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Assessing the effectiveness of a natural cellular material used as safety padding material in motorcycle helmets

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Abstract

The efficiency of cork as a material dedicated to energy absorption under impact loading is studied in the present work. The viability of the application of micro-agglomerate cork (MAC) padding on a motorcycle helmet, is studied using finite element simulations of impact tests, considering the specifications of the European Standard ECE-R.22/05.

Expanded polystyrene (EPS) is a widely used material, with excellent results in energy-absorption applications. However, after a first impact, the capability of EPS for energy absorption is significantly decreased, due to the almost total absence of elastic springback. However, cork is a material characterized by having both a good energy-absorption capability and high elastic return, due to its viscoelastic behavior, meaning that its capacity to keep absorbing energy is almost unchanged after the first impact.

In this work, a three-dimensional numerical model of the helmet–head system is developed, including the outer shell, safety padding and the head, together with its interactions and constitutive models suitable for the analyzed materials. Results show that the developed models can adequately reproduce the behavior of EPS and MAC, in the context of a preliminary analysis.

The referred helmet–headform is then submitted to impacts at different points, as specified by the European Standard. The results from helmeted impacts with EPS padding are compared against experimental values. The application of MAC in the protective padding of the helmet is studied and the results, concerning the acceleration of the gravity center of the head, Head Injury Criterion (HIC) values and kinetic energy are presented. Results obtained with EPS and MAC are compared and discussed. Concerning cork, although the maximum acceleration values of the headform and the HIC values were not verified to be within the established limits of the regulatory standard, the results are promising, launching a sound basis for a more thorough work on the application of cork as a new material for advanced applications as an energy-absorption system.

Keywords

cork, energy absorption, EPS, finite elements, head, helmet, impact, safety

1. Introduction

Motorcyclists have the highest risk of becoming seriously injured or even killed in traffic accidents.[1] In road crashes, car occupants are protected by safety belt systems, airbags, retracting steering systems, the padding of the car interior and the car body itself. On the other hand, the only protection offered to a motorcyclist is the safety helmet. Therefore, wearing a motorcycle helmet is the best way to prevent head injuries in a traffic accident. Reviews of motorcycle helmet effectiveness[2–4] show that wearing a helmet can reduce the risk of a head injury by up to 70%, implying that current helmet designs are effective but not ideal.

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The impact energy absorption provided by a motorcycle safety helmet is always of critical importance to the survivability of the driver (and passenger) during an accident. A well-designed helmet must be able to absorb as much energy as possible and to dissipate it to the whole helmet. In that sense, the development of a local-global damage network minimizes the peak acceleration and prevents the generation of excessive stress and strain profiles into the brain tissue of the motorcyclist.[5]

Motorcycle helmets are basically made from three different parts: the outer shell, the protective padding and the chin strap. The chin strap fixes the helmet to the head before, during and after an eventual impact. The outer shell is often made from a thermoplastic material such as acrylonitrile-butadiene-styrene (ABS) or polycarbonate (PC), or even composite materials such as glass-reinforced plastic (GRP), carbon-reinforced plastic (CRP) or kevlar. The protective padding, which is the focus of this work, is the helmet part that absorbs most energy during an impact. It is usually made from expanded polystyrene (EPS), which is a synthetic cellular material with excellent shock-absorbing properties and low cost. EPS, through its ability to develop permanent deformation, absorbs energy during the impact of the helmet, providing the required protection to the motorcyclist. This type of foam has an excellent first impact performance but dramatically loses its efficiency for subsequents impacts because, as already mentioned, the deformations caused by the first impact are permanent.

The likelihood of multi-impact crashes is an open issue in the community. It is possible, however, to cite motorcycle crash kinematic studies where it is evident that motorcycle crashes can be multi-impact situations, especially when involving high speeds.[6] It is also worth noting that there are nowadays well-accepted international standards that demand explicitly two impacts on the same helmet point.[7,8] Cork, being a viscoelastic material recovers its shape after an impact. Moreover, while EPS is known to be strain-rate independent for strain rates only up to 233 s^{-1},[9] higher strain rates may occur in impact situations. For these reasons, cork has a strong potential in overcoming such problems and is an excellent alternative to EPS.

For impact analysis, the mechanical behavior of the padding material must be known up to a strain rate of at least 300 s^{-1}. Once again, cork appears as an excellent alternative to EPS. Gameiro et al.[10,11] have shown that the mechanical behavior of cork stays mostly constant up to strain rates of 2,500 s^{-1}, maintaining excellent shock-absorption capabilities. There is a better load deformation distribution in cork compared, for example, to geometrically perfect honeycombs. Moreover, cork is a viscoelastic material with a high elastic return after deformation, meaning that its capability to absorb energy remains almost unchanged after the first impact, which is a very interesting feature in the case of multi-impact situations.

Finite element simulations of helmet impacts are used to give a better understanding of impact kinematics and to validate new preliminary solutions for safety systems. With the advance of CPU power, fully three-dimensional modeling can now be used to give detailed results on stresses and strains not only from the impacted helmet but also from the human head. Some representative examples can be found in the works of Bosch[12] on the optimization of head dummies, Mills et al.[13] and Aare[14] on oblique helmeted impacts and Chang et al.[15] on the effect of impact velocities, and there are studies on helmet design optimization[16,17] and the biomechanics of helmeted impacts[18] among others.

Therefore, two main objectives were targeted for this work: the development of a reliable three-dimensional helmet–head impact finite element model and the evaluation of the effectiveness and suitability of micro-agglomerated cork (MAC) as protective padding for a helmet application.

2. Helmet material properties

Before simulating a helmet impact, it is necessary to choose a suitable constitutive numerical model to simulate the mechanical behavior of each material and set its parameters. Therefore, numerical simulations were performed to validate the padding material models chosen. Figure 1 shows the setup of the numerical simulation, consisting of a cylinder with diameter $D_i = 22.8$ mm and length $L = 15$ mm. All movements of the bottom wall were restricted and a displacement $d = 13.5$ mm (corresponding to 90% average strain of the cylinder) was given to the top wall. To simulate the contact between the cylinder and the walls, a surface-to-surface contact with a friction coefficient of 0.5 was used.

