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Simulated depiction of head and brain injuries in the context of cellularbased materials in passive safety devices

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Abstract

The performance of passive safety devices to protect vulnerable road users, or otherwise endangered persons, from severe injuries in cases of impacts and accidents has improved notably in recent decades. The devices' levels of performance appear to have plateaued but the numbers of severe injuries and deaths caused in such incidents could be decreased further if new solutions are found. At first, the possibilities for improving the impact behavior of passive safety devices may appear to be restricted to device geometry; however, it is in fact also possible to rethink the applied materials and to utilize natural principles in their design. In this study, impact related brain injury mechanisms and injury criteria are investigated using dynamic simulations and Finite Element Head Models, results from which are compared with data collected from real-life accidents. As these tools are advancing considerably in terms of accuracy, information density and complexity, they provide, like expert knowledge from the fields of biomechanics, biomedicine and neuroscience, valuable input for further development.

Introduction

The main reasons for the occurrence of traffic collisions are increasing traffic density and the coming together of both predictable and unpredictable participants within a complex system (Jurecki & Jaśkiewicz, 2012; Jurecki, Jaśkiewicz & Zuska, 2013). Aside from regular road use, a simple stumbling can lead to head injury in industrial or workplace environments. As the head is an often unprotected part of the human body, these situations can lead to severe damage to the brain, which is generally only preventable or reducible by the use of passive safety devices such as helmets and safety caps (Ptak et al., 2016). While the hard outer shell of such devices serves to distribute the force applied at impact over a wider area, the dispersion of energy, by deformation, is achieved in most cases by a liner made out of Expanded Polystyrene (EPS), a cellular-based synthetic shock-absorbing material well known for its use in packaging, underneath. Although these safety devices are commonplace and have already prevented numerous otherwise fatal accidents, research has revealed that such helmets may not provide effective protection as the severity of injury may increase with the rotational acceleration during an impact. Thus, a reduction of the number of severe injuries and deaths caused by head impacts is still a major concern demanding evolution of the applied principles of energy distribution and shock absorption throughout the safety device. This article reviews state-of-the-art techniques used in the application of cellular-based materials in helmets and the usage of Finite Element (FE) Head and Brain Models to verify impact consequences concerning the integrity of the safety device user.

Materials in passive safety devices

Passive safety devices are primarily expected to absorb impact energy in an adequate, user-friendly way. They are required to distribute the applied, possibly critical force, over a large area and protect the secured system (e.g. the head) from damage through deformation of the energy-absorbing material. The destruction of the safety device occurs in naturally occurring cases of critical impact.

A safety helmet, as a representative of this category of safety devices, generally consists of three layers. Often, a hard outer and slightly shock-absorbing shell coats the main absorption liner; the third and innermost liner serves only for the wearer's comfort and does not contribute to further relevant shock absorption. As a state-of-the-art technology, the absorption liner is, in most cases of certified and road-legal safety helmets, made out of Expanded Polystyrene (EPS). EPS is mostly known for its applications in packaging but is also used in helmets due to the ease with which it is molded, its advanced shock-absorbing performance, low density and favorable benefit-to-cost ratio (Fernandes, 2017). For illustration purposes, Figure 1 offers a macro view of the structure of expanded polystyrene and a generalized stress-strain-curve for the material.

