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Impact of the Development of the Design of Firefighter Helmets on the Mechanical Shock Absorption Capacity

Agata Walczak[1*], Daniel Pieniak[1], Paweł Lonkwic[2], Włodzimierz Kupicz[3], Szymon Ptak[1], Piotr Piątek[1], Wiktor Wąsik[1], Artur Renkas[4]

[1] Department of Fire Technology, Faculty of Safety Engineering and Civil Protection, The Main School of Fire Service, 52/54 Slowackiego St., 01-629 Warsaw, Poland

[2] The University College of Applied Sciences in Chelm, The University College of Applied Sciences in Chelm, 54 Pocztowa St., 22-100 Chełm, Poland

[3] Military Institute of Automotive and Armor Technology, 1 Okuniewska St., 05-070 Sulejówek, Poland

[4] Department of Vehicle Operation and Fire-Rescue Equipment, Lviv State University of Life Safety, Kleparivska Street 35, Lviv, Ukraine

* Corresponding author's e-mail: dpieniak@sgsp.edu.pl

ABSTRACT

A firefighter's helmet is used as a basic personal protective equipment item. The purpose of the helmet is to absorb a part of mechanical impact acting towards the rescuer's cervical spine, which may lead to its injury. The aim of the study was to determine the effect of changes in the helmet design on the threshold passive forces transferred to the firefighter's cervical spine. The test subjects were firefighter's helmets compliant with the European standard for helmets used by fire brigades. The study was carried out under model conditions, using special equipment with a head model and an additional force sensor placed under it, where the cervical spine is anatomically located. The central impact energy was assumed to be 60 J. A semi-spherically ended beater was used. The experimentally determined force-displacement characteristics revealed two phases of force increase. Using polyurethane foam as a cushioning insert instead of the expanded polyester used in older designs reduced values of forces in the first phase of the characteristic. There were many cases where the critical passive force value was exceeded, which would have resulted in the cervical spine injury. Modifications in material selection and component manufacturing technology affect the protective capabilities of firefighter's helmets and result in their improvement. Nevertheless, helmets that are currently in use are still affected by forces whose values exceed the ones that are considered to be safe for a firefighter.

Keywords: fire helmet; impact loads; cervical spine loads; mechanical impact depreciation.

INTRODUCTION

According to the report on accidents at work in 2020 prepared by Statistics Poland, head injuries accounted for 9.8% of all injuries, while neck injuries, including the ones related to the cervical spine, accounted for 1.4% [1]. Injuries in the work environment are often caused by falling objects [2].

The main hazards present in rescue operations come from thermal and mechanical exposures. Mechanical hazards occurring during operations can be divided into static and dynamic ones [3]. The static load that affects a firefighter is related to their equipment and personal protective equipment (PPE). In addition, it can be caused by various other factors, for instance crushing a rescuer by elements of a collapsed building. The dynamic loading mode is characterised by a short-term, high-amplitude impulsive action [4]. Firefighters are usually exposed to low-velocity impacts, up to 100 m/s [5], or impacts when the energy is less than 136 J [6]. In rescue operations, firefighters' helmets are most often subject to single-impact loads, e.g. impact on a helmet from a falling structural element [7], a direct impact of protruding structural elements e.g. load-bearing elements or exposed rebar, as well as an impact on an invisible obstacle and injury from debris transported by a blast wave [8]. The most vulnerable part of the firefighter's body is the head, which is protected by a firefighter's helmet. Helmets compliant with the requirements of EN 443:2008 "Helmets used during firefighting in buildings and other facilities" [9], are approved for use in Europe. The essential function of a firefighter's helmet is absorbing the mechanical force that is directed at the rescuer's head, redistributing the intercepted kinetic energy from the direction of the greatest danger and dissipating it not causing a harm to the firefighter [10]. The helmet should work in the way to convert kinetic energy into another form of energy in a stable and controlled manner [11].

The main elements of a firefighter's helmet are a shell and a cushioning insert, which acts as a mechanical energy absorber. Shells were formerly made of laminate and their layers were produced using chemically hardened resins and various fibre mats and fabrics, such as glass or aramid one. In latest helmet designs, the aforementioned way has been replaced with an injection moulding technology in which a plasticised thermoplastic material containing finely chopped fibres is usually injected into the mould. The shell, as an external component of the structure, takes the impact, disperses it over a larger area and absorbs some of the energy. It also protects against the penetration of sharp elements towards the head. The cushioning insert (absorber) absorbs more mechanical impact energy than the shell, mainly due to the relatively long-lasting deformation [12]. This mechanism promotes increased strain work and effective dispersion of impact energy. Absorbers used to be made of expanded polyester, however currently producers use various types of polyurethane foam.

The helmet should limit acceleration [13] and redistribution of forces towards the rescuer's body [14, 15]. Therefore, firefighter's helmets are designed so that there is no contact between the helmet structure and the head, which could lead to a head injury [16]. As a result, some of forces are redistributed by the helmet design towards the spine, and this can cause loads on the cervical spine. The spinal column is a very important part of the skeleton and it is responsible for maintaining a correct body position [17], which is why, among other reasons, its damage is highly undesirable.

Based on finite element method (FEM) analysis presented in the paper [18], it was found that the load limit of the human cervical spine for quasi-static compressive loading is 3 kN. When such a force value occurs, bones start to be overloaded, which can lead to their injuries, while higher values result in a bone destruction. This threshold force level, which can be considered as the limit of acceptable compression forces, was also confirmed in the earlier work [19]. In another source of literature that dealt directly with research on helmets, where dynamic forcing was considered, the force of 5 kN was taken as the critical destructive value [14]. This force was determined based on the resistance of the skull, cervical vertebrae and the brain to mechanical damage [16, 20]. It should be stressed that before mentioned values are estimates. Therefore, the main purpose of this work is to determine the effect of the material and design development of helmets that comply with the European standard on the threshold passive forces transmitted to the cervical spine and an additional purpose is to describe the destruction processes of firefighter helmets. Issues of the effects of dynamic forces on structural elements are also presented by the authors in other fields, the results of which are described in publications [21, 22]. In publication [21], the authors presented the results of their own research involving on-line data acquisition of the operation of slip grippers in various operating conditions of their own design used in passenger lifts. And in publication [22], the authors presented the results of analyses developed from the research results described in article [21] using recursive graphs.