2.1. Material modeling of EPS foam

EPS foam is a material commonly used for many applications, such as the shock-absorbing packaging of electronic goods. This low-density foam has closed cells and is widely used for energy-absorption applications. The stress–strain behavior of EPS foam can be divided into three regions, as shown in Figure 2. The first region has linear elastic behavior, the second region is often seen as a stress plateau and the third corresponds to densification of the foam, where the cell walls are mostly compressed and the material loses its capability to absorb more energy.

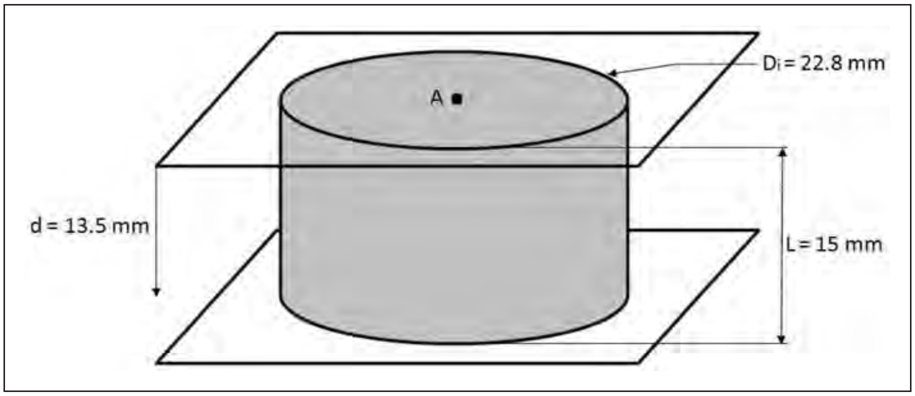

Figure 1. Setup of the numerical simulation used for mechanical characterization of the different padding materials.

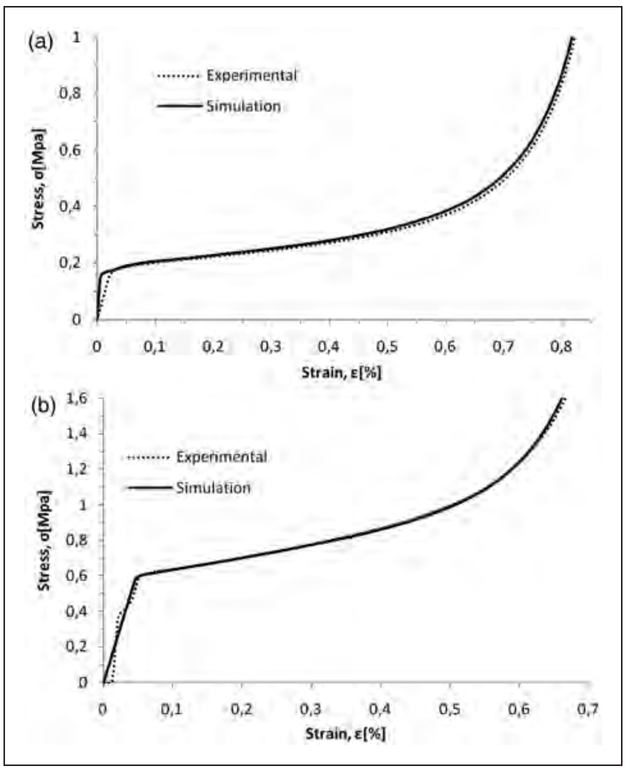

Figure 2. Theoretical and numerical stress–strain curves for EPS foam: (a) EPS 30 ($\rho = 30$ kg m^{-3}) and (b) EPS 60 ($\rho = 60$ kg m^{-3}).

The following set of equations gives a possible description for the behavior of EPS foam:

$$\sigma = \begin{cases} E\varepsilon & \text{if} \quad \varepsilon \in [0, \varepsilon_y] \\ \sigma_{c0} + \frac{P_0 \varepsilon}{1-\varepsilon-\mathrm{R}} & \text{if} \quad \varepsilon \in [\varepsilon_y, \varepsilon_l] \end{cases} \tag{1}$$

where E is Young's modulus, ε_y is the nominal strain corresponding to the yield stress ($\approx 0.5\%$), σ_{c0} is the compressive yield stress, ε_l is the maximum compressive nominal strain, P_0 is the effective gas pressure in the cells and R is the foam relative density (the ratio of the foam density to the density of a solid polymer). In these equations, the elastic behavior of EPS is modeled with Hooke's law 1(a), requiring as input Young's modulus and Poisson's ratio. The remaining stress–strain curve is modeled using a 'crushable foam' material model [Equation (1b)].[21] Additionally, the ratios of the initial yield pressures in hydrostatic tension and compression are $p_t/p_{c0} = 1.0$ and $\sigma_{c0}/p_{c0} = 1.933$, respectively.

Table 1. Mechanical properties of EPS foams used for the material characterization models of the helmet crown and padding

Material	ρ [kg m^{-3}]	E [MPa]	ν	σ_{c0} [MPa]
EPS$_{crown}$	30	7.42	0.1	0.15
EPS$_{padding}$	60	12.75	0.1	0.57

The remaining material parameters can be tuned to match the desired experimental curves, in this case the ones obtained by Coelho,[19] from compressive uniaxial tests. In this work, two different EPS densities (30 and 60 kg m^{-3}) are used for the padding. In fact, the chosen helmet model includes the lower density EPS in the upper part of the padding, known as the crown. The final material parameters for these foams are given in Table 1.

The results in Figure 2 show the comparison between experimental and numerical results for the behavior of the two EPS foams. From the presented results one can conclude that the numerical model used to simulate the behavior of EPS is adequate.

2.2. Material modeling of cork

Natural cork—the outer bark of cork oaks (*Quercus suber*)—is extremely difficult to use in industrial applications due to its micro-structural heterogeneity, which generates highly variable mechanical properties.[10,11] Consequently, in applications such as helmet padding, it is preferable to use MAC, which can be injected in molds and has more uniform and isotropic mechanical properties. In this work, a type of MAC similar to the one used by Gameiro[20] was selected. The mechanical properties of MAC are listed in Table 2. This material contains cork particles ranging from 0.5 mm and 2.0 mm in size, mixed with a polyurethane adhesive, latex, paraffinic oil and paraffin.