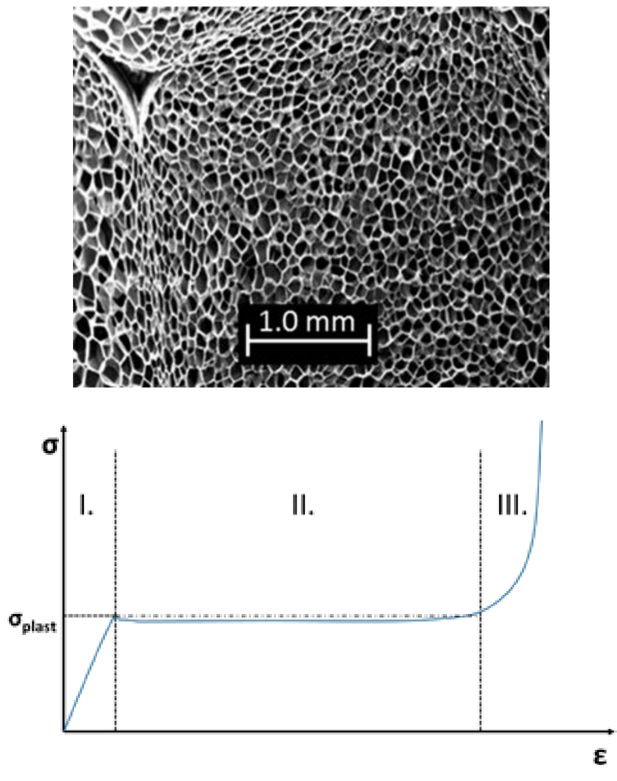

Figure 1. Macro view of EPS (top, adapted from (Vaitkus et al., 2006)) and a generic stress-strain-curve for EPS (bottom)

In the field of safety helmets, EPS with a density in the range of 30 to 90 kg/m^3, depending on the type of helmet, is used (Mills & Gilchrist, 2008a). The large amount of cell-enclosed air – around 97% of the EPS volume – enables EPS to meet unique demands. The inner structure of the individual globules, fused during heating with steam, is characterized by an irregular and variable, but on first glance honeycomb-like appearance (Mills, 2007). This structure enables EPS to redistribute a certain amount of impact energy through permanent deformation. In general, this process of permanent deformation can be separated into three stages as described by the typical uniaxial stress-strain-curve shown in Figure 1 above. The first stage is characterized by the near–linear, elastic part of the curve for very small strains, before the curve changes due to the progressive collapse of the cells after the yield point. This collapsing is especially recognizable in the areas of the interfaces between globules. Also, a tiny drop in the level of stress is perceptible at this point. Above the yield point, the deformation is unrecoverable and permanent. This initial change in the curve is followed by a wide stress plateau, the main characterizing property of the second stage. Here, the main absorption of the applied energy occurs. The stress plateau and the second stage end by densification; thus, the capacity for energy absorption decreases significantly as the cell walls and edges are pushed against each other (Vaitkus et al., 2006; Fernandes, 2017).

Because market pressures to "be greener" are increasing, the demand for sustainable products which perform at least at the level of the substituted material is rising. The development of these products therefore must consider more than simply replacing existing materials with renewable or recyclable ones. There is nowadays a tendency towards the application of principles found in natural structures such as honeycomb. A natural material that addresses both these environmental and performance concerns is cork, even if its honeycomb structure is not geometrically perfect. The structural appearance of cork is shown in Figure 2. Cork has been widely known as a material for centuries but is commonly recognized and used as little more than bottle stoppers, hypoallergenic floor panels or sandal soles.

Of particular interest is agglomerated cork: the combination of cork grains of a user-preferred size with a, typically, polyurethane (PU)-based binder. The material is highly adjustable in its properties and performs at least on a par with EPS (Fernandes, 2017; Ptak et al., 2017). The stress-strain-curve of

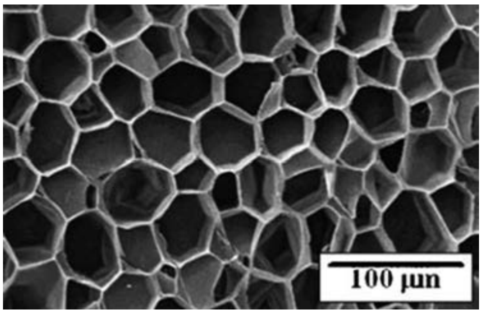

Figure 2. Structural appearance of cork (Silva et al., 2005)

cork can be seen in Figure 3 and is comparable to the corresponding curve for EPS, but differs in one fundamental property.