METHODS

In the study firefighter's helmets compliant with the requirements of the European standard for head protection for use during firefighting in buildings and other structures [13] were used. Various models of helmets produced by KZPT Kalisz S.A. (currently Brandbull Polska S.A.) were used. Helmets were manufactured in different years and had different maintenance history. The study additionally included a used helmet produced by Pacific Helmets Ltd. (New Zealand) and a new helmet produced by PAB Akrapović (Croatia). The unused ZS-03 helmet was stored under laboratory conditions, at the constant temperature and was not exposed to atmospheric conditions, while unused helmets produced by KZPT Kalisz S.A. (CV 102 model) and PAB Akrapović were stored

Table 1. List of analysed firefighter's helmets

No.	Manufacturer	Model	Not used/used	Years of use/storage
1	KZPT Kalisz S.A. (Poland)	ZS-03	Not used (N)	11
2	KZPT Kalisz S.A. (Poland)	ZS-03	Used (U)	10
3	KZPT Kalisz S.A. (Poland)	Ak-06 (A)	Used (U)	9
4	KZPT Kalisz S.A. (Poland)	Ak-06 (B)	Used (U)	5
5	KZPT Kalisz S.A. (Poland)	CV 102	Not used (N)	1
6	Pacific Helmets Ltd. (New Zealand)	F7F M3	Used (U)	9
7	PAB Akrapović (Croatia)	Pab Fire HT 04	Not used (N)	4

in the laboratory in their factory packaging, in a dry place at room temperature. Table 1 shows a summary of the tested helmets. The shells of the helmets were made of laminate, with the exception of the CV 102 shell that was made using an injection moulding technology. The cushioning inserts were made of polyurethane foams, with the exception of the one used in the ZS-03 helmet that was made using expanded polystyrene.

The study was conducted under model conditions. The tests were carried out using a DPFtest 1000 drop hammer (Labortech) (Figure 1a) and a hemi-spherically ended beater with a diameter of 20 mm and weight of 0.54 kg (Figure 1d). The helmet was placed on a head model (Figures 1b and 1c) with a system that allowed the head to be tilted, which made it possible to force an impact at different points. In addition to the force sensor located above the beater (active force), an additional force sensor was used under the element supporting the head model, in the place corresponding to the position of the cervical spine (Figure 1e). The latter recorded passive forces redistributed under the head model. The dynamic impact was forced at five points, which were selected according to the guidelines of the European standard [13]. A schematic location of the impact points is presented in Figure 2.

Fig. 1. Test benches for research on firefighters' helmets under dynamic (impact) mechanical loads: a) drop hammer, b) head model, c) helmet superimposed on the head model, place of central impact marked with laser beam, d) beater, e) additional sensor under the head model, in the place of the cervical spine

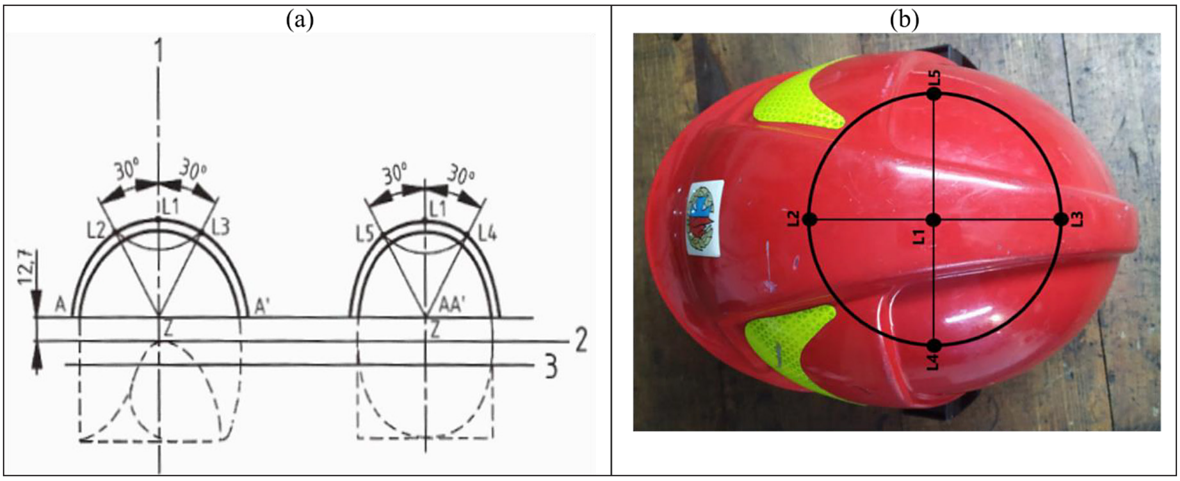
(a) (b)

Fig. 2. Impact points on a firefighter's helmet according to [13]: a) 1 – central vertical axis, 2 – reference plane, 3 – basic plane, L1, L2, L3, L4, L5 – impact points

RESULTS

Figures 3-9 summarise the experimental characteristics of the active (beater) and passive (support) forces in the function of the beater displacement. The characteristics of the active and passive helmet forces have a similar shape. Two phases of force increase can be distinguished. In the first phase, the increase in force occurs with less displacement of the beater than in the second phase. For helmets whose shells were made of laminate, the increase in force in the first phase is greater, compared to a helmet where the shell was made through injection moulding. The characteristics differ in the value of forces and displacements.