MAC has a characteristic compressive stress–strain behavior, similar to that of other closed-cell cellular solids. This behavior can be described by three clearly distinct regions: elastic, collapse (plateau) and densification, as shown in Figure 3. At low strains, cork deforms elastically. The collapse region is characterized by a plateau stress almost invariable with the increase of strain. Finally, at a critical strain, the cells walls start to touch each other and the stress level increases quickly. MAC has many of the characteristics expected from an efficient energy absorber since it presents a long stress–strain curve up to densification at relatively high strain rates (2,500 s^{-1}).[10] Despite the higher density when compared to EPS, this behavior combined with the almost total viscoelastic return (relevant when considering multiple impacts) and recyclability justify the application of this material for energy-absorption systems.

Table 2. Mechanical properties of micro-agglomerate cork.[20]

Mechanical Properties	ρ [kg m^{-3}]	E [MPa]	σ_y [MPa]	ν
Expanded material	293	15	—	—
Densified material	—	9000	1	0.325

One possible way to model the mechanical behavior of MAC during compression is to use a hyperelastic material model such as `*Hyper foam`.[21] This model requires uniaxial compressive data as input in addition to the Poisson's ratio of the material. As shown in Table 2, the mechanical behavior of MAC can be characterized by using two different Poisson's ratios. Therefore, it was necessary to choose an optimum average Poisson's ratio to be used in this model in order to fit the experimental data. To model correctly the viscoelastic return of the material a user-subroutine material model should be developed. Nonetheless, in the scope of this work, the referred model will be used and it will be shown that the results of numerical modeling are acceptable.

2.2.1. Results. The results obtained from the characterization of the behavior of MAC for different values of Poisson's ratio are shown in Figure 3. According to the results shown, it is possible to verify the differences between the real and simulated behavior of MAC. As previously described, the mechanical behavior of MAC can be characterized by three distinct regions: elastic, collapse (plateau) and densification. According to the numerical results, the elastic and collapse regions are not clearly defined. However, the densification

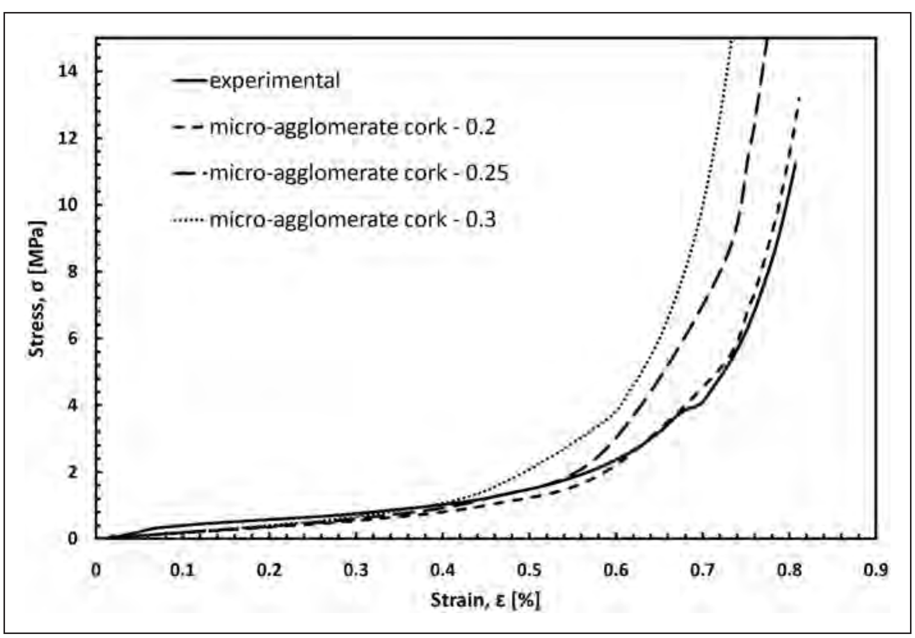

Figure 3. Stress–strain behavior of micro-agglomerate cork for different Poisson's ratios.

Table 3. Mechanical properties of ABS

ρ [kg m^{-3}]	*E* [MPa]	ν
1080	2344	0.325

region starts at approximately similar stress–strain values. According to the results in Figure 3 the best average Poisson's ratio to adequately model the real behavior of the chosen MAC is 0.2. In conclusion, the real behavior of MAC during the compression stages driven by an impact can be reasonably simulated by the adopted material model.

2.3. Material modeling of ABS

The outer shell is also of the utmost importance for a helmet's overall energy-absorption capabilities. More and more, classical thermoplastic shells are being substituted by advanced composite materials. In this paper the focus of the study is the padding material. Hence, a simple model for the mechanical behaviour of the shell was adopted, allowing for a clear comparison between the two padding materials under study. The work by Kostopoulos et al.[5] presents an extensive study on composite outer shells for helmets.

ABS is a stiff thermoplastic material very resistant to heat and to penetration. It is widely used in motorcycle helmets as the outer shell material. The outer shell material properties of ABS used in this work were based on the work of Bosch.[12] To simulate the material's behavior a linear-elastic material model was considered. This choice is supported by the fact that during an impact the outer shell is mainly responsible for spreading the impact's concentrated load and generally deforms only elastically. Thus, the model only requires Young's modulus, Poisson's ratio and the density. The material properties of ABS are listed in Table 3.

3. Finite element modeling and simulation

The motorcycle helmet used in this work is the NEXX XR1. This is a full-face motorcycle helmet manufactured by NEXX PRO Helmets. This helmet, shown in Figure 4, fully meets European Regulation ECE-R.22/05[22] and uses a dual-density protective padding, composed of two different parts: the main padding and crown insert, as shown in Figure 5.

3.1. Helmet model

The three-dimensional CAD model of the helmet used to model the different parts of the helmet was created

Figure 4. NEXX XR1 motorcycle helmet.

on a CATIA V5 CAD system.[23] In order to create the finite element model and simulate the different impacts, the commercial finite element package Abaqus,[21] in its Explicit version, was used. The image in Figure 5 shows the surface and finite element models of the different parts of the helmet. In this study, the effects of the comfort padding and the retention system (chin strap) were not considered.