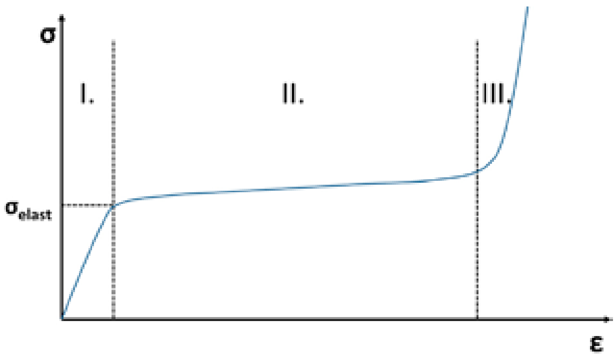

Figure 3. Generic stress-strain-curve of cork for uniaxial compression

Cork also deforms in three stages beginning with an approximately linear behavior for very small strains due to the elastic deformation of the cell walls. This stage is followed by a large strain deformation. The stress during this stage slightly increases but is nearly constant. This near constant level corresponds to the progressive cell collapse, but is also linked to the viscoelastic buckling of the cell walls, a phenomenon which allows cork to handle multiple impacts and return to its original shape. The plateau ends after plastic and viscoplastic yielding or brittle crushing in the moment of total cell collapse by densification, which explains the sharply increasing stress in the third stage. The briefly mentioned ability of cork to recover its initial shape due to its viscoelastic properties can happen up to 95% immediately after the handled impact (Gibson, Easterling & Ashby, 1981; Fernandes, 2017).

In summary, EPS and cork show a reduced energy absorption capability, especially after a critical impact, but in significantly different ways: in contrast to EPS, the performance of cork after multiple impacts and recoveries is comparable to that of its initial state. Considering cork's ability to handle multiple impacts, the consequent range of possible fields of application extends beyond the given example of passive safety devices into other impact-handling applications such as in shipyards or seafaring, where typically synthetic products like fenders could be substituted with those made from more sustainable materials with an improved environmental compatibility.

Furthermore, quasi-static tests and drop tower experiments reveal that cork offers this previously described behavior almost independent of initial strain rates (Gameiro & Cirne, 2007; Alves De Sousa et al., 2012). Specimens of natural and agglomerated cork subjected to such tests are shown in Figure 4. In general, for impact applications, the material's mechanical behavior must be known up to an initial strain rate of 300 s^{-1}. Aside from the already presented properties of cork, the strain rate independency of EPS, up to a value of 233 s^{-1}, shines a spotlight on cork as a more suitable shock-absorbing material (Alves De Sousa et al., 2012; Fernandes, 2017), especially with regard to personal safety gear such as safety helmets.

Figure 4. Tested samples of natural (dark) and agglomerated (light) cork

In direct comparison to EPS, agglomerated cork is characterized by a higher density of around 120 to 250 kg/m^3. Compared to an analogous competitive EPS liner with a density of 90 kg/m^3 and a thickness of 40 mm in a safety helmet, a corresponding cork liner offers a density of 216 kg/m^3 with a thickness of 35 mm (Fernandes, 2017). Obviously, the different densities for similar thicknesses results in a higher mass for the safety device, which makes it necessary to consider, in the case of a helmet, the higher initial impact moment for the skull and brain when wearing such a helmet (Ptak et al., 2017). Subsequently, consideration should be given to the biomechanical and neuroscientific responses during impact of a proposed geometrical design of such safety devices.

Brain injury and injury mechanism highlighting injury criteria

Typically, for a safety helmet for be road legal it requires certification. In the case of all EU countries the device needs to meet the demands of the regulation ECE R 22.05. There are different regulations for the helmets used in sports and workplace safety, the specific demands of which can vary widely according to the envisaged level of risk in the varying conditions in which the wearer is required to be protected. It is worth noting that the expected impact velocities and induced energies will differ between helmets worn in, for example, a high-speed motorcycle crash, a mountaineering accident or for head protection in an industrial environment. The considered geometries of helmets in these situations would also likely be different. In general, all regulations describe a common specific contact scenario, whereby the occurring impact energies need to be handled effectively to avoid severe injury of the device user. In the case of ECE R 22.05 this indicator is the Head Injury Criterion (HIC). The HIC is calculated by the following equation:

$$\mathrm{HIC} = \left(\left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\,\mathrm{d}t \right]^{2.5} (t_2 - t_1) \right)_{\max} \tag{1}$$

which considers the impact duration between times t_1 and t_2 and a resultant linear acceleration, $a(t)$. It should be noted that the total impact duration is should be 36 ms or less. The peak linear acceleration is not allowed to exceed 275*g* nor the HIC(36) allowed to exceed 2400 at several specified impact points on the helmet in order to receive approval (United Nations, 2002). Even if ECE R 22.05 considers a tangential load case, research during the last decades has revealed that, in most cases, impacts are oblique to a surface (Mills & Gilchrist, 2008b) and that rotational components of the acceleration in particular are contributing to severe injuries at the HIC(36) threshold of 1000 (Shuaeib et al., 2002; Fernandes, 2017).

