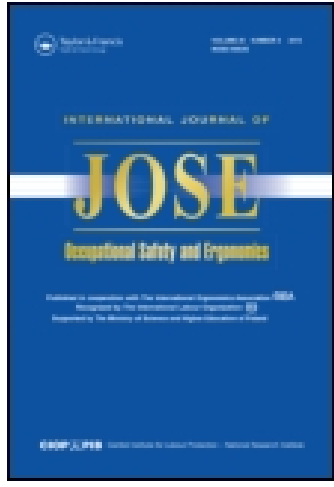


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## International Journal of Occupational Safety and Ergonomics

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/tose20>

### The Damping of Off-Central Impact for Selected Industrial Safety Helmets Used in Poland

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Published online: 08 Jan 2015.

To cite this article: Ryszard Korycki (2002) The Damping of Off-Central Impact for Selected Industrial Safety Helmets Used in Poland, International Journal of Occupational Safety and Ergonomics, 8:1, 51-70

To link to this article: <http://dx.doi.org/10.1080/10803548.2002.11076514>

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# The Damping of Off-Central Impact for Selected Industrial Safety Helmets Used in Poland

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The paper presents a review of head injury criteria and determines an assessment criterion for test results. Parameters characterizing the protection properties of off-central impacted industrial helmets are chosen and the test stands used in the Central Institute for Labour Protection to test those parameters are presented. The idea of damping 2 selected industrial helmets used in Poland is discussed. The test results of the parameters characterizing the protection properties are compared for damped and not damped helmets.

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industrial safety helmets    resistance to penetration    shock absorption  
side impact    protection    tests

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## 1. INTRODUCTION

The head is a very important part of the body and head injuries caused by accidents are very serious. Side impact is the most complicated (see, e.g., Hickling, 1986a) and the number of these injuries accounts for about 72% of all injuries for people wearing industrial safety helmets during occupational accidents. The discussed loads are different in relation to crown impact, that is, impact on the top of the helmet. During off-central impact, the strong dynamic impulse is short. The center of gravity of the head moves and the motion is the sum of the translation and the rotation.

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Existing accelerations and forces can create different injuries as well as skull fractures (or breakage of skull bones), brain injuries, and neck (or cervical spine) injuries. In order to reduce the load of the head to a human tolerance level it is very useful to study side impact on the shell for selected safety helmets.

The analysis of side-impact problems for industrial safety helmets given in the literature is fragmentary and incomplete. Publications on the medical effects of an impact, the tolerance criteria of an impact for the head and for the neck, and injuries associated with side impact are relatively numerous. Coleman (1986) presented an analysis of occupational head injury accidents categorized according to the industrial sector, the severity of the injury, and the age of the injured person. Barnes, Bell, Vassiliou, and Firth (1986) defined the medical question of the injury mechanism whereby the energy is transferred to the head and causes the injury. The aforementioned analyses already prove that the same dynamic options—the impact of the moving striker on the stationary headform and the moving headform on the stationary striker—cause different head injuries from the medical point of view. Proctor (1982) reviewed biomechanical aspects of accidents for users of helmets. Proctor and Rowland (1986) compared head injuries in conjunction with information on helmets being worn and gave some general guidelines for head protection. The same authors said that the stress acting on the head during the impact should be minimized. Hickling (1986a, b) analyzed in detail factors affecting helmet design and helmet displacement forces acting on a peak. Feeney (1986) examined the questions of some important design principles and discussed different organizational factors determining the process of designing a helmet. Hickling (1986a, b) discussed general aspects of helmet design.

Gilchrist and Mills (n.d.) analyzed different criteria of helmet design (biomechanical, materials used for prototype design). Those authors discussed the effects of an impact depending on chosen helmet modifications and on the shape of the striker. In another report, Mills and Gilchrist (1990) selected a test method for industrial safety helmets considering the point and the direction of the impact, the shape of the striking surfaces, the impact energy level, and the surrounding temperature.

Proctor and Rowland (1986) examined statistics of users wearing helmets during a strike and presented the distribution of injuries to different parts of the skull. Rowland (n.d.) analyzed the performance against the impact for industrial safety helmets depending on varying impact energies.

The same author investigated the strain generated in the helmet (i.e., on the headform) by impact and the degradation of the safety function for industrial helmets. Protection against side impact of helmets should be introduced into standards, which was proved by Rowland, Patel, and Keighley (1988). The authors also discussed existing loads. Rowland (1987) compared impact protection of an industrial safety helmet and of a Sikh turban.

Another problem to discuss was the formulation of selection criteria for industrial safety helmets, given in the National Institute for Occupational Safety and Health (NIOSH) Report (NIOSH, 1975). It gave an extensive review of factors influencing head protection and parameters determining safety (damping material, construction of the harness). For the anthropometry of the head, side impact is discussed and three axes of the movement of the skull on the vertebral column are considered as lines of special sensitivity. Hulme and Mills's (1996) report is another comprehensive work. The authors analyzed the effects of head rotation caused by impact, head injury criteria, the angle response of the head and the neck during an impact, and the structure of the neck of the most often used dummies.