According to the manufacturer's specifications, the helmet covers head sizes between 540 and 600 mm. According to European Standard ECE-R.22/05[22] the headform sizes for this range are between sizes C and M. Therefore, size J (570 mm) for the headform was used. The image in Figure 6 shows the headform (surface and finite element models). The mass properties used for the head are listed in Table 4.

3.1.1. Finite element mesh. In order to create the finite element model of the helmet the different parts were seeded at a spacing of 7 mm. Four-node linear tetrahedral elements (C3D4[21]) were used for the foam (padding and crown); the main padding was modeled using 63,870 elements and the crown insert 12,198 elements. The outer shell with a thickness of 3 mm (averaged value from the real outer shell), was modeled using 9,270 linear triangular shell elements (S3R[21]). The headform and the impact walls were modeled with rigid quadrangular elements (R3D4[21]). A summary of the mesh characteristics used for the different parts of the model is shown in Table 5.

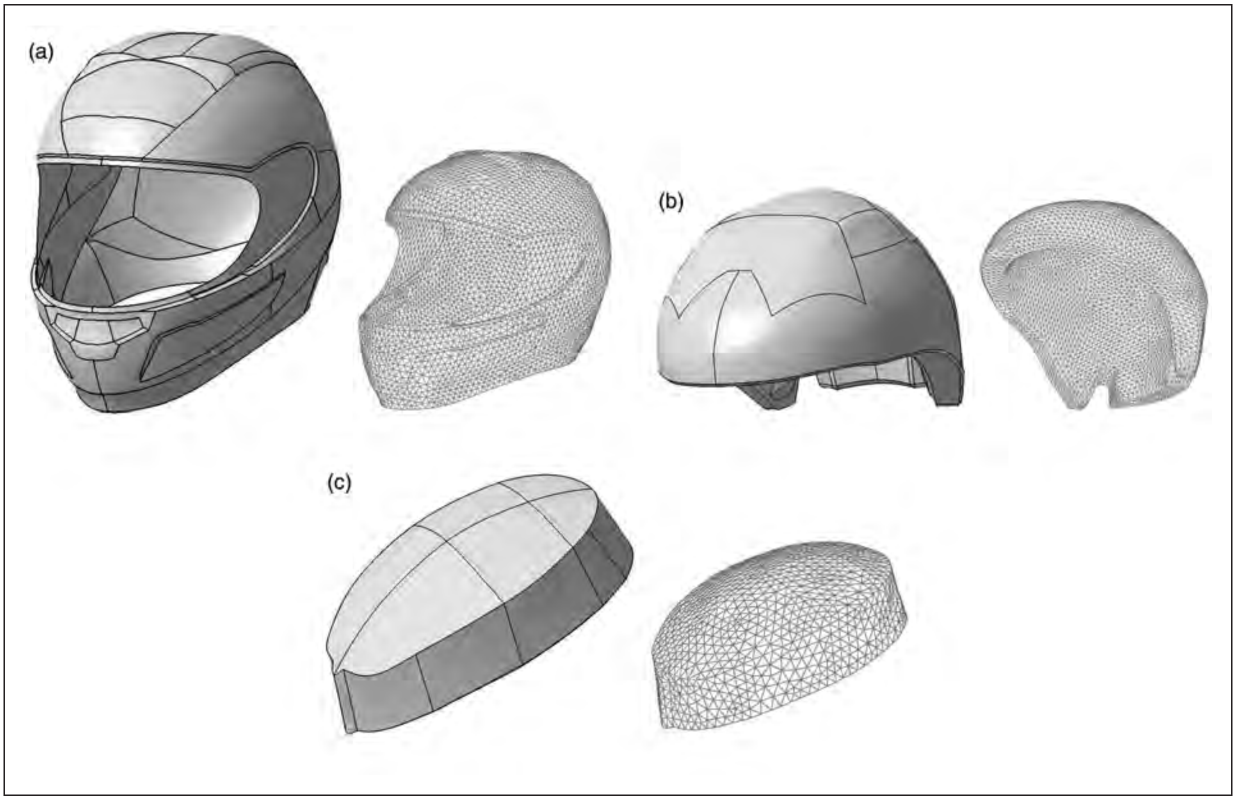

Figure 5. Surface and finite element models of the helmet parts: (a) outer shell, (b) main padding and (c) crown insert.

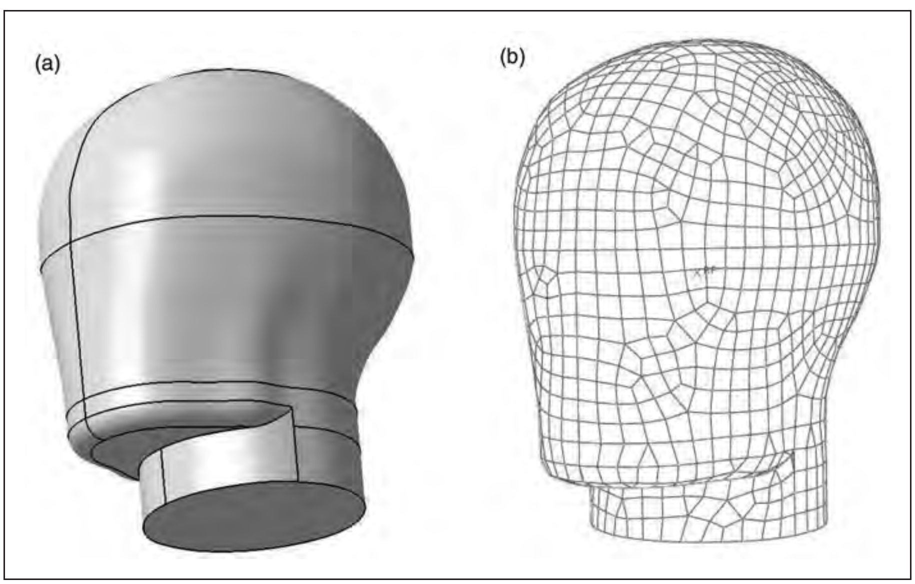

Figure 6. (a) Surface model and (b) finite element model of the headform (size J).