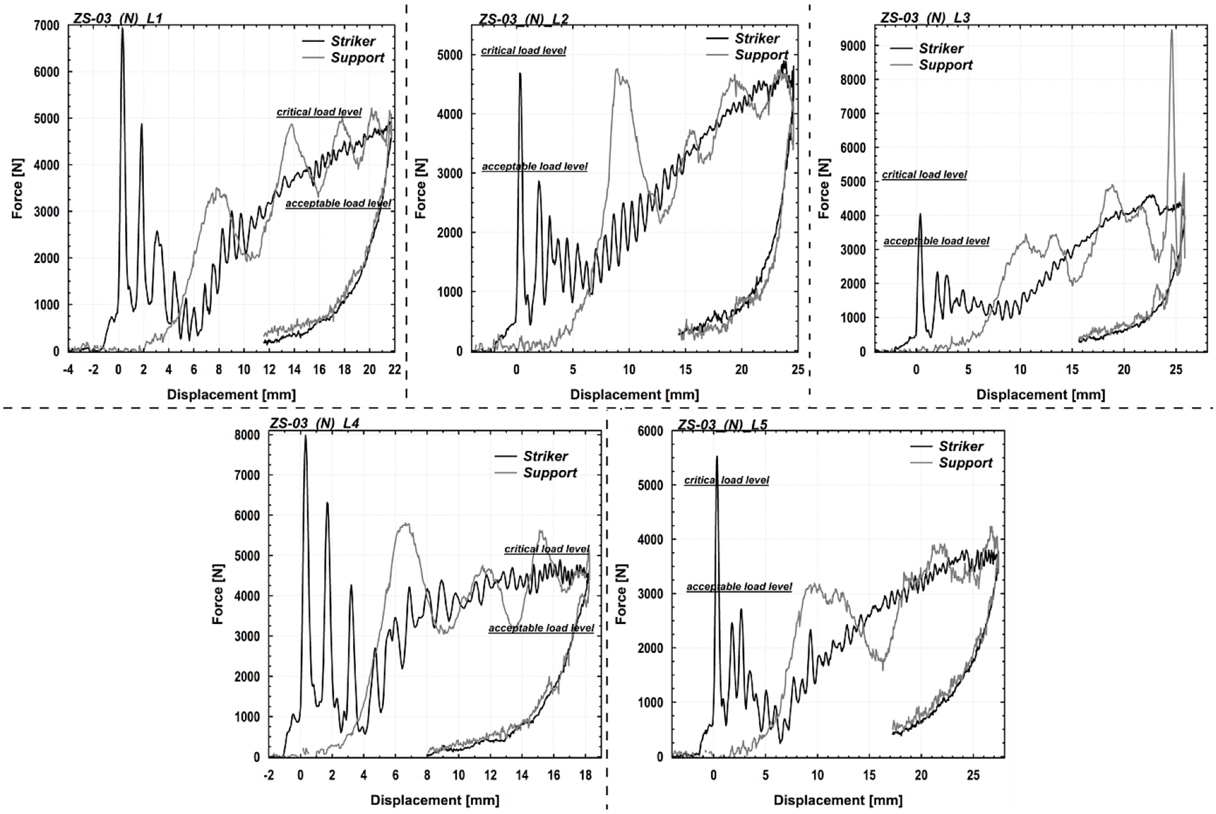

Fig. 3. Force-displacement characteristics of the not used (N) ZS-03 helmet obtained for the mechanical forcing location

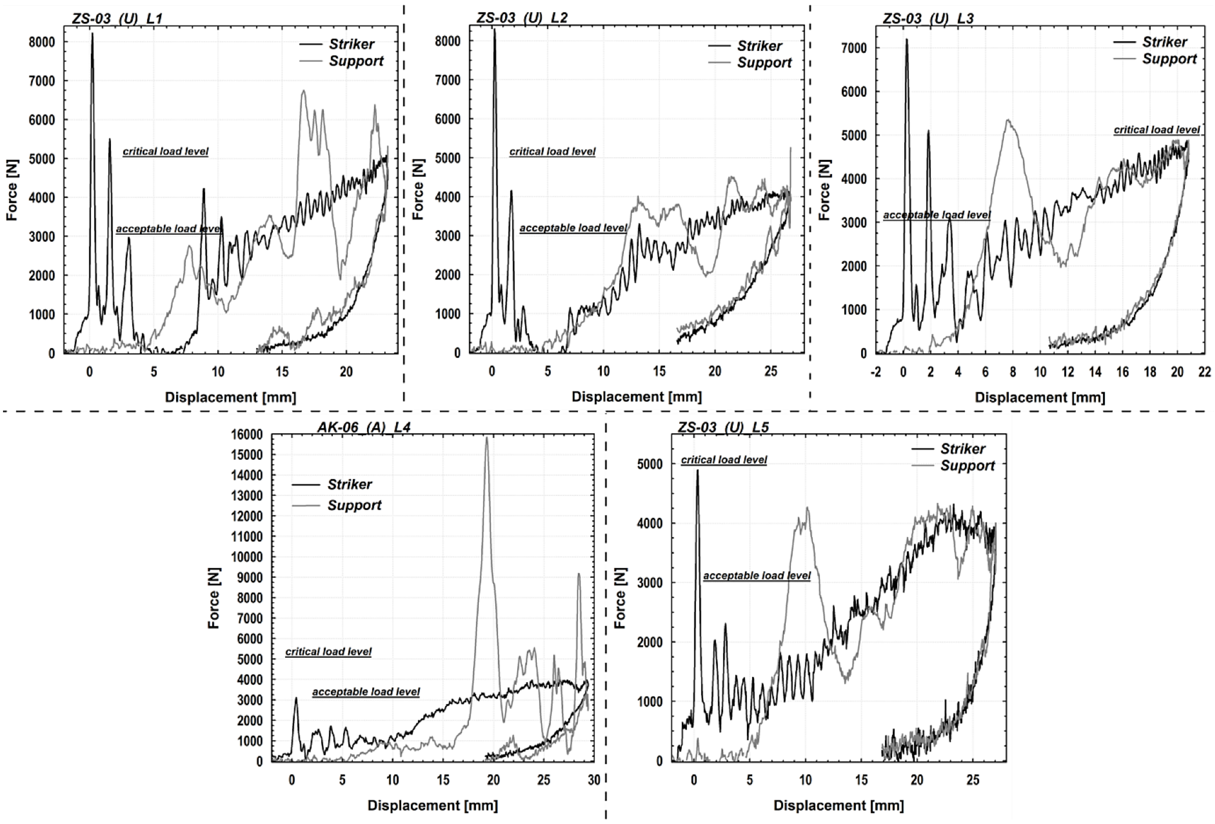

Fig. 4. Force-displacement characteristics of the used (U) ZS-03 helmet obtained for the mechanical forcing location