In the standards on industrial safety helmets, there is no comprehensive discussion of the problems of helmet resistance and test methods for an off-central impact. Let us analyze the European PN-EN 397:1997 standard (Polski Komitet Normalizacyjny, 1997), obligatory in Poland and in CEN (European Committee for Standardization) member states, old national standards BS 5240 (British Standard, 1987) and DIN 4840 (Deutsches Institut für Normung, 1981), and the international ISO 3873 standard (International Organization for Standardization [ISO], 1977). An analysis proved that the shock absorption test and the resistance to penetration test were carried out for the crown impact only.

From the mechanical point of view, an impact on a helmet is a central or off-central collision of two bodies. There are few publications on the aforementioned—theoretical and experimental—problems that are useful for off-central collision (e.g., Hoppmann, 1988; Timoshenko & Goodier, 1951). A relatively great number of publications is devoted to the general formulation of the collision theory (e.g., Gryboś, 1970; Kowalski, 1980; Leyko, 1975; Timoshenko & Young, 1962). Korycki's (1998) paper was also devoted to a theoretical analysis (principles of the conservation of momentum and of the conservation of energy) of an off-central impact of a striker on a helmet.

## 2. HEAD INJURY CRITERIA

From the literature it follows clearly that there is no concise, complex criterion of head and neck injury. There are a few criteria that can estimate human safety depending on the load acting alternatively on the head or the neck. Authors usually estimate test results by using only one injury criterion.

### 2.1. Head Injury Criterion

The Head Injury Criterion (HIC) represents a tolerance limit assigned to the maximum permissible linear acceleration exposure the head may experience without serious injury (see, e.g., NIOSH, 1975) and can be expressed as

$$\text{HIC} = \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} \quad (1)$$

where  $a$  is the linear acceleration of the head given in acceleration of gravity units (g), and  $t_1$ ,  $t_2$  are the times of the start and the end of acceleration impulse, respectively, given in seconds. This criterion is in common use in the automotive industry. The permissible value of HIC for industrial safety helmets is given as  $\text{HIC} \leq 1000$ . For side-impacted helmets, the aforementioned criterion fails to comply with real loads acting on the user's head. In this case the resultant acceleration of the center of gravity of the head is the sum of the linear and the angular components. We cannot assume the linear direction of the acceleration because in most cases the angular component of the acceleration is decisive.

### 2.2. Rotational Acceleration Criterion

Let us assume the injury criterion as rotational acceleration during a side impact that is not greater than 1700–1800 rad/s<sup>2</sup> (see, among others, Hulme & Mills, 1996). This value was assumed considering the mechanical strength of the cervical spine during rapid head rotation. In this case the complex character of existing acceleration is neglected, because two components are necessary to describe the problem (linear and angular acceleration). Similarly

to section 2.1, this criterion fails to comply with real existing loads during an off-central collision.

### **2.3. Closed Head Injury Criterion**

Gilchrist and Mills (n.d.) introduced the closed head injury criterion on the basis of the Wayne State Tolerance Curve. In this case the maximum acceptable value of the linear acceleration of the head is considered not to be greater than 300 g. This acceleration cannot cause brain injury. This criterion describes the loading of the head by using linear acceleration. The direction of loading does not conform to a real one and no angular movement of the head caused by side impact is introduced.

### **2.4. Open Head Injury Criterion**

Gilchrist and Mills (n.d.) introduced the open head injury criterion on the basis of the Wayne Curve. Let us define 5 kN as the maximum value of the admissible force acting on the head. This force is considered not to cause fracture of the bones of the skull. Head accelerations are neglected. The direction of the force, the kind, and the direction of the dynamic acceleration of the head are not specified. Of course, this criterion is very important for determining the permissible value of head loads during an off-central collision.

### **2.5. Neck Injury Criterion**

Gilchrist and Mills (n.d.) introduced the neck injury criterion on the basis of the Wayne Curve. It specifies the maximum permissible force, which could act on the cervical spine without serious injury. There is a big divergence of the force values, but there are maximum forces tolerated by the user's neck. According to different authors, the forces vary from 3.7 to 5.5 kN. We have chosen the value very close to the maximum, equal to 5 kN. Independently and tested both in conjunction with other parts of the skeleton, Gilchrist and Mills (n.d.) introduced the same level for the neck. The defined force is the same as for the open head injury criterion.

## 2.6. Choice of the Assessment Criterion for Test Results

Let us consider an assessment criterion based on the force acting on the user's head during a side impact as the most comprehensive for real existing loads and displacements. Both the open head injury criterion and the neck injury criterion specify the same value of force, that is, 5 kN. The same value is introduced as the tolerance level for an industrial safety helmet. According to this remark, this value is considered both for a central and an off-central impact (i.e., on the crown and on the side part of the helmet, respectively).

## 3. SHOCK ABSORPTION AND RESISTANCE TO PENETRATION TEST METHODS FOR INDUSTRIAL SAFETY HELMETS

The protective properties of industrial helmets are characterized by two basic mechanical parameters: shock absorption and resistance to penetration. By using the aforementioned parameters, we can assess an industrial safety helmet according to Standard No. PN-EN 397:1997 (Polski Komitet Normalizacyjny, 1997). In this standard shock absorption and resistance to penetration are tested only for a central collision that is on the crown part of the helmet.