3.1.2. Contact and impact conditions. To simulate the interfaces between the different parts of the helmet, the head–helmet system and the impact wall interaction were modelled using a surface-to-surface contact (explicit) with friction coefficient $\mu = 0.5$. The use of a high-friction coefficient prevents the main padding and the crown from sliding out of the shell's inner surface. In addition it also simulates the friction between the shell's outer surface and the impact surface. Also, a 'tie' type contact was used to simulate the real tie between the main padding and the crown insert.

According to the ECE-R.22/05 standard, the model (helmet and headform) is dropped, without any restriction, against an anvil with a velocity $v = 7.5\ \mathrm{ms}^{-1}$. In this work the authors used a flat anvil. However, it is worth noting the existence of other anvil geometries defined in the standard. The flat anvil was fixed and an impact velocity $v = 7.5\ \mathrm{ms}^{-1}$ was used in the model. The images in Figure 7 show the impact configurations according to the ECE-R.22/05 standard (points B, P, R and X).

The explicit (dynamic) solver of Abaqus was used to simulate the impacts with durations $\Delta t = 20$ ms, with the large deformation option.

4. Results and discussion

4.1. Validation of the EPS helmet model

As a first step, numerical simulations of helmeted impacts using only the EPS padding material were performed in order to validate the numerical simulation framework developed. This was achieved by comparing its results against experimental data provided by the helmet manufacturer.[25] These comparisons are shown in Figure 8. The Head Injury Criterion (HIC) proposed by Newman, as the most disseminated injury criteria,[26] is assessed as well.

Table 4. Mass properties of the headform (size J)

Mass [kg]	I_{xx} [kg cm^2]	I_{yy} [kg cm^2]	I_{zz} [kg cm^2]
4.7	200	260	180

Table 5. Finite element mesh characteristics used for the different parts of the helmet model

Part	Element type	Seed spacing	No of elements	No of nodes
Main padding	C3D4	7	63,870	13,274
Crown insert	C3D4	7	12,198	2,629
Shell	S3R	7	9,270	4,740
Headform	R3D4	10	1,687	1,663
Impact wall	R3D4	150	1	4

According to the results in Figure 8 there are noticeable differences between the experimental and numerical behavior for the different impacts. The maximum acceleration of the head and the HIC values [Equation (2)] calculated from the numerical and experimental analyses are shown in Table 6.

$$\mathrm{HIC} = \left\{ \left[\frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1) \right\}_{\max} \qquad (2)$$

For points P and B, the agreement between experiment and simulation is reasonable. However, for points R and X, there are significant deviations. The differences between experimental and numerical results may be explained by the adoption of a simplified numerical model. For instance, the retention system and the comfort padding were not modeled. Especially for point X, where the differences are more evident, it should be noted that in the real helmet the zone around the X point has several attached parts (metallic and plastic, for instance the visor locking system and the chin strap fixation system) that contribute to a change in the energy-absorption properties, as a lesser quantity of padding is included. In the simulation, by considering just the padding in that area, a better response under impact was obtained. However, despite the differences, the numerical model was considered adequate enough for a preliminary study of the cork material.

4.2. EPS and MAC

It should be noticed that in this study the authors performed a simple substitution of EPS for MAC concerning all padding components. This would lead to a significant increase in the helmet weight, from 1.35 to

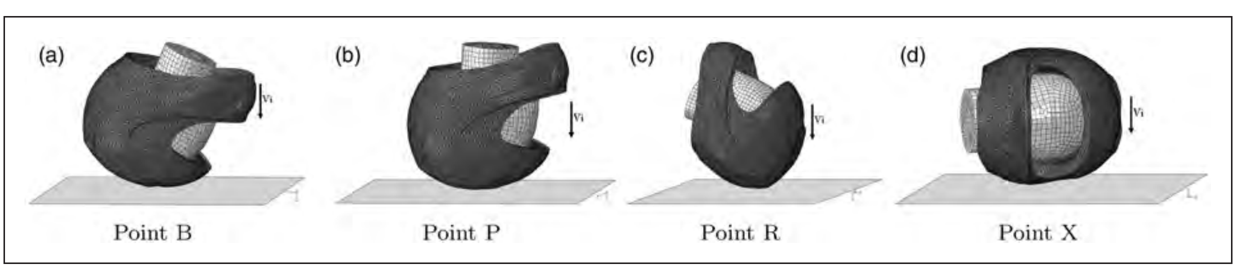

Figure 7. Different impact configurations.