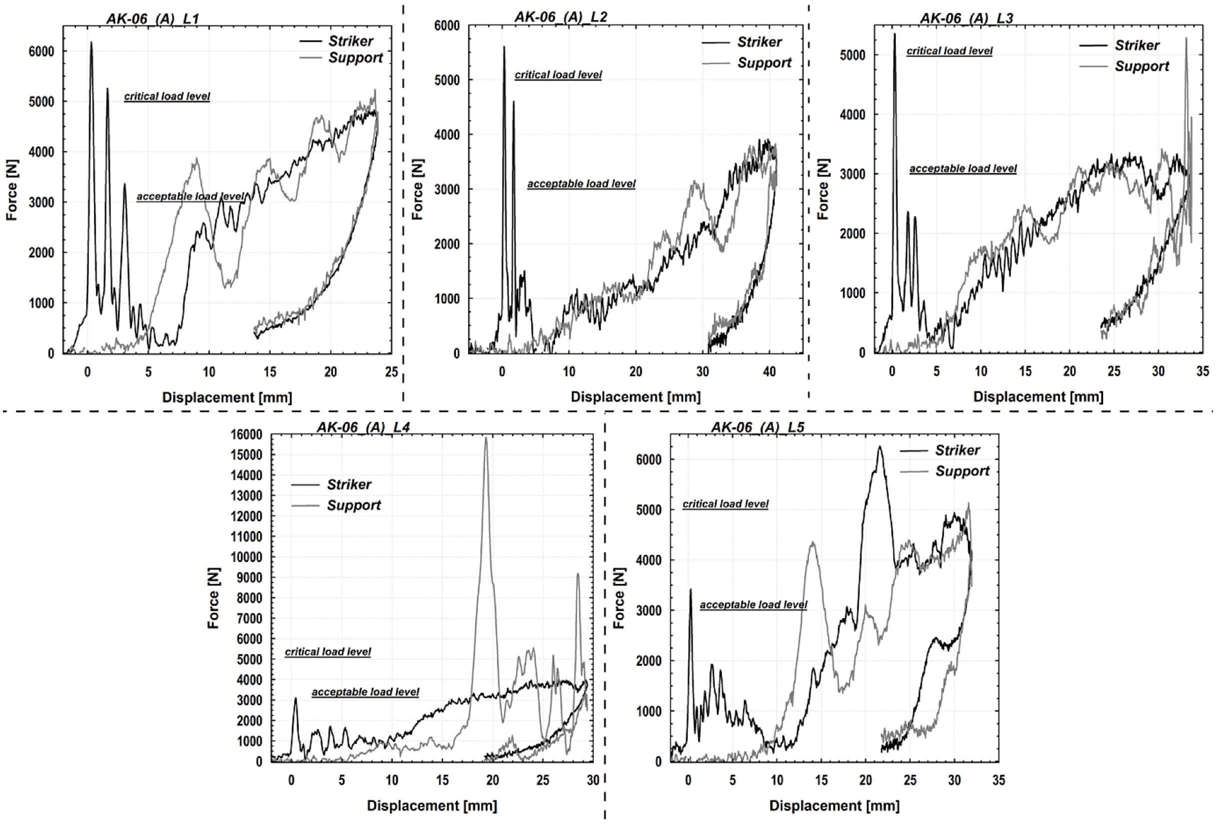

Fig. 5. Force-displacement characteristics of the used (A) AK-06 helmet manufactured in 2009 obtained for the mechanical forcing location

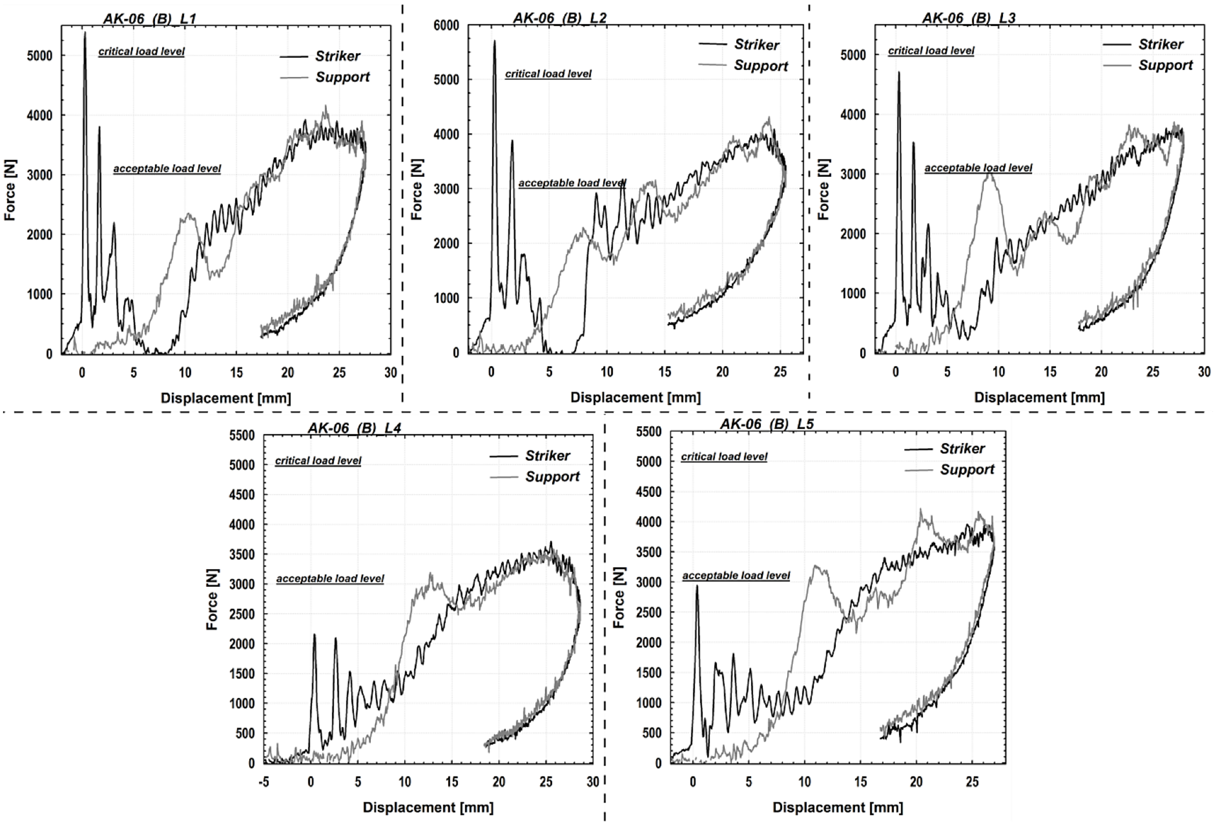

Fig. 6. Force-displacement characteristics of the used (B) AK-06 helmet manufactured in 2012 obtained for the mechanical forcing location