### 3.1. Assumptions in the Shock Absorption Test Method

- Shock absorption is measured by the maximum force transmitted to the headform on which the helmet is fitted. A falling striker is the impacted mass (the mass of  $5.0_{-0.00}^{+0.10}$  kg and the radius of the hemispherical striking face  $50 \pm 1$  mm).
- Impact is performed in the normal direction to the external surface of the helmet mounted on the headform.
- The impact force acting on the headform is measured by recording the acceleration of the falling striker.
- The base of the shock absorption measuring apparatus is monolithic and its mass is greater than 500 kg.
- The headform is mounted rigidly and its angle of inclination is adjustable.
- The free fall distance of the striker before impact is  $1000 \pm 5$  mm.

### 3.2. Assumptions in the Resistance to Penetration Test Method

- Resistance to penetration is described by whether or not contact is made between the punch and the fixed headform. Resistance to penetration is considered sufficient if the punch does not contact the headform.
- Impact is performed in the normal direction to the external surface of the helmet mounted on the headform.
- The base of the shock absorption measuring apparatus is monolithic and its mass is greater than 500 kg.
- The headform is mounted rigidly and its angle of inclination is adjustable.
- The punch has the mass of  $3.0^{+0.05}_{-0.00}$  kg, the impacting cone with the radius of the point  $0.5 \pm 0.1$  mm and the angle of the point  $60 \pm 0.5^\circ$ . The height of the cone is 40 mm and its hardness is 45 Rockwell HRC.
- The free fall distance of the striker before impact is  $1000 \pm 5$  mm.

### 3.3. Determination of the Collision Points on the External Surface of the Helmet

In order to perform a shock absorption test and a resistance to penetration test during side impact, it is necessary to determine the collision points (of the striker and of the punch) on the external surface of the helmet. Let us assume that impact will be performed in two perpendicular planes:

- the symmetry plane of the head wearing the helmet;
- the plane perpendicular to the above longitudinal plane, containing the crown point of the shell.

Introducing the symmetry of the cross-section, the tests were performed along three curves (see Figure 1):

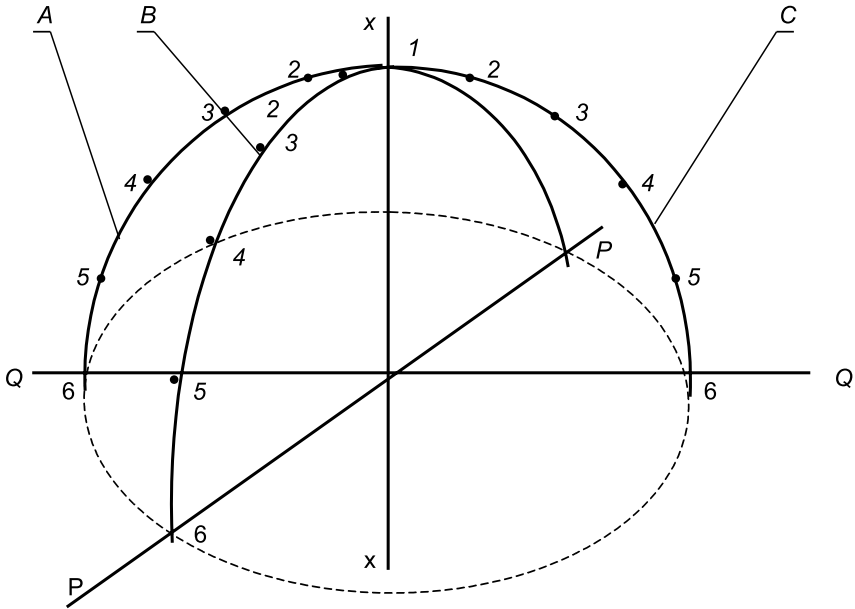
- curve A, which is the frontal part of the symmetry plane section;
- curve B, which is any half of the cross-section;
- curve C, which is the back part of the symmetry plane section.

Each of these curves contains six measurement points. Number 1 is located in each case on the crown of the helmet. Curves A, B, and C are divided equidistantly. It is clear that each point on the external surface of the shell is described by the angle of inclination of the headform (in relation to the x-x axis).

The shock absorption and the resistance to penetration tests are not



performed at point 6, because this point is located on the edge of the shell. This part of the helmet can have different structural reinforcement, a water groove, fixing elements of the chin strap, the ear protector, and so forth.



**Figure 1. Location of measurement points on the shell of a safety helmet.** *Notes.* x-x—axis resulting from the section of characteristic planes; 1QQ—symmetry plane of the head, 1PP—plane perpendicular to the symmetry plane of the head; A, B, C—curves resulting from the section of the shell of the helmet by two characteristic planes, along these curves the measurement points are located; 2-6—measurement points of the force.