Case study: dynamic simulation of a motorcycle accident to investigate the applicability of HIC

To investigate the link between motorcyclist kinematics and the possible types of injury occurring related to HIC during motorcycle accidents, the authors simulated such collisions with a helmeted Hybrid III 50th percentile male dummy in coupled MADYMO and LS-DYNA codes. The simulation was intended to model the effects of a HIC(36) impact situation and is shown graphically in Figure 5.

A collision between the helmeted dummy, at a velocity of 60 km/h, and a road barrier gave a peak resultant linear acceleration of approximately 236*g* corresponding to a HIC(36) of 816. The graph of the resultant linear acceleration is shown in Figure 6.

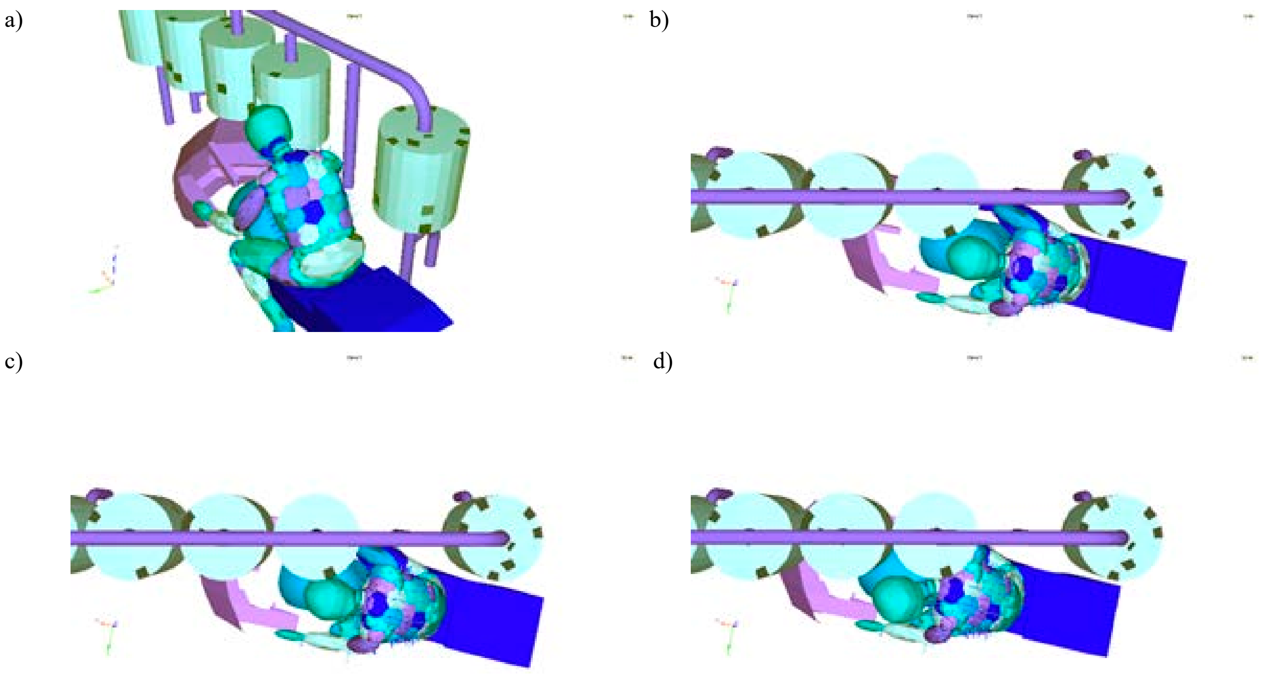

Figure 5. Graphical representation of a motorcycle impact scenario at a velocity of 60 km/h: initial view (a), at *t* = 0 ms (b), at *t* = 10 ms (c) and at *t* = 30 ms (d)