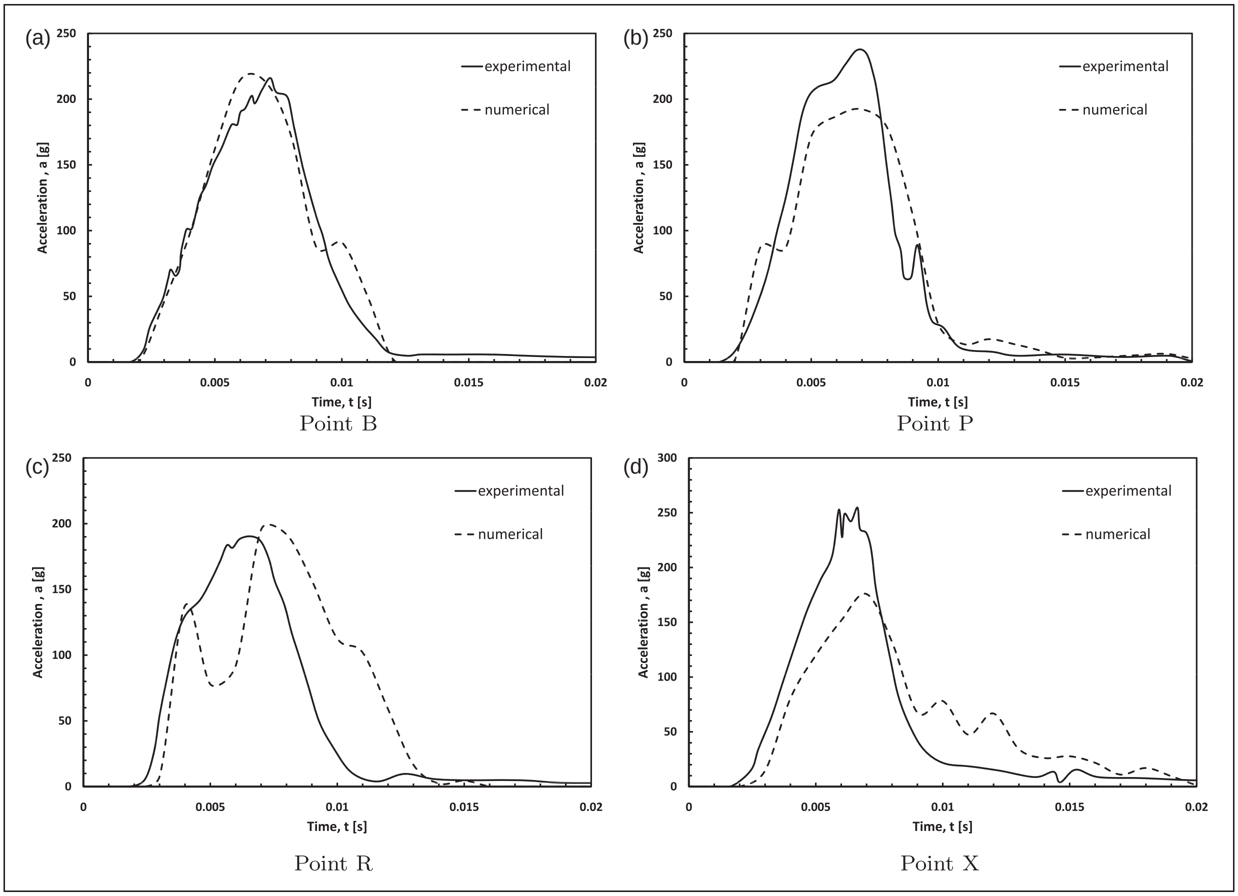

Figure 8. Comparison between finite element analysis and real impact test results.

Table 6. Maximum acceleration of the head and HIC values calculated from the numerical and experimental studies

Impact point		a_{max} [g]	HIC
Point P	numerical	192	1,612
	experimental	239	1,886
Point B	numerical	215	2,409
	experimental	219	2,404
Point R	numerical	195	866
	experimental	190	1,519
Point X	numerical	179	549
	experimental	256	2,017

around 2.23 kg. In fact, by using only MAC the overall thickness of the padding can be reduced, as the following results will demonstrate. Nonetheless, the authors will present a direct comparison for the same padding geometry for both EPS and MAC, showing the potential of MAC in replacing (partially or totally) EPS. The variation of the head acceleration for the different impacts performed, according to the ECE-R.22/05 standard, is shown in Figure 9.

The maximum acceleration of the head and the HIC values calculated for the different impacts using EPS and MAC padding are listed in Table 7.

In most cases EPS exhibits better behavior, that is, lower values for HIC and the head acceleration. However, it must be stressed that this padding geometry was specifically designed for EPS by the helmet manufacturer. Thus, a new specific design must be made for cork padding considering the use of MAC. The impact point on the back of the helmet shows better energy-absorption properties for MAC, which is most probably due to the particular helmet design in that area, as shown in Figure 10.

The variation of the kinetic energy with time for the different impacts performed is shown in Figure 11. As expected, and given the higher weight (due to the higher density of MAC), the kinetic energy is higher for the impacts performed with the MAC padding. However, according to the results shown, the energy-absorption capability of the MAC padding is better than for the EPS