#### 4. TEST STANDS FOR SHOCK ABSORPTION AND RESISTANCE TO PENETRATION TESTS OF INDUSTRIAL SAFETY HELMETS

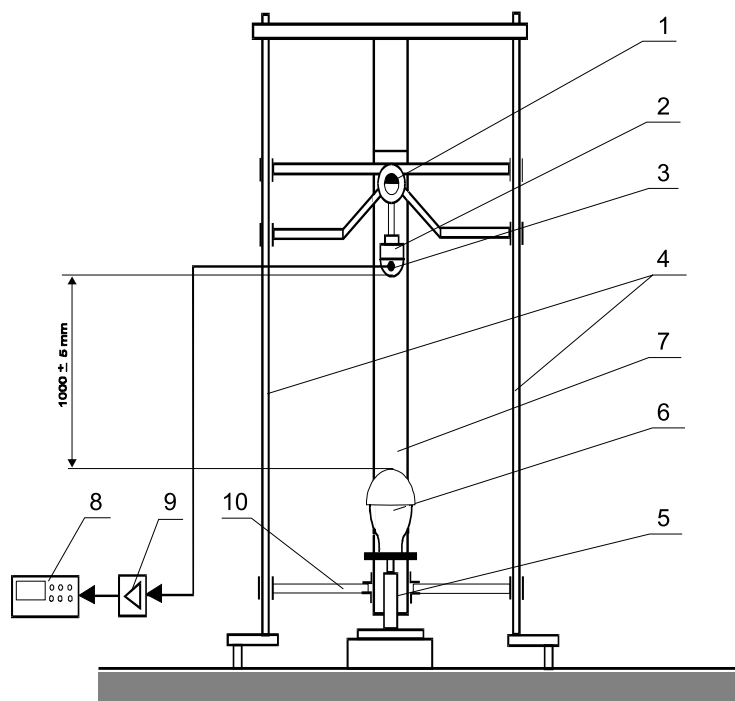
Shock absorption and resistance to penetration of industrial helmets for an off-central collision are tested on a specially designed test stand, installed in the Central Institute for Labour Protection (Łódź, Poland).

##### 4.1. A Stand for a Shock Absorption Test

Figure 2 shows a diagram of a stand for a shock absorption test of industrial safety helmets. It is situated on a monolithic concrete foundation, which

offers full resistance to the effect of the impact and is installed in such a way that there is no the return compression wave. The guided fall of the striker is performed on two parallel guide poles (4). The striker's (2) parameters (mass, geometry of the striking face) are given in section 3.1. The striker is lifted by a truck (10), which is guided on a bracket column (7). At the end of the lifting phase the striker is blocked in an electromagnetic release device (1). The location of the device is adjustable and determines the free fall distance of the striker. The aforementioned solution makes it possible to fix the free fall distance as equal to  $1000 \pm 5$  mm, independently of the headform's (6) angle of inclination.

An Endevco (type 7231C-750, USA), acceleration transducer (3) inside the striker measures the transient acceleration of the falling mass during the impact on the helmet. The electrical signal from the acceleration transducer is transmitted to an Endevco (type 106) amplifier with a low-pass analog

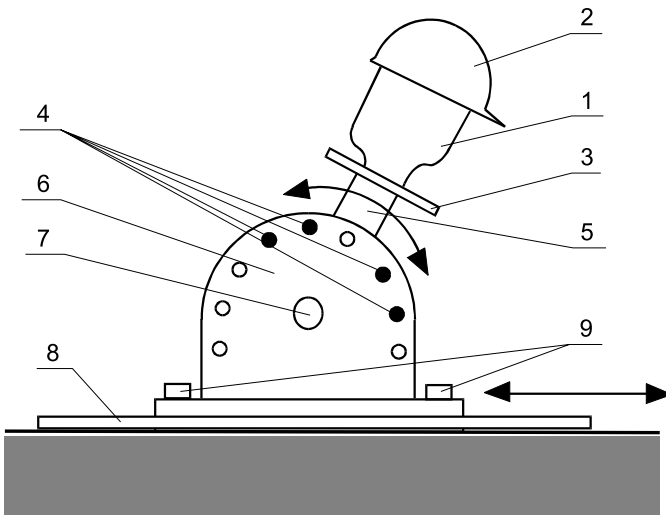


**Figure 2. A stand for a shock absorption test of a helmet during side impact.**

*Notes.* 1—electromagnetic release device; 2—striker; 3—Endevco (type 7231C-750, USA) acceleration transducer; 4—guide poles; 5—mechanism fastening the headform; 6—headform; 7—bracket column; 8—Kikusui (type COM 7101A, Japan) digital oscilloscope with memory; 9—Endevco (type 106, USA) amplifier with an analog filter; 10—lifting truck for the striker.

filter (9) and to a Kikusui (type COM 7101A, Japan) digital oscilloscope with memory (8). The aforementioned set of the measuring apparatus makes it possible to record striker acceleration and consequently to determine characteristic data, that is, its maximum values, the duration of the impulse, and so forth.