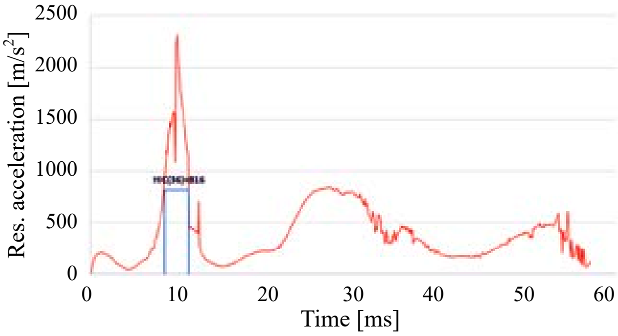

Figure 6. Acceleration chart with HIC(36) for the modelled impact scenario

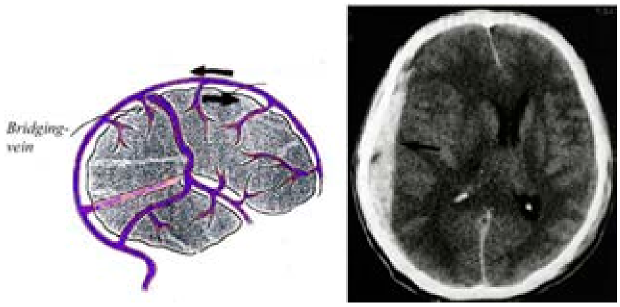

Figure 7. Injury mechanism for Subdural Hematoma (left) and related CT (right) (Kleiven, 2002)

The non-rigidity of the crash barrier construction and the usage of a corkliner safety helmet serve to lessen the acceleration and, consequently, HIC.

Taking the previously modelled scenario and further movement of the dummy into account, clearly a situation in which the dummy's arm becomes trapped within the road barrier construction is foreseeable. This scenario forces the simulated dummy to turn so that its torso faces and stops abruptly at the crash barrier. Even though the calculated HIC(36) of 816 of the initial impact is below the general threshold of 1000, which limits the likelihood of severe but non-life-threatening head injuries (Shuaeib et al., 2002; Karliński et al., 2016), the rotational components of acceleration and the potential additional injuries to the brain, skull and possibly neck that this may cause need also to be considered. In conclusion, although wearing a helmet reduces the risk of death during or after a motorcycle crash by approximately 37 % (Ouellet et al., 2013), the discrepancy between the performance of a certified helmet and occurrences of severe injuries due to rotational acceleration necessitates consideration of injury criteria and mechanism in the design and approval of safety devices. One possible reason to not consider these mechanisms in regulations such as ECE R 22.05 is that there is currently no accepted head rotation threshold (Bourdet et al., 2016).

As rotational acceleration occurs during a cranial impact, damage to the concerned intracranial structures due to shear stresses may occur. Typically, Diffuse Axonal Injury (DAI) and Subdural Hematoma (SDH) are identified as being quite common life-threatening injuries in cases of severe impacts. The cause of SDH is the tearing or rupture of the veins that bridge the subdural space as a consequence of shearing forces caused by the relative motion between the skull and brain, pictured in Figure 7 (Kleiven, 2002; Ratajczak, Sąsiadek & Będziński, 2016; Fernandes, 2017).

Similarly, Diffuse Axonal Injury also arises from the mechanism of relative motion, but affects the integrity of neuronal axons in the brain tissue connecting the white and grey matter and is, among other symptoms, linked to axonal swelling. DAI is especially recognizable in cases of longer duration rotational accelerations than those typically leading to SDH. Both types of injury can be life-threatening and are connected to possible long-term disability or vegetative states after such incidents (Kleiven, 2002; Fernandes, 2017).

Injury criteria supported by FE Head and Brain Models

With respect to the complex nature of the movements experienced during impact and the affected areas of the brain, considering only HIC(36) as an injury criterion for head and brain injuries – or the Neck Injury Criterion for neck injuries – within the ECE R 22.05 standard might be leading to inadequate results and improper conclusions. Consequently, techniques for correlating real-life accident data with injury criteria, through the use of FE simulation, in order to advance injury criteria, were developed. The commonly used Simulated Injury Monitor (SIMon) and Strasbourg University Finite Element Head Model (SUFEHM) criteria are based on FE Head Models; they consider rigid skull and deformable brain structures. Thus, besides being used to investigate and define injury criteria regarding a specific injury mechanism, the main advantage of FE based simulation is to depict the interaction of the skull and the brain structures, which is not considered in the HIC or comparable injury criteria. This technique leads to an advanced understanding and the possible validation of injury mechanisms. Compared to the HIC, the advanced knowledge linked to the computed results from these models has become, in general, very promising in terms of injury prediction, which has motivated researchers to propose numerous implementations of model-based head injury criteria for procedures of helmet impact testing (Bourdet et al., 2016). The benefit of relying on FE Head and Brain Models for the future development of safety devices is therefore obvious. The accuracy and applicability of these models depends on the density of information concerning the materials and their properties as well as assumptions regarding boundary conditions. State-of-the-art FE models are considered to be the Harvard Medical School FEM, Wayne State University Head Injury Model (WSUHIM) and SUFEHM: across the different iterations of the models, the tendency to implement differing skull thicknesses and more complex material models including elements such as dura, falx cerebri or cerebrospinal fluid (CSF) to minimize oversimplification is clearly observable. In an attempt to take the specific movement of the brain inside the skull into account and thereby consider possible damage to the brain's surface, Yet Another Head Model (YEAHM) is considered as a recent contribution to the state-of-the-art models (Kleiven, 2002; Tinard, Deck & Willinger, 2012; Fernandes, 2017).

