations of road barrier structure and properties will be protective barriers used on bridges, embankments, steep and sinuous parts of mountain roads, dangerous bends (on road arcs with a small radius), as well as in places where close to the road are objects and solid obstacles (viaducts supports, poles, buildings), a collision with which can be especially dangerous for drivers and passengers of vehicles. None of the barrier constructions used today is considered as a fully satisfactory solution. This applies particularly to those on bridges. So far there has been no successful attempt to develop a barrier construction that would operate properly both in the case of small cars and heavy trucks and buses; we mean such barriers,

that would absorb varied sizes of impact energy. A barrier broken on a bridge by a vehicle leads to a traffic accident with very serious consequences. Special attention is required by objects over railway tracks, rivers and water reservoirs. The breaking of a barrier breaking over high-speed rail tracks can lead to a train crash with incalculable consequences. This study is the first one of several publications that summarise research on textile road barriers to justify scientific and construction works about their use in the area of road safety. Further publications will present the subject of the construction and material solutions for barriers together with a mechanical model of their operation and simulation studies of the dampening of impact energy by textile knitted barriers.

Characteristics of road barriers

Road barriers are the main type of appurtenances enhancing road safety. Their foremost task is to protect road users. There are several types of road barriers – permanent concrete barriers, steel barriers, and cable barriers.

Concrete (***Figure 1***) and steel barriers (***Figure 2***) exhibit high rigidity and low deformability. A vehicle colli-

Figure 1. *Concrete barrier [3].*

Figure 2. *Steel barrier [4].*

Figure 3. *Cable barrier [5]*

Figure 4. *ROCCOR double steel net structure [6].*

sion with a permanent concrete barrier leads not only to extensive damage of the car but also to serious injuries of the passengers. Steel barriers used on bridges and overpasses do not ensure complete safety of vehicle occupants, as a collision may break the barrier, often leading to vehicle penetration [1]. Cable barriers (***Figure 3***, see page 99) exhibit much higher deformability (up to 1.5 – 2.0 m) upon collision in comparison to the two other barrier types [2].

As a response, the Swiss company Geobrugg manufactures special ring-net barriers which are an alternative to rigid road barriers [6]. This company is focused on **safety engineering**, which means taking every possible action to increase **human safety**. Geobrugg nets are typically made of two separate meshes with different structures. ***Figure 4*** presents an example of a ROCCO® double steel ring net. Such nets are characterised by a dynamic load capacity ranging from 100 kJ to 8000 kJ, thanks to which they can stop a boulder weighing up to 20 tons falling from 32 m. Examples of Geoburrg nets used in road settings are shown in ***Figure 5*** [6].

Lodz University of Technology together with ATH University of Bielsko-Biala has developed a new concept of highly deformable and durable knitted mesh-like barriers. This barrier will have two variants of solutions. The first one is based on the multilayer structure of the technical a-jour net of knitted fabric, and the second - on the hybrid construction of the sandwich composite structure of 3D knitted fabric [7]. These barriers will have three characteristic features, namely a significant deformable nature (stretching or bending), which in the case of knitted mesh will be 6 m, whereas in the case of the 3D structure the size of the deflection will be 3 - 4 m, characterised by dynamic strength in the range from 3000 - 5000 kJ of impact energy absorbed and a multi-stage energy absorption system.

The reasons for the assumptions presented, which take into consideration both the high dynamic strength of knitted barriers and their simultaneous high susceptibility to deformation, are associated with two features: Firstly it is assumed that the raw materials used- both the threads and yarns, which will be used to build ropes for the manufacture of mesh barriers, will be characterised by several times higher tensile strength than steel wire ropes. In the case of 3D barriers, which operate on a compressive force, in the internal layer of distance knitted fabric polymer "rods" with high values of bending stiffness will be used. Threads (fibres) applied in the barriers will be textile materials from the area of technical linear products. They are widely applied, i. a. in ballistic protection, geotextiles, as textiles used in the building industry, in the automotive industry, in personal protection, among others. Commonly used are high-strength para-aramid fibres, polyethylene fibres (HPPE), glass fibres, PBO fibres, carbon fibres, graphite fibres and basalt fibres [8, 9]. Para-aramid fibres like Kevlar and Twaron have five times greater strength than steel (at the same value of mass) (E = 70 - 120 GPa, tensile strength up to 3.4 GPa) and they are also used for the production of ropes. Polyethylene fibres, like Dyneema and Spectra, are ten times more resistant than steel. A very important feature of these fibres is their high energy absorption capacity ot impact. They are used for the production of cords, in ballistic protection, in the production of fishing nets as well as parachutes. PBO poly (p-phenylene-2,6-benzobisoxazole) fibres (Zylon) have twice greater strength than Kevlar fibres. Also noteworthy are glass fibres of the S-Glass type or fibres of the M5 type (PIPD), with a very high tensile strength (E = 310 GPa, tensile strength up to 5.8 GPa). Graphite fibres, with