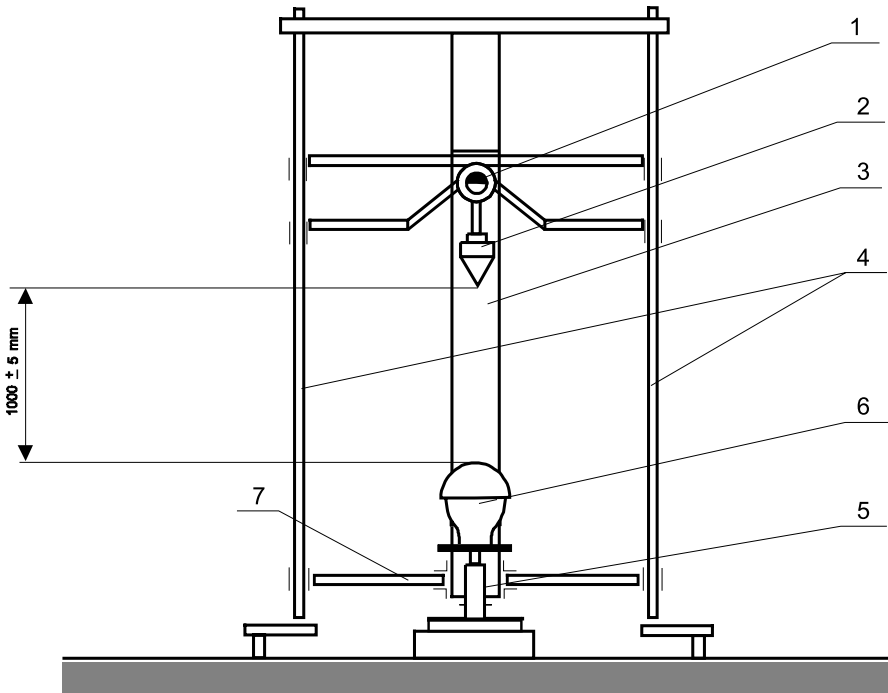
The shock absorption tests of off-centrally impacted helmets were performed with a special interlocking mechanism of the headform. Figure 3 shows a diagram of this mechanism. The headform can be rotated around the vertical axis, inclined in relation to the same vertical axis at the angle of 0–90° and translated in the horizontal plane. The rotation of the headform around the axis is secured by the connection of two plates (3). The headform is inclined by using a rotating beam (5), which is fixed between plates (6) with a clamping screw (4). The whole mechanism is translated in the horizontal plane on a guide rail (8) and fixed with a set of screws (9). This structure provides that the impact of the striker can be carried out at any point of the shell, assuming the normal direction to the helmet surface.



**Figure 3. A diagram of a mechanism that enables an inclination of the headform at a given angle.** Notes. 1—headform, 2—testing helmet, 3—plates that enable the rotation of the headform around the axis, 4—clamping screw, 5—rotated beam, 6—plates holding the beam, 7—rotation axis of the beam, 8—guide rail, 9—screws blocking displacement.

## 4.2. A Stand for a Resistance to Penetration Test

Figure 4 shows a stand for a resistance to penetration test of helmets. Its structure is very similar to that for shock absorption tests of helmets discussed in section 4.1. There are only a few differences in some details of the structure. The stand for the resistance to penetration test does not include measuring apparatus, because the test is described by whether or not contact occurs between the punch and the headform. Instead of the striker, a punch (2) is applied. Its parameters (mass, geometry of the end, hardness) are given in section 3.2. The contact surface is made of a thin leaden plate, which is located on the headform under the test helmet. The plate allows determining the contact between the punch and the headform. When contacting the leaden plate, the punch-edge leaves a trace on it.



**Figure 4. A stand for a resistance to penetration test of a helmet during side impact.** Notes. 1—electromagnetic release device, 2—punch, 3—bracket column, 4—guide poles, 5—mechanism fastening the headform, 6—headform, 7—lifting truck for the punch.

## 5. TESTING SHOCK ABSORPTION AND RESISTANCE TO PENETRATION OF SELECTED INDUSTRIAL SAFETY HELMETS

### 5.1. Choice of Tested Helmets

We tested two types of safety helmets used on a large scale in the industry in Poland. One of these is a Prosna helmet (manufactured by Kaliskie Zakłady Przemysłu Terenowego, Kalisz, Poland), which has a shell made of polyester-glass laminate and whose harness is attached to the shell at four points. Of course, the laminate provides relatively good damping of the impact impulse, even though the helmet does not have additional protective padding. The shell of the second helmet, Unierg (manufactured by Zakłady Tworzyw Sztucznych, ERG, Bieruń, Poland), is made of injected polyethylene and its harness is attached to the shell at six points.

### 5.2. Testing Shock Absorption

Shock absorption was tested according to methods discussed in section 3.1. The helmets were tested on the stand described in section 4.1. The