It is possible to envisage the direction of future development of Head and Brain Models. Considering more and more precise geometrical structures and mechanical properties, models may allow for not only the depiction of mechanical impact behavior, but also the prediction of the likelihood and location of injuries experienced by the vulnerable device user. Obviously, links to the fields of forensics and accident reconstruction are established, furthering understanding of neuroscientific injury prediction, a field which has traditionally relied upon surgical experience and published empirical data.

Conclusions

Accidents are occurring which affect more than simply valuable objects such as land and sea vehicles. When vulnerable (road) users are involved, the focus switches naturally to the human being's integrity. As their safety can be ensured through wearing passive safety devices, such devices need to perform in accordance with regulations such as ECE R 22.05. Unfortunately, even by wearing certified personal safety gear, life-threatening, or at least severe injuries, cannot always be avoided and may lead to death or long-term disability of the device user. In this respect, clearly the demands of certification are not sufficient.

Typically, impact energy is mainly absorbed by an EPS liner due to its favorable mechanical properties and costbenefit ratio. Nevertheless, the occurring rotational components of acceleration cannot be handled by a single layer without considering the mechanism of injury. Cork represents an alternative material which is able to perform better than EPS and to handle multiple impacts. The ability to handle multiple impacts, in particular, enables cork to be used as a sustainable shock-absorbing material in a variety of new applications such as seafaring. Cork's high adjustability and sustainable nature are clearly not going to solve the problem of rotational acceleration during head impacts alone; but through reconsidering the types of shock-absorbing materials used in helmets, informed by feedback from the fields of biomechanics and neuroscience, cork as a material may well provide one technical solution in the development of next-level safety devices.

Furthermore, this interdisciplinary and undoubtedly important feedback leads to advanced FE Head and Brain Models, allowing for more detailed structures and boundary conditions and avoiding oversimplification. This serves to improve the application of FE modelling as a tool for injury prediction. Information gleaned from dynamic simulations is helpful to understand the related injury mechanisms; this can generally serve to benefit, in addition to the development of safety devices, the fields of forensics and medical education.

References

1. Alves De Sousa, R.J., Gonçalves, D., Coelho, R. & Teixeira-Dias, F. (2012) Assessing the effectiveness of a natural cellular material used as safety padding material in motorcycle helmets. *Simulation*, 88(5), pp. 580–591. doi: 10.1177/0037549711414735.
2. Bourdet, N., Mojumder, S., Piantini, S., Deck, C., Pierini, M. & Willinger, R. (2016) *Proposal of a new motorcycle helmet test method for tangential impact*. Proc. of the International IRCOBI Conference on the Biomechanics of Impacts, pp. 503–504.
3. Fernandes, F.A.O. (2017) *Análise Biomecânica de impactos com capacetes: novos materiais e geometrias, Biomechanical analysis of helmeted head impacts: novel materials and geometries*. Universidade de Aveiro.
4. Gameiro, C.P. & Cirne, J. (2007) Dynamic axial crushing of short to long circular aluminium tubes with agglomerate cork filler. *International Journal of Mechanical Sciences* 49(9), pp. 1029–1037. doi: 10.1016/j.ijmecsci.2007.01.004.
5. Gibson, L.J., Easterling, K.E. & Ashby, M.F. (1981) *The Structure and Mechanics of Cork*. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 377(1769), pp. 99–117.
6. Jurecki, R.S. & Jaśkiewicz, M. (2012) Analysis of road accidents in Poland over the last ten years. *Scientific Journals of the Maritime University of Szczecin* 32 (104), pp. 65–70.