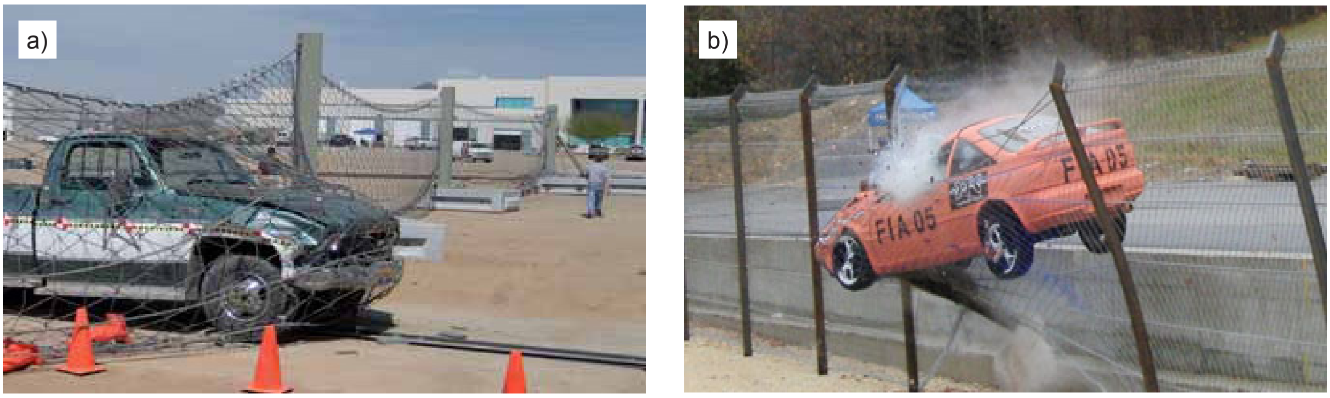

Figure 5. *Barriers in road settings: a) road block b) road barrier [6].*

a well shaped and oriented graphite crystal structure, have comparable strength to aramid fibres. A popular textile raw material – polyamide threads of the Nylon type, have 2.5 times greater strength than steel. These features of high-strength textile raw materials, both technical threads and ropes, lend credence to the high scientific and application potential of the new technology of textile barriers, which can compete with existing steel barriers.

The equivalent feature of high strength of threads or ropes used is their high flexibility. In the newly proposed structure of ropes, a simultaneous connection of high strength with high elasticity is assumed, which is very difficult to achieve in one product. Until now, the ropes produced are characterised by high strength, high Young's modulus and low elongation or by high flexibility at low tensile strength. The feature forming the flexibility of barriers is their specific structure of stitches. In the case of mesh barriers, an important parameter of their construction is appropriately selected shapes and sizes of holes. In addition, the openwork structure is strengthened by a multi-axis system of weft stitches. It should be noted that in the concept of multi-layer barriers, the construction of appropriate layers differs both in their structure and in their mechanical properties.