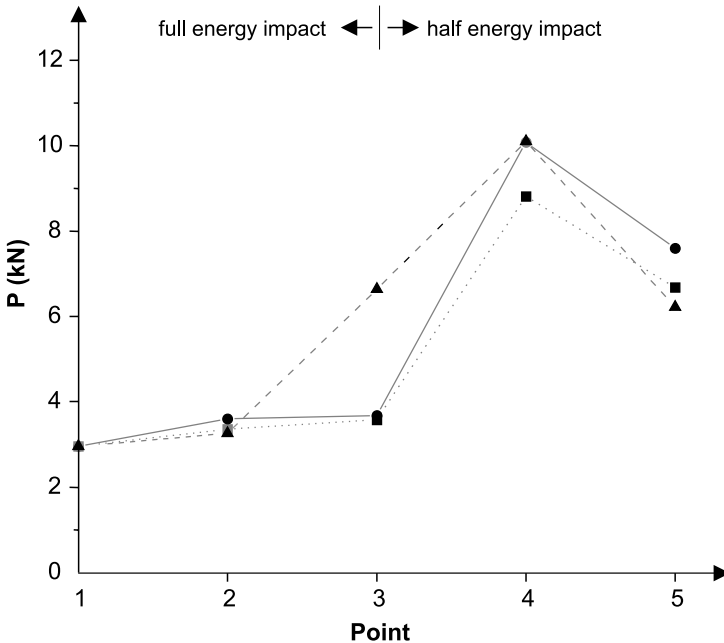
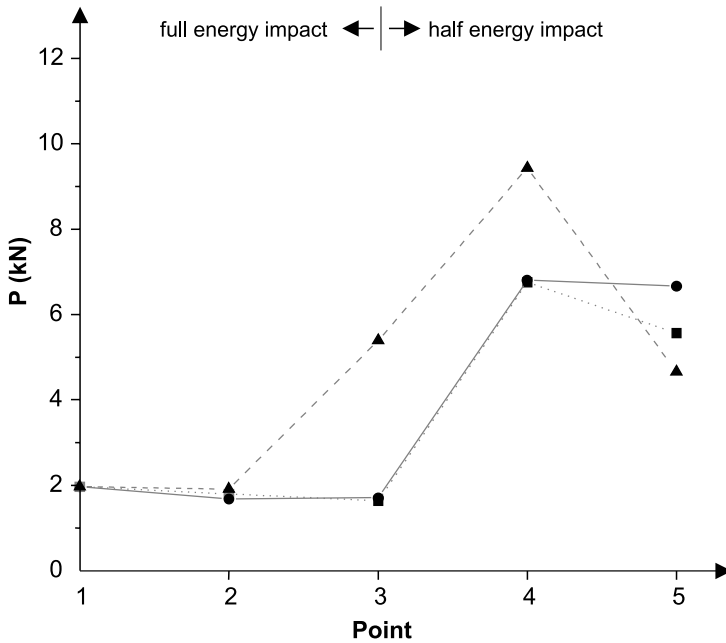


Figure 5. Maximal value of the force transmitted to the headform during impact in a Prosna type helmet. Notes. ■—front impact, ●—back impact, ▲—side impact.

requirement concerning the striker is that the kinetic energy during the impact should not be more than 49 J. It is easy to conclude that for the lower impact points on the helmet, the force transmitted to the headform grows. When the impact force is greater than 5 kN, energy at the next point of the lower location is reduced by half. We reduced the free fall distance of the striker, for example, from 1 to 0.5 m. The results are shown in Figures 5 and 6. The forces transmitted to the headform during impact at the chosen points are obtained along all three curves: A (front impact), B (side impact), and C (back impact).



**Figure 6.** Maximal value of the force transmitted to the headform during impact in a Unierg type helmet. Notes. ■—front impact, ●—back impact, ▲—side impact.

### 5.3. Testing Resistance to Penetration

Resistance to penetration was tested according to methods described in section 3.2 on the test stand described in section 4.2. Resistance to penetration is assessed by the contact between the punch and the helmet fixed on the headform. This requirement is fulfilled if the punch does not contact the headform. The obtained results are given in Table 1 for both types of the helmets. Each table contains information concerning the contact between the punch and the headform.

**TABLE 1. Results of Resistance to Penetration Tests of Helmets Type Prosna and Unierng**

Location of the Point	Point				
	1	2	3	4	5
Front of the shell	no	no	no	yes	yes
Side of the shell	no	no	no	yes	yes
Back of the shell	no	no	no	yes	yes

## 6. CHOICE OF PROTECTIVE PADDING. THE STRUCTURE AND THE TESTING OF A MODEL OF A HELMET EQUIPPED WITH PROTECTIVE PADDING

The essential problems concerning the construction of the helmet with increased protection against off-central impact were

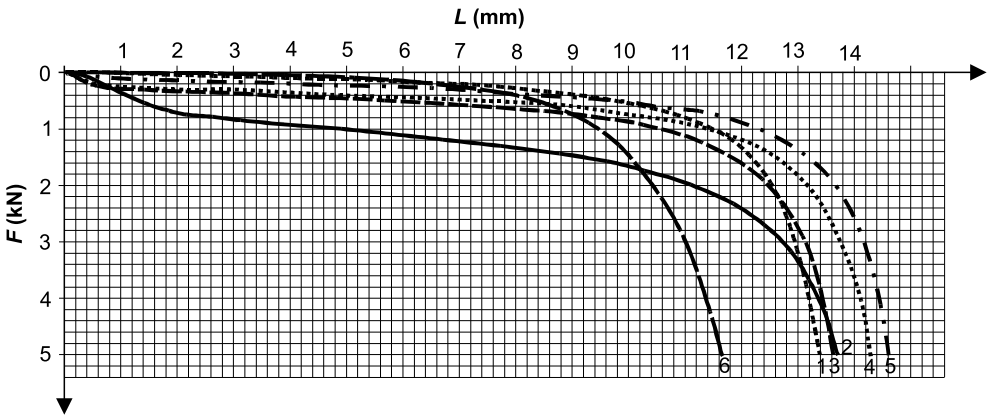
- the choice of suitable protective padding absorbing the impact energy,
- the choice of its shape,
- the location of protective padding inside the helmet.