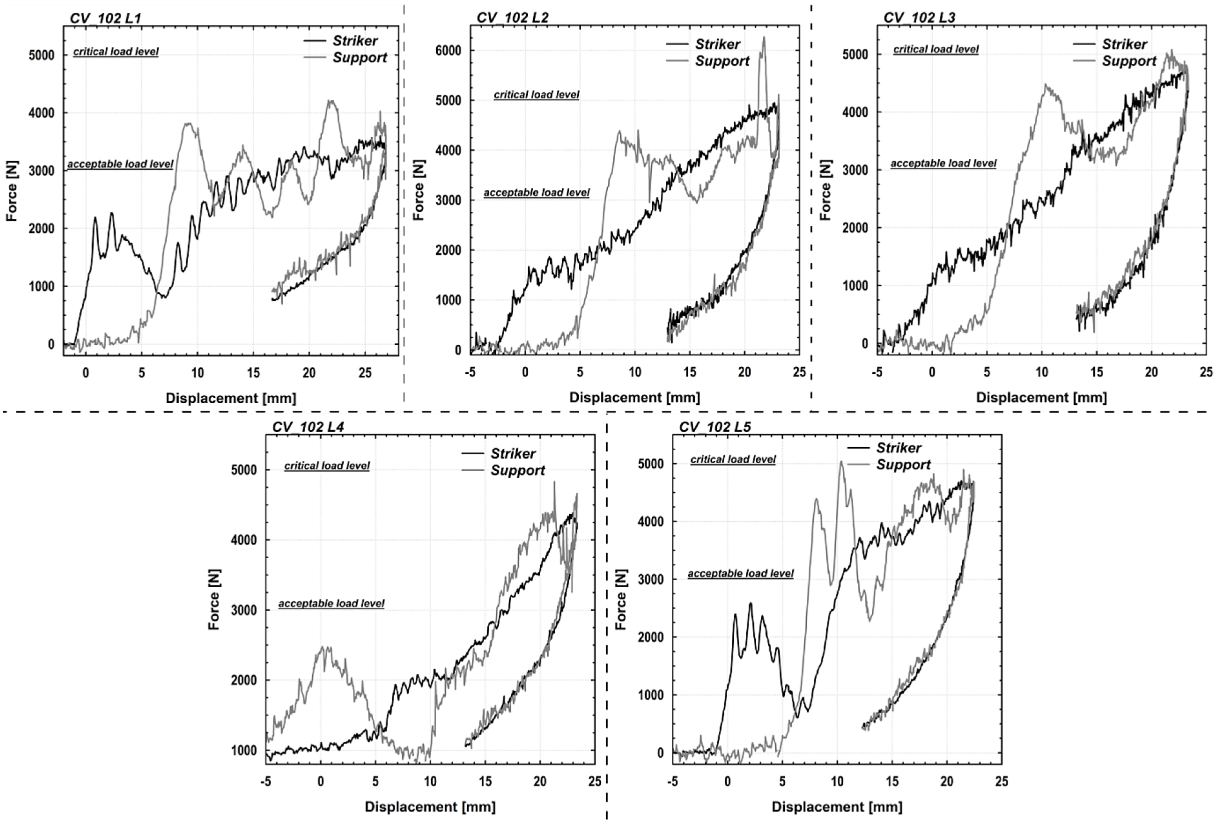

Fig. 7. Force-displacement characteristics of the not used (N) CV 102 helmet obtained for the mechanical forcing location

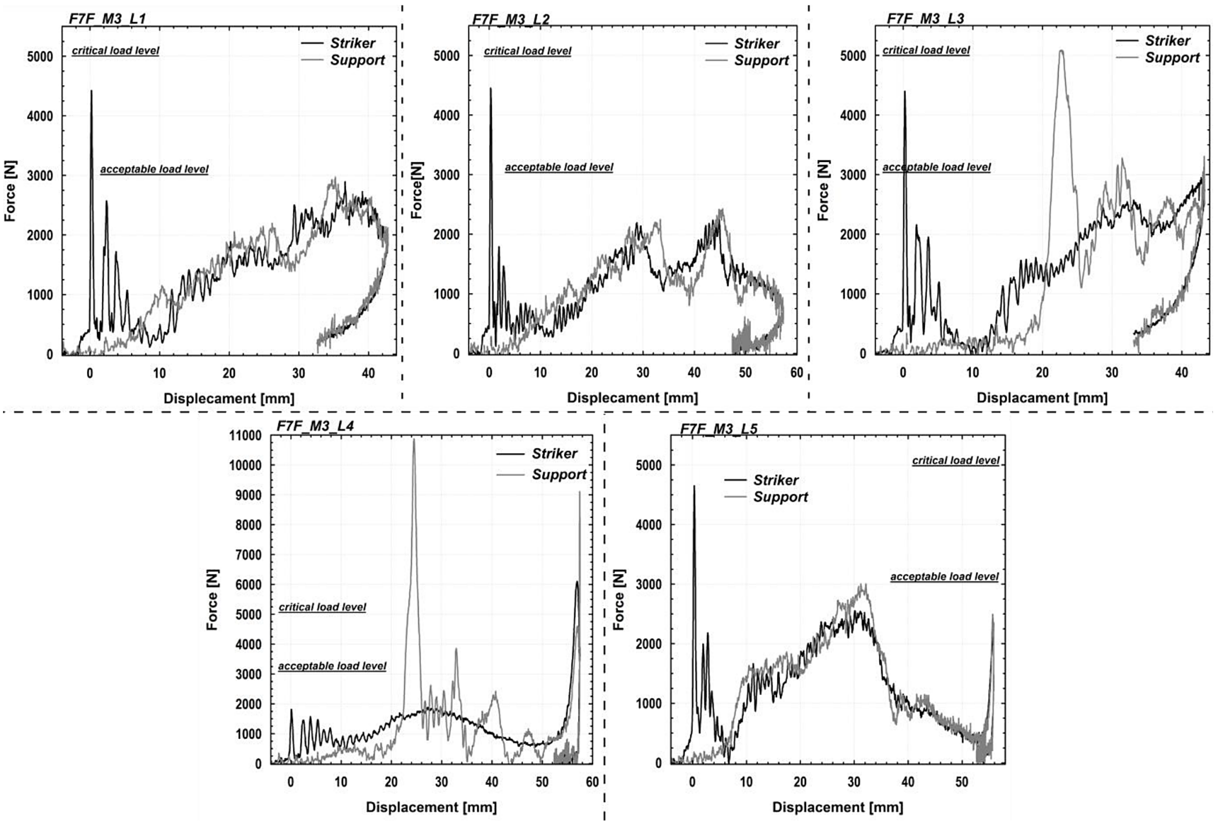

Fig. 8. Force-displacement characteristics of the used (U) F7F helmet obtained for the mechanical forcing location