Table 1. *g-forces acting on the human body upon vehicle impact into a barrier.*

Vehicle speed, km/h	**Deformation zone of a vehicle together with barrier deformation, m**											
	Concrete barrier	**Steel barrier**		**Cable barrier**		**Elastic knitted barrier**						
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6,0**
40	13	6	4	3	3	2	2	2	1	1	1	1
50	20	10	7	5	4	3	3	2	2	2	2	2
70	39	19	13	10	8	6	6	5	4	4	4	3
90	64	32	21	16	13	11	9	8	7	6	6	5
100	79	39	26	20	16	13	11	10	9	8	7	7
110	95	48	32	24	19	16	14	12	11	10	9	8
130 - motorway	133	66	44	33	27	22	19	17	15	13	12	11
150	177	88	59	44	35	29	25	22	20	18	16	15
170	227	114	76	57	45	38	32	28	25	23	21	19
200	315	157	105	79	63	52	45	39	35	31	29	26
220	381	190	127	95	76	63	54	48	42	38	35	32

Legend: 🟩 - safe g-force (20 × g), 🟨 - intermediate g-force (from 20 × g to 45 × g),
🟥 - g-force leading to serious injury or death (over 45 × g)

Table 2. *Force exerted on the human body by the seat belt as a result of a vehicle collision with three types of barriers.*

Barrier type	**Concrete barrier**	**Cable barrier**	**Knitted barrier**
Vehicle speed, km/h	130	130	130
Human body mass, kg	62	62	62
Deformation zone, m	0.5	1.5	6.0
Force exerted on the seat belt, kN	82.41	27.47	6.87

Physiological aspects of g-forces acting on humans upon vehicle impact into a barrier

g-Force is a state in which a body is subjected to external forces other than gravity. It is customary to express *g*-force as a multiple of standard gravitational acceleration (*g*).

The effects of acceleration depend on its magnitude, duration, and direction in relation to the occupant. The human body can sustain 3 *g* for up to 3600 s (60 min), 4 *g* for up to 1200 s (20 min), 5 *g* for up to 480 s (8 min), and 8 *g* for a few seconds. A short-term acceleration affecting a person for a split second may not lead to any serious consequences during vehicle collision with a barrier, while accelerations amounting to tens or hundreds of *g* are likely to result in severe injury or even death.

In a NEON car crash test, the behaviour of three dummies, including those of 3- and 10-year-old children in rear car seats, was examined at a speed of 50 km/h. During a frontal collision, the *g*-force affecting the driver and passengers reached 42.5 *g* over 0.075 s, leading to the decapitation of the dummy of a 3 year-old [10].

In order to determine the magnitude of *g*-forces suffered by occupants during a vehicle impact into a barrier, *g*-force simulation was performed. The value of the force exerted on the seat belt by the occupant and the value of the impact energy resulting from a vehicle impact into an obstacle (road barrier) were determined as well. Simulations were performed for four types of barriers: permanent (concrete), steel, cable, and elastic multiaxial knitted barriers. For the purpose of calculations, the speed of the car was assumed to range from 40 to 220 km/h and the deformation zone of the vehicle was adopted at 0.5 m [11 - 14]. In the calculations concrete barriers were treated as an undeformable obstacle; the deformability of steel barriers was in the range of a = 1.0 - 1.5 m, that of cable barriers a = 2.0 - 2.5 m, and that of elastic barriers a = 3.0 - 6.0 m. The *g*-force was determined by calculating the negative accelerations of vehicles according to the formula: $a = v^2/2s$ in m/s^2, where, a – negative acceleration of the vehicle determined for a given speed and deformation (the deformation zone of the vehicle plus barrier deformability), v – speed of the vehicle in m/s, s – deformation zone of the vehicle plus barrier deformation in m. The *g*-force results obtained are presented in ***Table 1***.

The green colour designates safe *g*-force values, not exceeding 20 *g*. The yellow colour signifies border values in the range from 20 *g* to 45 *g*, and the red colour corresponds to *g*-forces exceeding 45 *g,* which, from a medical point of view, is a threshold above which one suffers serious injury or death. Analysis of the results obtained showed that a sixfold increase in speed from 40 km/h to 220 km/h leads to a 30-fold increase in *g*-force for each type of barrier examined. The highest *g*-force values (up to 133 *g*) were obtained for concrete barriers at a vehicle speed of 130 km/h, which is the motorway speed limit. In this case the amount of deformation involves only the 0.5 m deformation zone of the vehicle. In the case of elastic knitted barriers, the amount of their deformability plus the deformation zone of the vehicle reached 6.0 m, thus decreasing *g*-forces 12-fold, down to 11 *g*.