The basic requirements for protective padding can be formulated as follows:

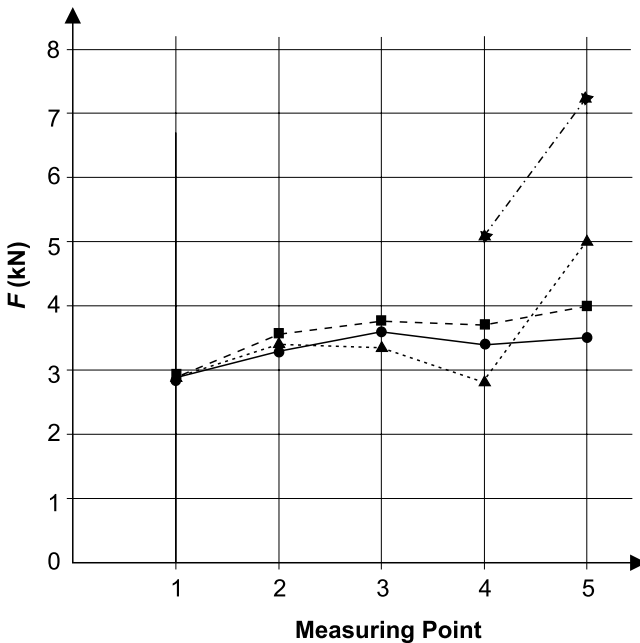
- maximum thickness from 10 to 15 mm (considering the free space between the harness and the shell of the helmet),
- the behavior of the padding: force versus displacement, which enables absorbing impact energy of 49 J with the loading force not greater than 5 kN.

For the aforementioned requirements, we selected and tested porous polyurethane, microrubber, upholstery padding, foamed polystyrene of different densities, and bubble polyurethane foil. We tested samples of exactly defined geometrical dimensions (i.e., a cylinder 50 mm in diameter and 15 mm high). During the compression of each sample compressive force and thickness change were registered. The first tests proved that upholstery padding and bubble polyurethane foil are useless for the aforementioned applications. Thus, we tested samples made of foamed polystyrene (of density 13, 22, 29, and 67 kg/m<sup>3</sup>), porous polyurethane, and microrubber. The obtained results are shown in Figure 7.

Samples made of foamed polystyrene of high density (67 kg/m<sup>3</sup>) showed the best properties and this kind of material was chosen as protective



**Figure 7. Characteristics of materials used for protective padding of helmets (samples 15 mm thick and 50 mm in diameter).** Notes. 1—porous polyurethane, 2—foamed polystyrene of density  $67\text{kg/m}^3$ , 3—foamed polystyrene of density  $29\text{kg/m}^3$ , 4—foamed polystyrene of density  $22\text{kg/m}^3$ , 5—foamed polystyrene of density  $13\text{kg/m}^3$ , 6—microrubber.



**Figure 8. Shock absorption of a Prosna type protective helmet with protective padding made of foamed polystyrene.** Notes.  $\times$ —at the top of the shell,  $\circ$ —from the front of the shell,  $\square$ —from the back of the shell,  $\triangle$ —from the side of the shell,  $\star$ —in the attachment plane.



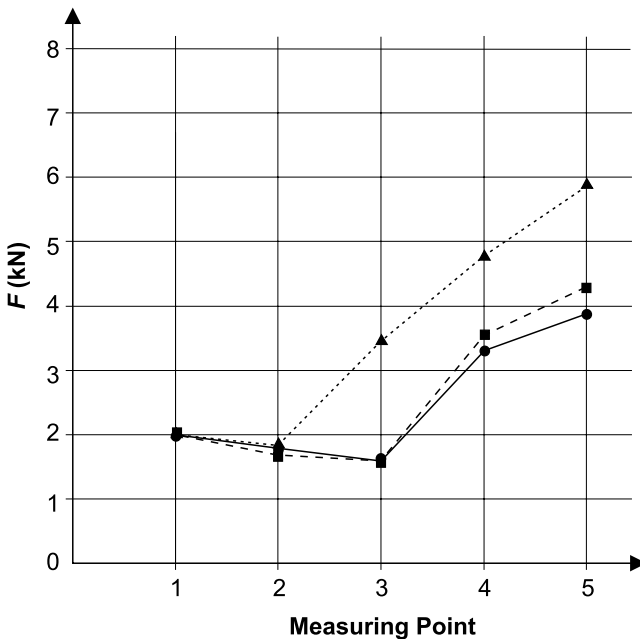
padding. This kind of material provides the most effective absorption of the loading force on the range 0–5 kN. The additional advantages are

- low specific gravity (padding made of this material does not influence the mass of the whole helmet),
- relatively low price.

In order to prepare the Prosna and Unierng types of safety helmets for the tests, pieces of padding made of foamed polystyrene of density  $67 \text{ kg/m}^3$  were introduced between the shell and the headband. The thickness of the padding was within the 10–15 mm range, and the length and the width of the adapted pad were about 50 mm.

The surface of the pad was shaped in such a way that the pad was maximally adjacent to the internal surface of the shell. The center of the pad in line with the point that was impacted during shock absorption and resistance to penetration tests.