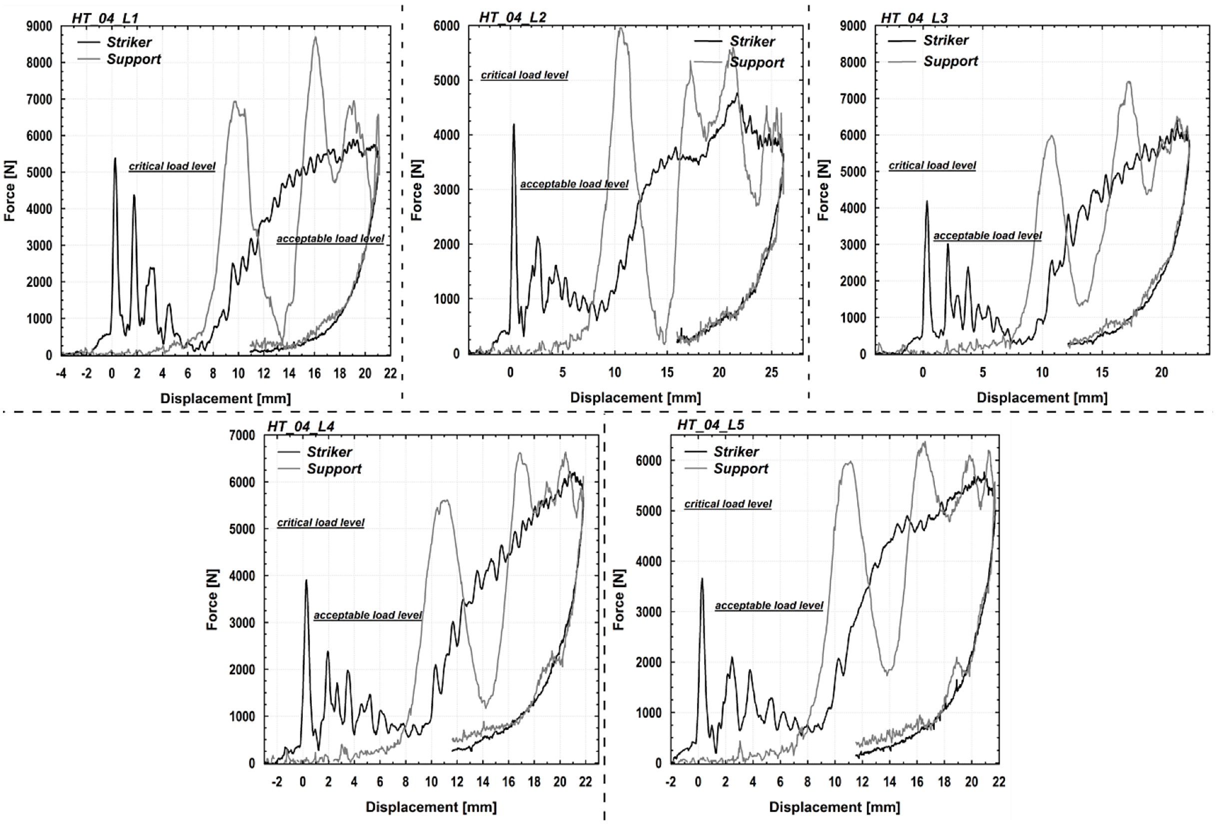

Fig. 9. Force-displacement characteristics of the not used (N) HT 04 helmet obtained for the mechanical forcing location

Table 2 shows the results of the study on achieving threshold forces. Red "Yes" indicates achieving threshold force, while black "No" means the threshold force was not achieved. In this study, the force of 5 kN was taken as the critical value and the force of 3 kN was taken as the acceptable value. The majority sign ">" indicates clear exceeding of the threshold force, while the sign "=" indicates slight exceeding of the threshold force after it has been reached or the value being equal to the threshold value.

Figures 10 present photographs showing types of damage to firefighter's helmet shells, i.e. visible cracks, chips and dents. Some of the cracks are nearly circular and propagate from the point of impact, following the directions of propagation of the impact wave (Figure 10a). In the case of the helmet whose shell was made through injection moulding (Figure 4c), the crack pattern is linear (Figures 10m, 10n).

Figure 10 also presents photographs of selected damage to the cushioning inserts. Damage can be seen in the form of localised surface deformation (indentation) (Figure 10d) and point deformation (Figures 10c, 10k) where the active force from the beater is concentrated. Cracks are also visible,

Table 2. Achievement of passive force thresholds depending on a helmet and an impact point

No.	Acceptable load level	Critical load level	Impact points	Helmets
1	Yes	Yes	L1	ZS-03_(N)
2	Yes	No	L2	ZS-03_(N)
3	Yes	Yes	L3	ZS-03_(N)
4	Yes	Yes	L4	ZS-03_(N)
5	Yes	No	L5	ZS-03_(N)
6	Yes	Yes>	L1	ZS-03_(S)
7	Yes	Yes=	L2	ZS-03_(S)
8	Yes	Yes=	L3	ZS-03_(S)
9	Yes	No	L4	ZS-03_(S)
10	Yes	No	L5	ZS-03_(S)
1	Yes	Yes	L1	AK-06_2009_kw_2007
2	Yes	No	L2	AK-06_2009_kw_2007
3	Yes	No	L3	AK-06_2009_kw_2007
4	Yes	Yes	L4	AK-06_2009_kw_2007
5	Yes	Yes	L5	AK-06_2009_kw_2007
6	Yes	No	L1	AK-06_2009_kw_2012
7	Yes	No	L2	AK-06_2009_kw_2012
8	Yes	No	L3	AK-06_2009_kw_2012
9	Yes	No	L4	AK-06_2009_kw_2012
10	Yes	No	L5	AK-06_2009_kw_2012
11	Yes	No	L1	CV 102
12	Yes	Yes=	L2	CV 102
13	Yes	Yes=	L3	CV 102
14	Yes	No	L4	CV 102
15	Yes	Yes=	L5	CV 102
16	No	No	L1	F7F_M3
17	No	No	L2	F7F_M3
18	Yes	Yes=	L3	F7F_M3
19	Yes	Yes >	L4	F7F_M3
20	No	No	L5	F7F_M3
21	Yes	Yes	L1	HT_04
22	Yes	Yes	L2	HT_04
23	Yes	Yes	L3	HT_04
24	Yes	Yes	L4	HT_04
25	Yes	Yes	L5	HT_04

which indirectly indicates the way in which forces are redistributed through the multi-piece helmet structure (Figures 10g, 10h) towards the rescuer's body. It is also worth mentioning that this form of destruction was obtained in the case of the absorber, which came from a helmet with no maintenance history. Cracks and small deformations were observed at the point of the impact for the absorber presented in Figure 10g. Damage along with perforation of the absorber was observed for the samples shown in Figures, 10k, 10l, 10t and 10u. The deepest damage was observed in the case shown in Figure 10u. No damage to the absorber originating from HT_04 helmet has been observed.