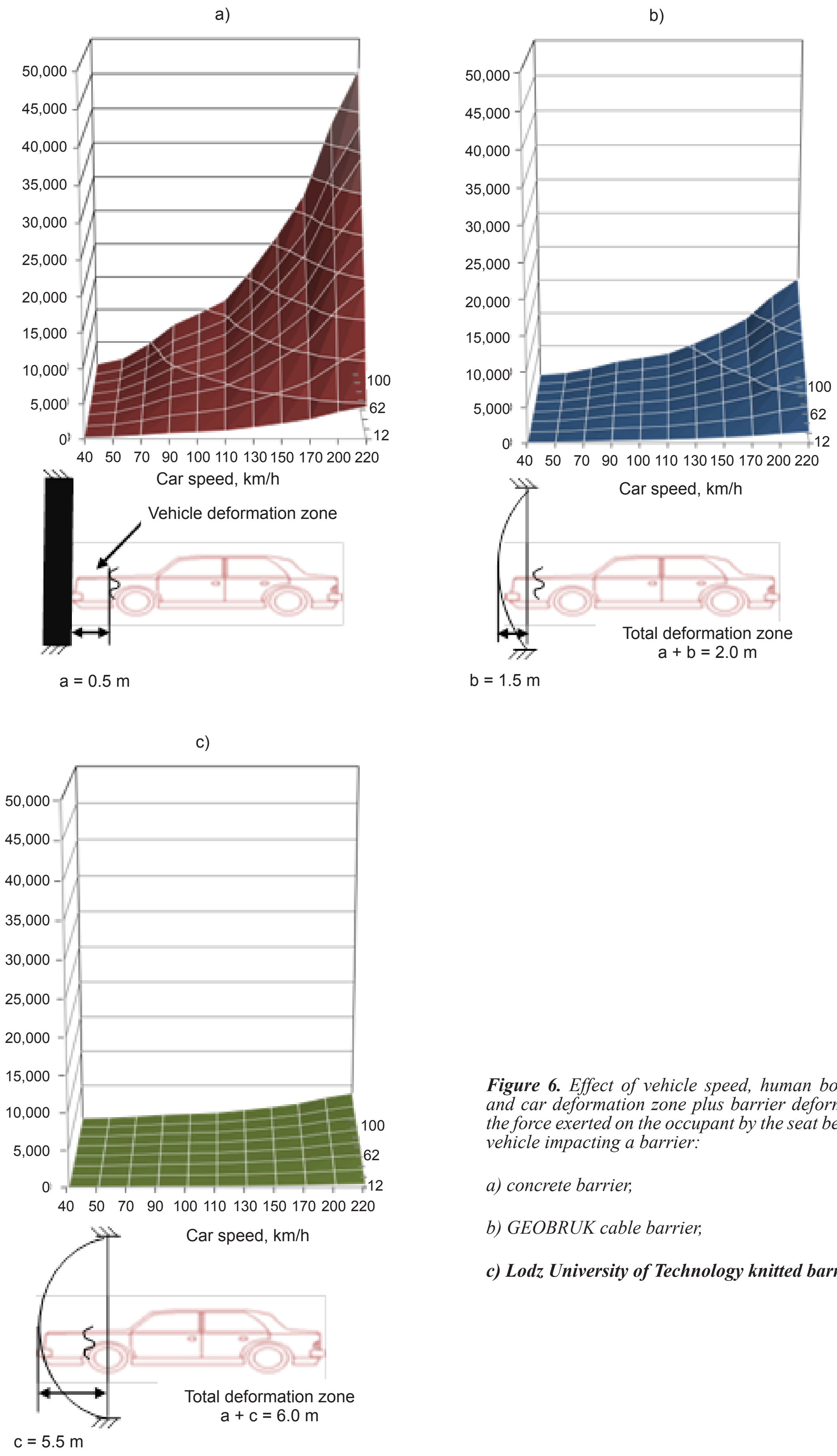

***Figure 6.** Effect of vehicle speed, human body weight, and car deformation zone plus barrier deformability on the force exerted on the occupant by the seat belt upon the vehicle impacting a barrier:*