7. Jurecki, R.S., Jaśkiewicz, M. & Zuska, A. (2013) The variety of the behaviour of drivers at risk accident situations. *Scientific Journals of the Maritime University of Szczecin* 35 (107), pp. 38–46.
8. Karliński, J., Ptak, M., Działak, P. & Rusiński, E. (2016) The approach to mining safety improvement: Accident analysis of an underground machine operator. *Archives of Civil and Mechanical Engineering* 16(3), pp. 503–512. doi: 10.1016/j.acme.2016.02.010.
9. Kleiven, S. (2002) *Finite Element Modeling of the Human Head*. Ph.D. thesis. Royal Institute of Technology, Stockholm, Sweden.
10. Mills, N.J. (2007) *Polymer Foams Handbook Engineering and Biomechanics Applications and Design Guide*. Elsevier.
11. Mills, N.J. & Gilchrist, A. (2008a) Finite-element analysis of bicycle helmet oblique impacts. *International Journal of Impact Engineering* 35(9), pp. 1087–1101. doi: 10.1016/j.ijimpeng.2007.05.006.
12. Mills, N.J. & Gilchrist, A. (2008b) Oblique impact testing of bicycle helmets. *International Journal of Impact Engineering* 35(9), pp. 1075–1086. doi: 10.1016/j.ijimpeng.2007.05.005.
13. Ouellet, J.V, Thom, D.R., Smith, T. & Hurt, H.H. (2013) *Helmets and Neck Injuries in Fatal Motorcycle Crashes*. International Motorcycle Safety Conference.
14. Ptak, M., Blicharski, P., Rusiński, E. & Karliński, J. (2017) Numerical Simulations of Composite Frontal Protection System According to EC 78/2009. *Lecture Notes in Mechanical Engineering*. Springer, Cham, pp. 423–429. doi: 10.1007/978-3-319-50938-9_44.
15. Ptak, M., Kaczyński, P., Fernandes, F.A.O. & de Sousa, R.J.A. (2016) Computer simulations for head injuries verification after impact. *Lecture Notes in Mechanical Engineering*.
16. Ptak, M., Kaczyński, P., Fernandes, F.A.O. & de Sousa, R.J.A. (2017) Assessing impact velocity and temperature effects on crashworthiness properties of cork material. *International Journal of Impact Engineering*. Elsevier Ltd, 106, pp. 238–248. doi: 10.1016/j.ijimpeng.2017.04.014.
17. Ratajczak, M., Sąsiadek, M. & Będziński, R. (2016) An analysis of the effect of impact loading on the destruction of vascular structures in the brain. *Acta of Bioengineering and Biomechanics* 18(3), pp. 21–31. doi: 10.5277/ABB-00552-2016-02.
18. Shuaeib, F.M., Hamouda, A.M.S., Radin Umar, R.S., Hamdan, M.M. & Hashmi, M.S.J. (2002) Motorcycle helmet – Part I. Biomechanics and computational issues. *Journal of Materials Processing Technology* 123(3), pp. 406–421. doi: 10.1016/S0924-0136(02)00048-1.
19. Silva, S.P., Sabino, M.A., Fernandes, E.M., Correlo, V.M., Boesel, L.F. & Reis, R.L. (2005) Cork: properties, capabilities and applications. *International Materials Reviews* 50(4), pp. 256–256. doi: 10.1179/174328005X41168.
20. Tinard, V., Deck, C. & Willinger, R. (2012) New methodology for improvement of helmet performances during impacts with regards to biomechanical criteria. *Materials and Design*, 37(August), pp. 79–88. doi: 10.1016/j.matdes.2011.12.005.
21. United Nations (2002) *ECE Regulation 22. Uniform provisions concerning the approval of protective helmets and their visors for drivers and passengers of motor cycles and mopeds*. [Online] Available from: https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r022r4e.pdf [Accessed: April 10, 2017]
22. Vaitkus, S., Laukaitis, A., Gnipas, I., Keršulis, V. & Jelis, S.V.Ė. (2006) Experimental Analysis of Structure and Deformation Mechanisms of Expanded Polystyrene (EPS) Slabs. *Materials Science* 12(4), pp. 323–327.