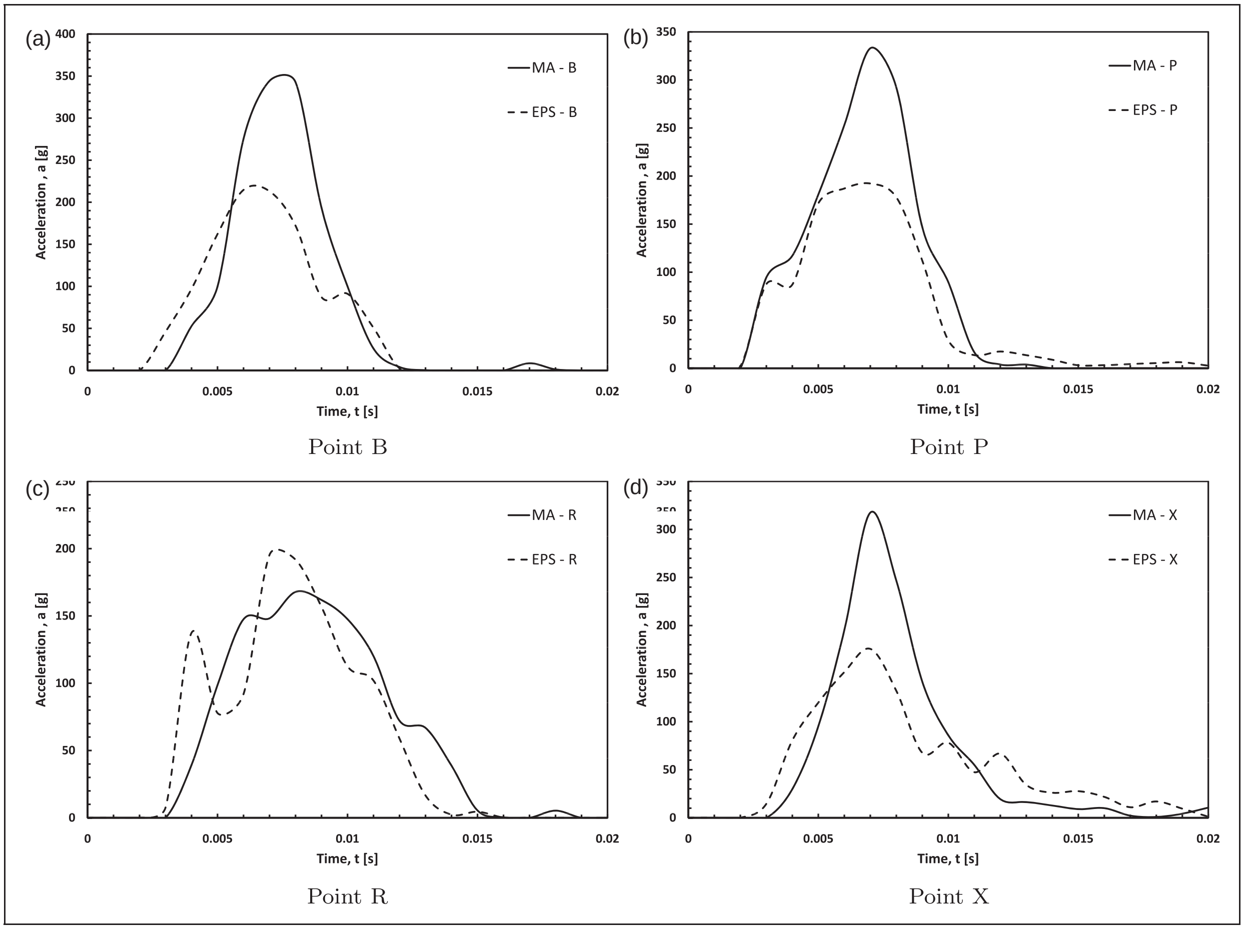

Figure 9. Variation of the head acceleration for the different impacts studied with EPS and MAC padding.

Table 7. Maximum acceleration of the head and HIC values calculated for the numerical studies performed for EPS and MAC padding

Impact point	Padding	a_{max} [g]	HIC	Limits
Point P	EPS	215	1,612	
	MA	344	2,909	
Point B	EPS	192	2,409	
	MA	333	2,899	HIC $<$ 2400
Point R	EPS	195	866	$a_{max} < 275g$
	MA	167	1,250	
Point X	EPS	179	549	
	MA	317	858	

padding, yielding a higher reduction of the impact energy in the same time interval.

From the kinetic results presented, an improved design incorporating thinner MAC padding is desirable. In fact, given the particular material properties including virtually full elastic return after deformation,

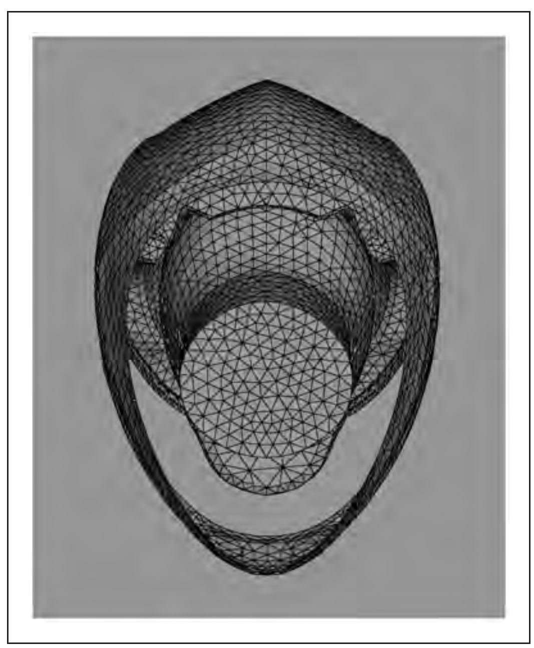

Figure 10. Configuration of the back of the helmet.