a) concrete barrier,

b) GEOBRUK cable barrier,

***c) Lodz University of Technology knitted barrier**.*

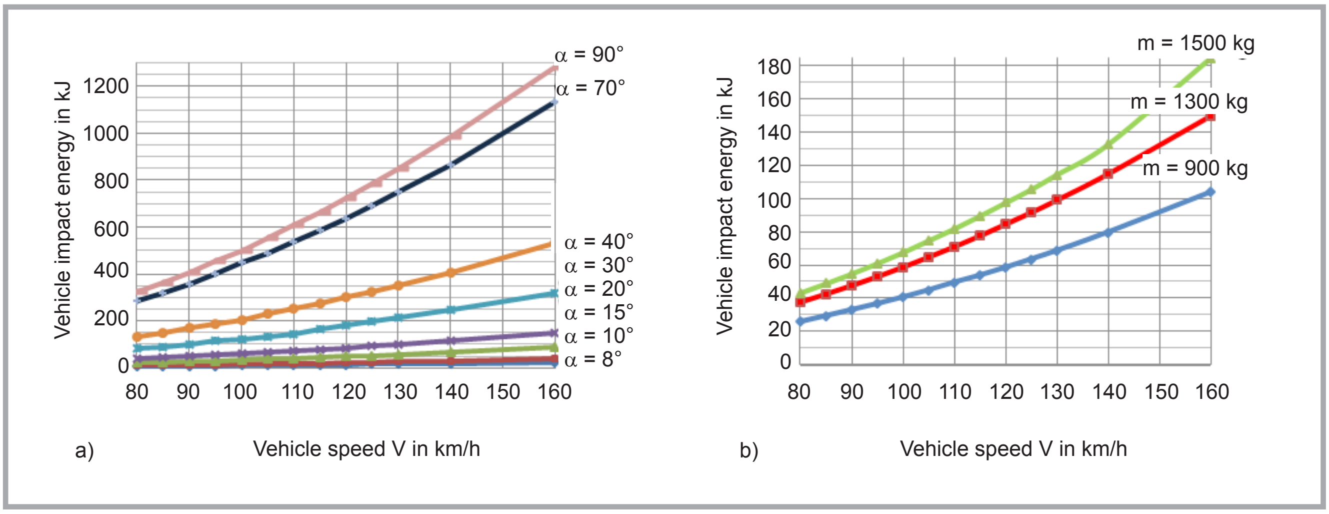

***Figure** 7. Impact energy distribution for cars: a) impact energy values for cars weighing 1300 kg, b) impact energy values for cars at different angles of impact.*

Force exerted on the seatbelt by the occupant

The next phase of the study involved determining the force exerted on the seat belt by the human body. The vehicle speed used for calculations was 130 km/h and the average human weight was taken to be 62 kg. A simulation was performed for three types of barriers: concrete, cable and knitted barriers, with maximum total deformations of 0.5, 1.5, and 6.0 m, respectively [15].

Calculations were done according to the formula: F = m a/9.81, where F – force acting on the seat belt in N, and m – human weight in kg. The results obtained are presented in ***Table 2***.

Analysis of the results showed that the force exerted on the human body by the seat belt resulting from a frontal vehicle impact into a concrete barrier is 82.41 kN, into a cable barrier – 27.47 kN, and into an elastic knitted barrier – 6.87 kN. The relationship between barrier deformability and the force exerted by the seat belt was found to be a linear one. The diagrams presented in ***Figure 6*** show changes in the force exerted by the seat belt in relation to the type of barrier used.

Energy of vehicle impact into a barrier

A simulation was performed for changes in the energy generated upon a vehicle impact into different barriers. The impact energy of a car colliding with a barrier depends on the car weight (m), speed (v), and angle of impact (α).

The impact energy was calculated using the formula $E = ½\ m(v \sin \alpha)^2$, and is treated as an impact severity (IS) factor [16, 17], which makes it easier to compare the barrier behavior during various road situations. It was assumed that elastic textile barriers can absorb from 3000 to 5000 kJ of kinetic energy from a car collision. Impact simulations were performed in accordance with the Polish standard **PN-EN 1317-2 Road restraint systems. Performance classes, impact test acceptance criteria and test methods for safety barriers**. During the study two different calculation models were used for cars and trucks [18 - 20].