DISCUSSION

From the force-displacement characteristics obtained in the study, a similar failure mechanism

Fig. 10. Damage to the helmet shells and cushioning inserts of firefighter's helmets after the impact: a, c, e, g, i, k, m, r, v) at the central point (L1 according to Figure 2); b, d, f, h, j, l, n, w) at the lateral point (L5 according to Figure 2)

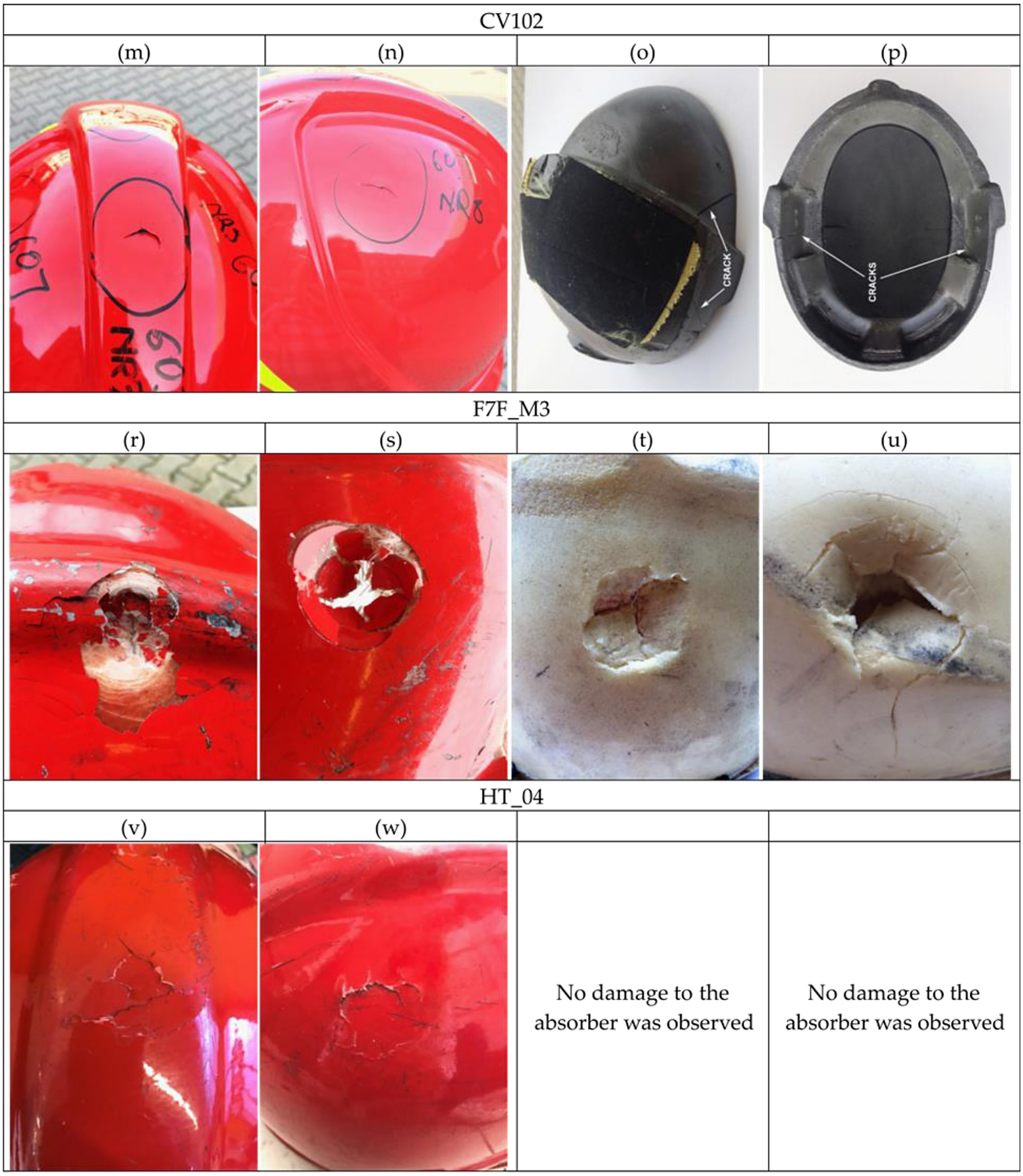

Fig. 10. Cont. Damage to the helmet shells and cushioning inserts of firefighter's helmets after the impact: a, c, e, g, i, k, m, r, v) at the central point (L1 according to Figure 2); b, d, f, h, j, l, n, w) at the lateral point (L5 according to Figure 2)

can be observed for helmets in which the shell was made of a layered composite (laminate) (Figure 3-6, Figure 8-9), while in the case of a helmet with a shell made by injection moulding (Figure 7) a different damage mechanism was revealed, particularly in the first phase of impacting the helmet by a beater. Subsequent development of helmet designs led to applying new solutions [23], which influenced obtained values of forces and displacements, as well as the magnitude and nature of damage to helmet components. For instance, in the case of the ZS-03 helmet produced by the Polish manufacturer, expanded polystyrene used to make the cushioning inserts was first replaced with expanded polyurethane foam. Subsequently, different types of polyurethane foams were used, as evidenced by the characteristics of foams extracted from helmets manufactured in different years, presented in Walczak et al. 2018 [24]. Later, an injection moulding sequence for the production of shells was developed. Nevertheless, there are still ongoing studies that are to enhance properties of head protection items and which are described in scientific papers [25, 26, 27].

The shell of firefighter helmets is the first element to receive and partially dissipate mechanical forcing energy to prevent concentrated stress and penetration [28]. If the energy value is high, the shell will not absorb all the energy and it will be transferred to the cushioning insert and the head [29]. Therefore, the protective properties of helmets depend on two elements, i.a. the stiff outer shell and the flexural inner liner, as described in recent literature sources [30]. Shells of firefighter's helmets are most commonly made using two different technologies. Older models and some of more recent ones (e.g. BHS produced by Kontekst sp. z o.o.), include a laminated shell, manufactured based on a three-dimensional preform and reinforcement in the form of glass and aramid fibre fabrics. The shells of newer helmets are mainly manufactured by a direct injection moulding technology, using thermoplastic polymers (matrix) and staple fibres, e.g. glass and aramid ones (as reinforcement). The following study concerned mainly helmets with laminated shells. Conducted studies revealed high values of active forces, with little displacement in the initial contact of the beater with the helmet (in the first phase of the force-displacement characteristics). At L1 point, for example, they ranged from 450 to 825 N (Figure 3-6, Figure 8-9). In a helmet with an injection-moulded shell, the active force values were much lower in the initial phase and were recorded at longer displacement. For instance, at L1, the maximum value of the active force in the initial phase was approximately 225 N (Figure 7). In the work by Pieniak et al. that concerned a helmet with a shell made by the injection moulding method, similar active force-displacement characteristics were obtained at laboratory temperature, and the maximum active force in the initial phase was approximately 250 N [31].