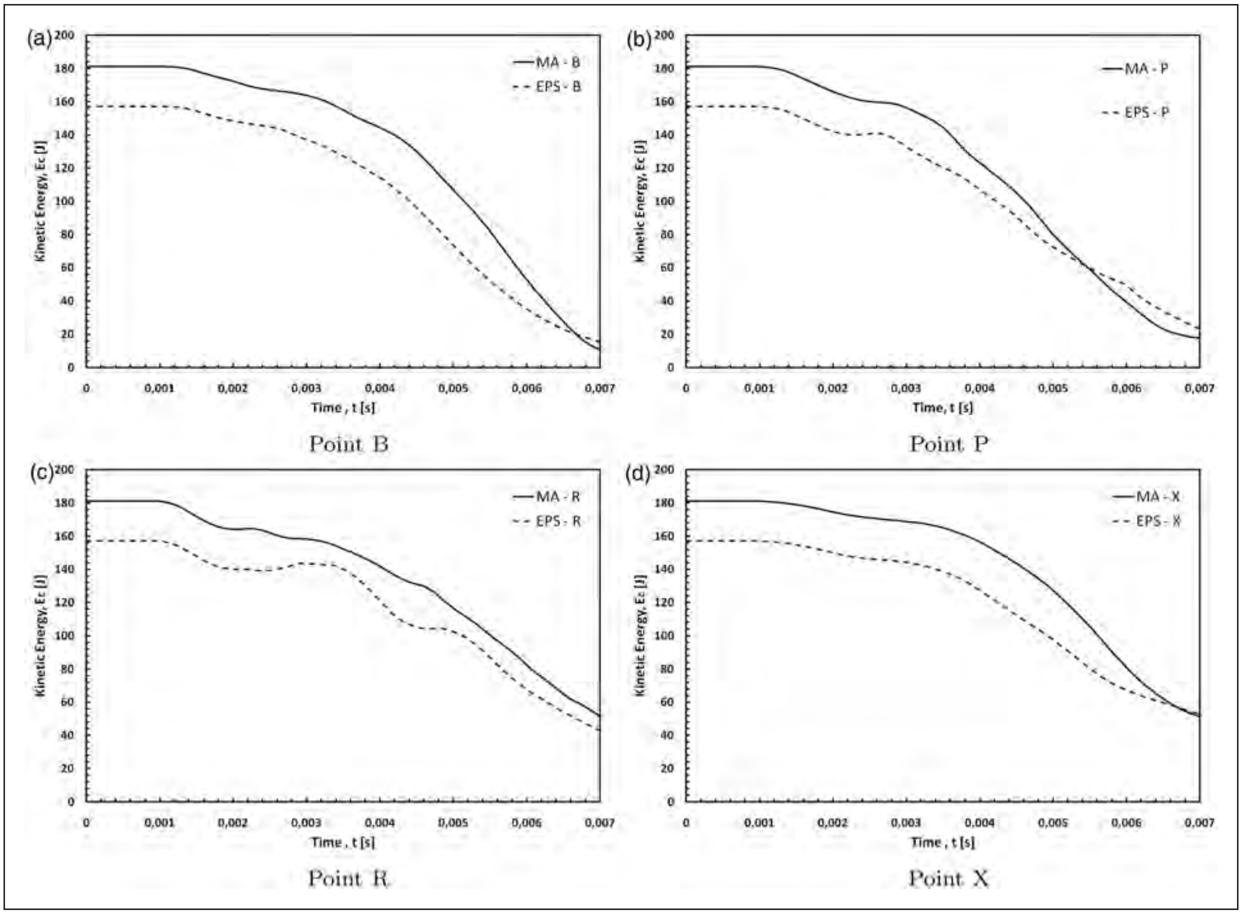

Figure 11. Variation of the kinetic energy for the different impacts studied with EPS and MAC padding.

it is possible to promote improved designs, still meeting the requirements of the standards and achieving a lower weight. In order to support these conclusions the EPS and MAC padding thicknesses after impact were compared. The images in Figure 12 show the initial and final thickness for the impact point (point B).

According to the results presented, the EPS padding exhibits large permanent deformations after the first impact. Before the impact the padding thickness was $L_i = 33$ mm, and after the impact this thickness was reduced to $L_f = 14.3$ mm. This reduction represent an average 57% deformation. Therefore, the energy-absorption capability of the EPS padding after the first impact is considerably reduced.

On the other hand, the MAC padding thickness is practically unchanged before and after impact. The initial padding thickness was $L_i = 33$ mm. Right after the impact this thickness was reduced to $L_f = 28.5$ mm, representing an average 14% deformation. Besides being less deformable for the same impact energy, cork recovers back to its initial thickness with a (visco)elastic return.

Comparing these results it can be concluded that the MAC padding (when compared to the EPS padding) has an obvious advantage when double or multiple impacts are relevant. The likelihood of these kinds of situations is naturally low, but is still taken into account in some standards, especially the ones devoted to competition helmets.

5. Conclusions

In this paper, a complete replacement of EPS by MAC was carried out for the sake of a direct comparison between the two materials for a given padding design. No study was devoted to the influence of the shell material or geometry on the impact response.

The results now presented lead to the overall conclusion that MAC padding has clear advantages in the event of double or multiple impacts, occurring around the same representative area, compared to EPS padding. Despite the higher specific weight, cork withstands large impact energies at the expense of a few millimeters of thickness. Additionally, it is a sustainable

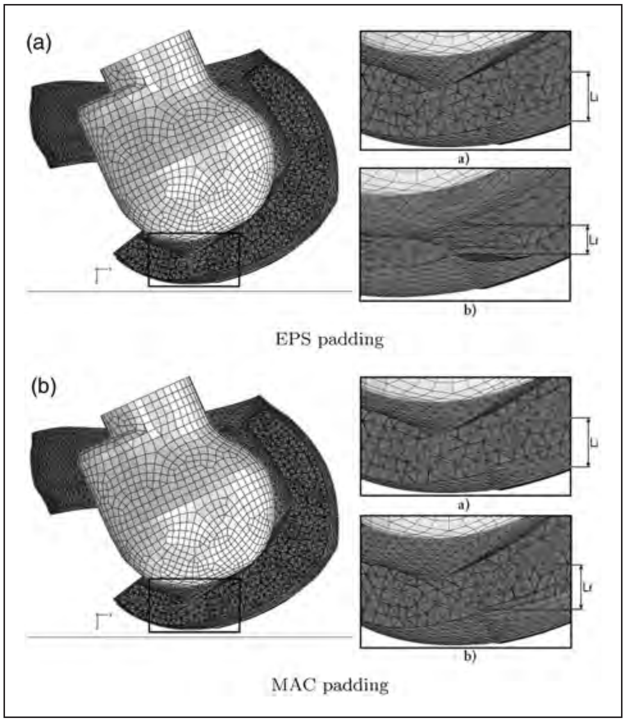

Figure 12. Padding thickness, insets: (a) before impact and (b) after impact.

and recyclable material. This work opens a very promising research field into the study of EPS+MAC compounds by combining the best properties of each material for safety applications.

Other conclusions of the work presented here can be rendered in the following points:

- Despite the differences between experimental and numerical impact results, the developed numerical model of the helmet impact can be considered valid. The differences can be explained by a simplified numerical model, since fixation devices, the retention system and the comfort padding were not modeled. The latter is responsible for the fitting between the helmet and the head and may have relevance for the impact kinematics.[12] The head–helmet model will be further improved in future work.
- For the particular shell and padding designs considered in this work, the results of the different impacts performed showed that the capabilities of MAC as an energy-absorption material is compatible with EPS for a single impact (see Figure 11) but obviously more interesting for subsequent impacts occurring in adjacent areas. However, acceleration peaks are more severe for cork (see Figure 9), which indicates that a proper (thinner and lighter) and optimized design for the MAC padding must be carried out in order to reduce the final weight.
- According to the current results, the helmet using MAC padding would not get approval from regulation ECE-R.22/05. The results have shown that the calculated maximum acceleration of the head and the HIC were exceeded in almost all the impacts performed. However, this work's preliminary results are very promising when it is taken into account that only 14% of the MAC padding was required to absorb the impact energy. Hence, thinner and lighter padding, or even composite padding employing EPS and MAC, can be studied in future work.
- After the first impact, the thickness of the EPS padding is strongly reduced compared to the MAC padding. This effect indicates that, when a second impact in the same region is to be considered, the capability of the EPS padding to absorb the impact energy is critically lower than for the MAC padding. Whether or not to include multi-impacts in the standards is still a topic under discussion among specialists.
- MAC is a promising impact energy-absorption material, specially when multi-impacts are important. MAC can also be combined with EPS in dual-material padding. These design solutions can combine the advantages of both materials, and are presently being considered and studied by the authors in order to be presented in a future work.

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Conflict of interest statement

None declared.

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