Calculations for cars were made for a vehicle weight of 900 - 1500 kg, speed of 80 - 130 km/h (with a 5 km/h increment), and angles of impact of 8° - 20° and 20° - 90° (the latter representing frontal collisions).

In the case of trucks, vehicle weight was considered in the range of 10,000 to 38,000 kg and the speed was taken to be v = 80 - 120 km/h, with the same angles of impact (α = 8° - 90°) as for car calculations.

Analysis of the energy of a vehicle impact into a barrier showed that:

a) in the case of angles of impact α = 8° - 20° (in accordance with PN-EN 1317-2), for cars weighing 900 - 1500 kg and moving at a speed of 80 - 160 km/h, the impact energy was E_U = 4.3 - 184.5 kJ. Above α = 20° and up to α = 90° (frontal collision), the impact energy reached a maximum of E_{Umax} = 1577 kJ.
b) in the case of trucks weighing from 10 t to 38 t (including a bus vehicle weighing 16 t), for impact angles of α = 8°–20° and speeds of v = 80–120 km/h, the impact energy was in the range of E_U = 47.8 - 2469 kJ (E_U = 76.5 - 1039.6 kJ for the bus vehicle). The impact energy for angles above α = 20° and up to α = 90° (representing frontal collisions) was in the range of E_{Umax} = 617.2 - 21,106.9 kJ. The impact energy values obtained are presented in ***Figures 7*** and ***8***.

The following impact parameters lead to impact energies falling within the maximum mechanical strength of elastic knitted barriers (5000 kJ):

- v = 90 km/h at a vehicle weight of m = 38 t and impact angle of α = 40° (impact energy E_U = 4907 kJ),
- v = 115 km/h at a vehicle weight of m = 38 t and impact angle α = 30° (impact energy E_U= 4845 kJ).

In the case of bus vehicles the maximum parameter values for elastic barriers are:

- a speed of v = 90 km/h at an impact angle of α = 80° - 90° (impact energy E_U = 4849 - 5000 kJ),
- a speed of v = 95 km/h at an impact angle of α = 70° (impact energy E_U = 4916 kJ), and
- a speed of v = 100 km/h at an impact angle α = 60° (impact energy E_U = 4627 kJ).