Cellular materials such as expanded polypropylene (EPP), expanded polystyrene (EPS) or expanded polyurethane foam (EPU) are used to produce cushioning inserts of protective helmets. The destruction mechanism of these materials allows the large amount of energy to be absorbed under low stresses [32]. In the case of motorbike helmets, expanded polystyrene is most commonly used due to its convenient cost-benefit ratio [33,34]. Expanded polystyrene was also used in firefighter's helmets as a cushioning insert, but it has been replaced with various types of expanded polyurethane foam. EPS foams are capable of absorbing energy, but when exposed to multiple impact, this capacity deteriorates. It is connected with the change in the stiffness level due to higher density of the material [35]. As a result, a permanent plastic deformation of materials occurs, especially in high-energy collisions [36]. The increase in stress values in the stress-strain characteristics in the plateau range indicating cumulative structural changes was noted in the work [3]. While being maintained, a firefighter's helmet is exposed to mechanical impacts, which may have resulted in changes occurred in the material of the insert. In addition, it was noted that the maximum values of active forces in the initial phase of the force-displacement characteristics were higher for helmets with a cushioning insert made of expanded polystyrene (Figs. 3-4) compared to helmets whose inserts were made of expanded polyurethane foam (Figs. 5-9). This might be due to the greater rigidity of polystyrene foam. Only in the case of this insert, there was no fracture of the material, but only a plastic deformation (Figures 10c, 10d). The work by Walczak et al. showed that materials made from expanded polystyrene are stiffer than foams made from polyurethane [3]. The exception was the polyurethane foam used in the production of the AK-06 helmet (B), which was also characterised by high stiffness. The active force values observed in the present research for the AK-06 helmet (B) in the initial phase of the force-displacement characteristics are lower than those recorded for the ZS-03 helmets (Figures 3-4, 6). Nevertheless, in this case, little foam cracking was observed compared to the other damaged polyurethane foams (Figures 10k, 10l).

The force and displacement values vary depending on a helmet type. This is related to the use of materials with different properties [37]. In most cases of the central impact (L1), the rupture of a fibre weave or a shell and the crack in the cushioning insert resulted in a lower value of active forces in the second phase of the force-displacement characteristic (Figures 6-7, 9). The exception is the AK-06 (A) helmet (Figure 5), for which the observed displacement was lower. In the case of the helmet Ak-06 (B), which was manufactured later, the value of the active forces in the second phase was lower. The highest values of forces in the first phase and high values of forces in the second phase of the force-displacement characteristics were obtained for the helmet in which neither the fibres nor the cushioning insert (ZS-03) broke, (Figure 3-4). It was also noted that the maintenance of the ZS-03 helmet affected only the increase in the value of the maximum active force in the first phase of the characteristic curve. The values of displacement and maximum active force in the second phase did not change significantly.

Impact energy is absorbed, among other things, by the destruction mechanism [38]. In the case of laminated shells, the characteristic failure mechanism is matrix cracking, delamination, fibre/matrix debonding and a fibre breakage [39]. In the discussed study, only the ZS-03 helmets did not sustain a fibre breakage. On the other hand, matrix cracking, delamination and fibre/matrix debonding were observed. No damage to the cushioning insert was observed only in the case of the HT 04 helmet. This might result in high values of active forces in the second phase of the force-displacement characteristics, higher than those recorded for other helmets. However, it should be noted that force-displacement characteristics, including force values, depend on the point of impact. This is related to the shape and thickness of the helmet components [40]. For example, in the case of AK-06 helmet (B), at point L4 it was observed that the fibres reinforcing the shell broke (Figure 10j) and a permanent deformation, as well as a fracture of the cushioning insert occurred (Figure 10l), while at point L1 there was no fibre breakage (Figure 10i) and the plastic deformation of the foam was slight (Figure 10k). The values of the active force obtained at the final stage were lower at the point where more damage was recorded (Figs. 6a, 6d). In the laminate shell cases, there was initiation and propagation of primary cracks. Linear cracks developed in two (Figure 10n) and three (Figure 10m) directions. The same mechanism of destruction of helmets with an injection-moulded shell, at room temperature, was noted in the work of Pieniak et al. [31].

Overally, firefighter's helmets should be designed to prevent the contact between the central helmet structure and the head, which may result in head injuries [14]. Therefore, some forces are redistributed through the design of the helmet towards the cervical spine. The central impact can lead to compressive loads on the cervical spine. In the experiment whose results are presented in the following work, an additional sensor was used under a model of the head. Remembering about all inadequacies that may occur while simulating real hazards in laboratory conditions, it can be concluded that the passive force sensor (support) enabled the identification of forces with vector directions that greatly coincided with the axis of the cervical spine. In the paper [18], it was shown that compressive loads of the cervical spine may cause deformations that possibly result in overloading, injuring or even destroying the cervical spine. In the same paper [40], based on the distribution of principal (compressive) deformations obtained using the FEM method, the strength limit of the human cervical spine for quasi-static compressive loading was found to be 3 kN, while in another paper, the critical value of the force resulting from a central impact on the parietal part of the head was considered to be 5 kN [14]. The paper [41] demonstrated higher spinal ligament strength at higher loading rates. Therefore, adopting the force values from the works [14] in the analyses seems to be more appropriate for dynamic load situations of an impulsive nature. Therefore, the following study considered both values, except that the value of 3 kN was considered to be an acceptable value. Unfortunately, the own research has revealed many cases where the accepted force thresholds were exceeded, and this applies to almost all of tested the helmets. In the case of more recent helmet designs, critical forces (AK-06 (B)) were not exceeded or force thresholds were exceed less frequently and less significantly (CV 102), as shown in Table 2. It should be noted that the helmet currently manufactured by Brandbull Polska S.A. (formerly KZPT Kalisz S.A.) is still the CV 102 helmet.

CONCLUSIONS

The following conclusions have been drawn from the research and analyses:

- The design of firefighter's helmets has been changing in recent years due to using different materials and technologies. The development is reflected in the values of the active forces transmitted towards the rescuer's head. In addition, the values of the passive forces that are directed towards the cervical spine are changing.
- The failure mechanism of shells made with injection moulding and lamination technologies and inserts made with different foams was different. Different characteristic shapes and

force and displacement values were obtained. It was observed that the fracture of the shell and the perforation of the cushioning insert, in most cases, resulted in the decrease in the values of forces acting in the central direction to the cervical spine.

- In spite of changing the manufacturing technology, impact energies that can occur during rescue operations still need to be considered as highly risky for the cervical spine since the thresholds values of forces were reached or exceeded.
- Further research, focused on the application of new material technologies and designs (shape, component connections, etc.), seems to be necessary.

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