Both Prosna and Unierng types of helmets were then tested in order to estimate the protective parameters: shock absorption and resistance to penetration. The results are shown in Figures 8, 9, and in Table 2.



**Figure 9. Shock absorption of a Unierng type protective helmet with protective padding made of foamed polystyrene.** Notes.  $\times$ —at the top of the shell,  $\circ$ —from the front of the shell,  $\square$ —from the back of the shell,  $\triangle$ —from the side of the shell (in the attachment plane).

**TABLE 2. Results of Resistance to Penetration Tests of Helmets Type Prosna and Unierng with Protective Padding**

Location of the Point	Point				
	1	2	3	4	5
Front of the shell	no	no	no	no	no
Side of the shell	no	no	no	no	no
Back of the shell	no	no	no	no	no
Attachments plane in the Prosna helmet	—	—	—	no	no

## 7. ESTIMATION OF THE SHOCK ABSORPTION AND RESISTANCE TO PENETRATION TESTS

### 7.1. A Shock Absorption Test of a Prosna Helmet

For a centrally (i.e., at the top of the shell) impacted helmet the force transmitted to the headform was not greater than 3 kN. Thus, we satisfied the basic criterion of shock absorption, which requires a force not greater than 5 kN.

At points 2 and 3 the force transmitted on the headform was just a little greater than at point 1. The values were different depending on the impact point and were about 3.5 kN. The assumed criterion of the shock absorption test was also satisfied.

At point 4 there is a visible decrease of the force transmitted to the headform (at the point on the side of the shell). The obtained force was comparable with the force for the centrally impacted helmet and was equal to a little less than 3 kN. The other values of the force were practically the same and were obtained at the impact points in the front and in the back of the shell. In fact, the Prosna helmet satisfied the introduced criterion for this impact point.

Point 5 is located close to the edge of the harness. The force transmitted to the headform grew, but the criterion of the shock absorption test was satisfied, too.

For the Prosna helmet we additionally tested shock absorption at points 4 and 5 located in the plane that contains the top of the shell and the center of the attachments of the harness to the shell. The plane does not contain one of the three planes with the measurement points discussed earlier.

Thus, for point 4 the admissible force of 5 kN was slightly exceeded. At point 5 the obtained force was greater than 7 kN.

## 7.2. A Shock Absorption Test of a Unierg Helmet

For the centrally impacted helmet (i.e., at the top of the shell) the force transmitted to the headform was not greater than 2 kN. Of course, we satisfied the basic criterion of shock absorption, which requires a force not greater than 5 kN.

At points 2 and 3 located on the back and the front of the shell, the force transmitted to the headform was greater than at the top of the shell. Force during impact at points 4 and 5 grew rapidly but its maximal value was less than assumed in the assessment criterion (equal to 5 kN).

At points 2, 3, 4, and 5 on the side of the shell (in the plane of the attachments of the harness to the shell), the force transmitted to the headform progressively grew. The impact at point 5 resulted in a force greater than 5 kN, that is, the assessment criterion was not fulfilled.

## 7.3. Resistance to Penetration Tests of Both Types of Helmets

It follows from the resistance to penetration tests of Prosna and Unierg helmets that in every case the punch does not contact the fixed headform. Thus, helmets of both types with a pad made of foamed polystyrene are resistant enough to penetration both for central (at point 1) and off-central impact (at points 2–5).

## 8. CONCLUSIONS

The described structural modifications resulted in a significantly increased protection against off-central impact for the two selected industrial safety helmets used in Poland. This follows directly from the test results of Prosna and Unierg helmets with a pad made of foamed polystyrene. It is easy to make the following conclusions:

- In order to solve the problem we have analyzed the head and neck injury criteria used. For the purpose of the tests one of the analyzed human safety criteria (Gilchrist & Mills, n.d.; Hulme & Mills, 1996; NIOSH, 1975) was accepted. The assessment criterion was based on the force acting on the user's head and neck during side impact. The maximal value of force was assumed in this case as equal 5 kN.
- Both modified structures are resistant to penetration on the assumed level at all points of the outer surface of the shell. There is visible improvement

in comparison to helmets without protective padding—the assumed criterion was not satisfied for the last two points located closer to the edge of the harness.

- The protective padding between the shell and the harness with the headband, results in a very significant improvement of shock absorption during off-central impact. At points located close to the edge of the shell of both tested helmets, the assessment criterion was not fulfilled. The obtained improvement is slightly smaller for impact at the attachment points of the harness to the shell. It is impossible to locate a pad of sufficient thickness in these parts because of the limited free space between the shell and the headband. Shock absorption is much better than for helmets without a protective pad. In this case, the assumed criterion was fulfilled at only three points located at the top of the shells of both helmets (i.e., partially for point 3).
- In Standard No. PN-EN 397:1997 (Polski Komitet Normalizacyjny, 1997) shock absorption and resistance to penetration are tested only for the central impact. On the other hand the test results presented here can be very important for protection against off-central impact. In conclusion, it would be useful for the Technical Committee that prepares standards for industrial safety helmets to become interested in these problems. The described problems and methods of shock absorption and resistance to penetration tests should be very interesting for future work in standardizing.

Thus, the described modification of selected helmets results in a structure that significantly protects the user in off-central collisions.

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