The new approach to developing elastic knitted barriers which are to be used as

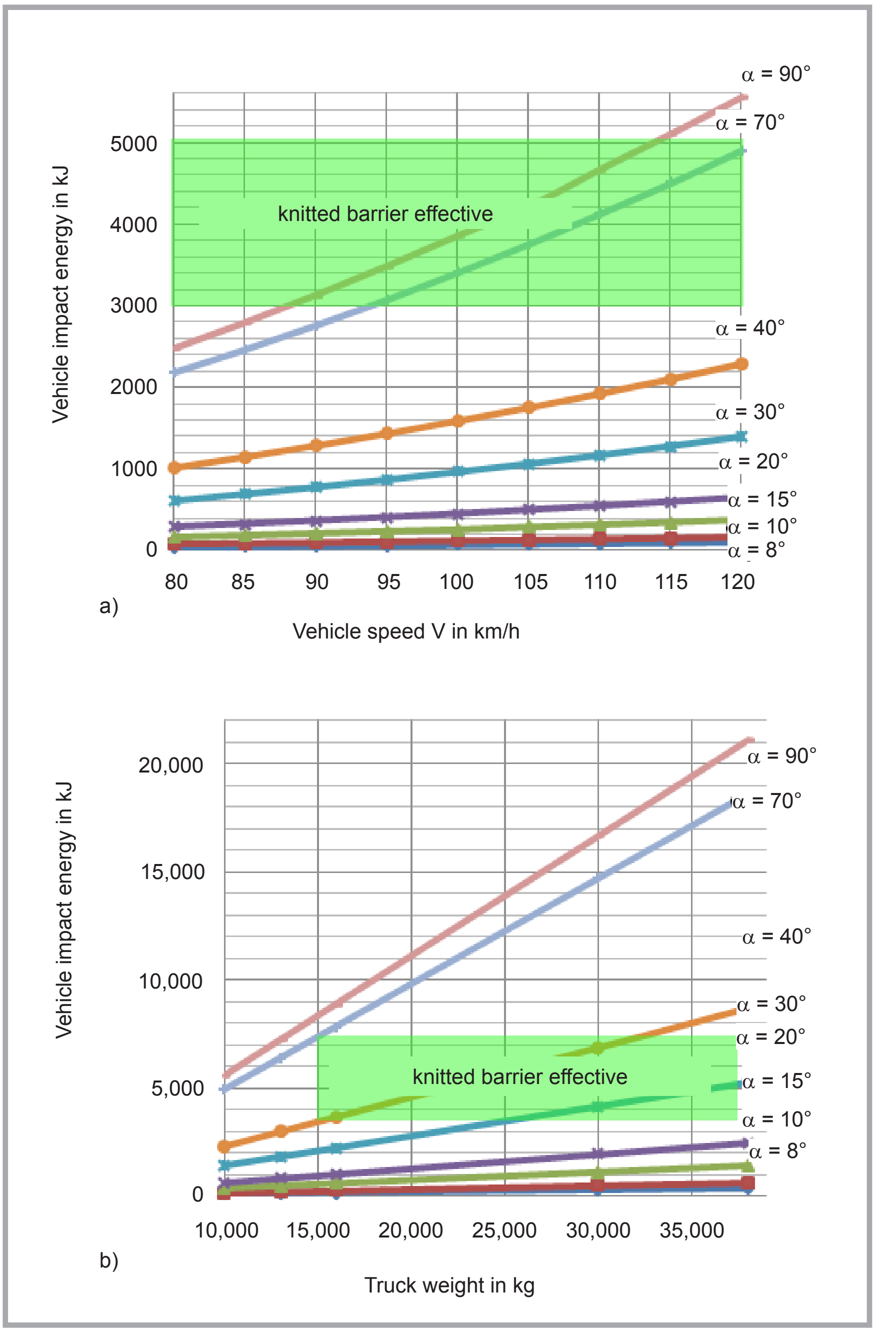

Figure 8. *Impact energy distribution for trucks: a) impact energy values for trucks weighing 10 t, b) impact energy values for trucks moving at different speeds.*

road appurtenances is based on the technical structure of openwork warp-knitted (mesh-like) fabrics of monoaxial or multiaxial multilayer construction [13].

SUMMARY

- There are three types of barriers commonly used in road construction: concrete, steel, and cable barriers. However, such barriers do not guarantee an appropriate level of safety to vehicle occupants in the event of a collision. Total deformability of these barriers together with the vehicle deformation zone is in the range of 0.5 to 3.5 m.
- An alternative solution to rigid road barriers is offered by the Swiss company Geobrugg, manufacturing barriers with a special mesh structure which are mainly used for minimising safety risks. Geobrugg barriers inspired the authors of this paper to research highly deformable and durable knitted mesh-like barriers.
- Simulation of the g-forces acting on the occupant and of the forces exerted on the seat belt by the occupant upon vehicle impact into various types of barriers showed that a 12-fold increase in the sum of barrier deformability and the vehicle deformation zone leads to a 30-fold decrease in the g-force acting on the occupant (in comparison to rigid concrete barriers).
- During a collision of a car moving on a motorway with a speed of 130 km/h with a concrete barrier, a force of 133 g is generated, which leads to permanent injury or death of the driver and passengers, while the force generated in the case of an elastic barrier is 11 g, at which the vehicle occupants are likely to survive.
- The calculations performed proved that at the time of an impact of a car moving with a speed of 130 km/h, the force exerted by the human body on the seat belt is 82.41 kN for an undeformable concrete barrier and 6.87 kN (12 times less) for an elastic knitted barrier.
- Elastic knitted barriers with a mechanical resistance of 5000 kJ can absorb the kinetic energy of a car weighing 900 - 1500 kg at an impact angle in the range of α = 8º - 90º (frontal collision) and at a speed of 160 km/h, as the maximum impact energy generated in such an event is E_{Umax} = 1577 kJ.
- In the case of trucks weighing from 10 to 38 t traveling at v = 80 - 120 km/h and at α = 8º - 90º, the highest impact energy is E_{Umax} = 21,107 kJ, which considerably exceeds the capacity of knitted barriers. Under real life conditions, knitted barriers may absorb the energy of truck impacts in the range of v = 90 km/h, α = 40º to v = 115 km/h, α = 30º. For bus vehicles, the working range of a knitted barrier ranges from v = 90 km/h, α = 90º to v = 100 km/h, α = 60º.

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INSTITUTE OF BIOPOLYMERS AND CHEMICAL FIBRES

IBWCh

Team of Synthetic Fibres

The section conducts R&D in melt spinning of synthetic fibres

Main research fields:

- processing of thermoplatic polymers to fibres
  - ☐ classical LOY spinning
    - fibres with round and profiled cross-section and hollow fibres
    - special fibres including bioactive and biodegradable fibres
    - technical fibres eg. hollow fibres for gas separation, filling fibres for concrete
  - ☐ bicomponent fibres
    - side-to-side (s/s type) self-crimping and self- splitting
    - core/sheath (c/s type)
- processing of thermoplastic polymers to nonwovens, monofilaments, bands and other fibrous materials directly spun from the polymer melt
- assessment of fibre-forming properties of thermoplastic polymers inclusive testing of filterability.

Equipment:

Pilot-scale equipment for conducting investigations in melt spinning of fibres

- spinning frames for
  - ☐ continuous fibres 15 – 250 dtex
  - ☐ bicomponent continuous fibres 20 – 200 dtex
- drawing frames for continuous filaments 15 – 2000 dtex
- laboratory stand for spun bonded nonwovens, width 30 cm
- laboratory stand for investigation in the field of staple fibres (crimping, cutting line)
- laboratory injection molding machine with a maximum injection volume of 128 cm^3
- testing devices (Dynisco LMI 4003 plastometer, Brabender Plasticorder PLE 330 with laboratory film extrusion device)
- monofilament line for 0.3 – 1 mm diameter of the monofilaments.

Implemented technologies (since 2000):

- texturized polyamide fibres modified with amber for the preparation of special antirheumatic products
- polyolefin hollow fibres for gas separation
- bioactive polypropylene POY fibres
- modified polypropylene yarns
- polyolefin fibres from PP/PE waste.

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11th Joint International Conference
CLOTECH'2015

on
INNOVATIVE MATERIALS & TECHNOLOGIES IN MADE-UP TEXTILE ARTICLES,
PROTECTIVE CLOTHING AND FOORWEAR
June 17th-19th, 2015 Lodz, Poland

organized by

- Lodz University of Technology, Institute of Textile Architecture, Department of Clothing Technology and Textronics,
- Kazimierz Pulaski University of Technology and Humanities in Radom, Department of Design, Footwear and Clothing Technology
- Central Institute for Labour Protection – National Research Institute.

11th International Scientific-Technical Conference CLOTECH'2015 was held on June, 17-19 at the Technical University of Lodz. CLOTECH International Conference has been held regularly every two (three) years and is oriented towards the dissemination of knowledge and achievements of national and foreign research centers in such areas like: innovation and development directions of protective clothing, gloves and footwear, resulting from the development of new technologies, new textile and apparel production technology, computer techniques in design and presentation of apparel, certification of products as tools to support the competitiveness of the products. The aim of the conference was broad dissemination of knowledge about the latest materials and technological solutions in the production of clothing, gloves and footwear. The conference was attended by more than 80 guests from different countries like; USA, China, India, Germany, Finland, Czech Republic, Slovakia, Belgium, Switzerland, Turkey, Spain, Portugal, Ukraine, Russia, Portugal, Lithuania and Poland.

The CLOTECH'2015 conference was focused on the following topics:

- advanced materials and technologies in the production of clothing and footwear,
- directions for innovation and development of clothing and footwear,
- new trends in the fashion, design and construction of clothing,
- comfort and well-being,
- protective clothing,
- therapeutic clothing,
- sportswear,
- intelligent textiles and clothing (textronics, PCM, sensors, actuators, etc.),
- mass customization and rapid prototyping,
- clothing testing and modelling,
- thermal manikins,
- textile finishing,
- computer techniques in designing and making up clothing,
- marketing and competitiveness of textiles in the European market,
- standardization and certification of textiles and clothing.

Lodz University of Technology, **Faculty of Material Technologies and Textile Design**,
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