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Chapter 15

On the Use of Polyurethane Foam Paddings to Improve Passive Safety in Crashworthiness Applications

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Additional information is available at the end of the chapter

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1. Introduction

The use of cellular materials in general in the automotive industry, and polymeric foams in particular, has been increasing significantly for the last few decades. These materials are used within a particular vehicle for many different purposes, among which are, for example, sound and thermal insulation, vibration damping, fire protection and, of course, crashworthiness. Thus, crashworthiness, safety and protection parameters are strongly influenced by the materials used and, as a consequence, polymeric foams play a major role in the vehicle's crashworthiness levels. In absolute terms, the energy absorption capability of this class of materials can lead to significant improvements on the vehicle's passive safety, better protecting the passengers from aggressive impacts, by absorbing impact energy in a gradual and controlled manner. In addition, design limitations due to environmental constraints are growing steeply as are safety concerns. Whilst the former often leads to a reduction in the weight of the vehicle, the latter will most probably lead to the opposite. Therefore, the combination of properties such as low density, low cost and design flexibility with a great energy absorption capability, is what makes cellular materials so attractive for the automotive industry.

Presently, vehicle structures with high levels of crashworthiness protection are almost always light-weight and must deform in such a way as to dissipate the largest amount of impact energy possible. Several distinct mechanisms may contribute to this, such as, for example, plastic deformation, wrinkling, heat generation, etc. [20, 35]. One way to achieve these effects is to fill tubular or hollow metallic or composite structures with cellular materials, such as foams. During the last few decades, many researchers have been working on these issues [22, 28, 30–32].

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Polyurethane foam is nowadays being widely used in many energy absorption engineering applications such as cushioning and packaging [4, 15, 50]. Its use in automotive industry as an energy absorbing material in passive safety mechanisms goes beyond the protection functionality since it also provides more comfort, insulation and sound absorption. Thus, the role of this class of materials in vehicles is of special interest from both the consumer and the manufacturer points of view.

On a microscopical level, most cellular materials, including polyurethane foams, have the ability to absorb energy while deforming due to the mechanics of cell crushing. In the process of absorbing impact energy, cell walls deform plastically and get damaged (e.g. fractured) [7, 18].

Vehicle-to-vehicle side-impacts and vehicle rollover are presently among the most common types of car accidents and collisions. Additionally, these are also frequently the most serious accidents in terms of occupant injuries [6, 8, 39, 48]. Among these, frontal and side impact are the most severe. As a consequence, quite a large effort has been widely focused in improving passive and active safety mechanisms for frontal impact situations for the last decades. However, more recently, the number of serious injuries resulting from side-impacts has brought the attention of many researchers to the importance of developing similar or adapted mechanisms for such collisions [12, 33, 53]. In this type of collisions, the risk and/or the severity of the resulting injuries is frequently a direct consequence of the contact between the occupants and the lateral structure of the vehicle, given the reduced space between the occupant and the door [21]. Pelvic and chest areas have been reported by many authors as the the two areas most affected in this type of car-to-car collision [29, 43, 44].

In the late 1990s Morris *et al.* [37] observed, through a series of numerical simulations of side-impact collisions, that the space available between the structure of the vehicle and the passengers is one of the most important parameters with direct influence on the levels of occupant's injuries. This statement was also supported by many other researches, as can be seen, for example, from the works of Tencer *et al.* [49] and Schiff *et al.* [44]. Morris *et al.* state that the space available not only has influence on the impact velocity but also on the point of the velocity profile at which the door initiates contact with the occupant. These authors also evaluated the benefits of the use of paddings of different sizes in the door interior and of lateral airbags. Lim *et al.* [26] also studied, numerically, the inclusion of padding material for protection of the occupant pelvic area and concluded that it significantly reduced the severity of the resulting injuries. Additionally, Majumder *et al.* [29] studied the dynamic response of the pelvis and established fracture limits in side-impact collisions. These authors supported their conclusions with the results from numerical simulations using finite element modelling software. One of the most important conclusion these researchers derived from their work was that with a more appropriate design of the lateral door and the inclusion of padding material on the level of the pelvic area, the risk and/or severity of occupants' injury could be significantly reduced.

Based on the previous considerations, the authors propose the use of cellular materials, among which polyurethane foams, within an energy absorbing system specifically designed in such a way as to significantly improve passive safety on the event of side-impacts. This system

consists of a foam like impact padding confined inside the lateral doors of the vehicle. In order to be efficient, this foam padding must be mounted aligned with the occupant's pelvis, protecting one of the most critical areas in this type of collision. From the experiments and analyses made it is expected that this padding may absorb a significant part of the impact energy, and thus minimise both the forces transmitted to the body of the occupants and, most importantly, the magnitudes of the decelerations experienced, consequently reducing possible injury levels of the occupants of the vehicle.

The design of structures and the choice of materials for crashworthiness and protection systems within a vehicle are also of major importance and relevance for the overall safety of the driver and passengers. These are two of the research fields where there is still quite a large margin for improvement [16, 17, 24, 41, 46]. In the present work, the authors will present, discuss and compare the applicability of several distinct types of cellular materials for impact and energy absorbing paddings.

2. Polyurethane foam as an energy absorbing material

The behaviour of three polymer based structural foams under compressive impact loading — polypropylene, polyamide and rigid polyurethane foam — has been investigated by Avalle *et al.* [4]. As a conclusion, these materials are indicated as players of a very important role in passive safety systems. These authors obtained stress-strain curves in both static and impact loading (dynamic) conditions for the materials examined for different densities at room temperature. They analysed in detail, using energy-absorption and efficiency diagrams, the energy absorption characteristics of each material. Among the materials tested, these authors observed that polyurethane foam is the less sensitive to strain-rate and the one that presents the longest intermediate plateau stage. These facts distinguish this material from the remaining foams studied. The authors also concluded that the rigid polyurethane foam exhibited one of the highest efficiency levels, however, it lost its integrity during compression.

The energy absorption behaviour properties of polyurethane foam were also investigated by Anindya and Shivakumar [2]. The authors evaluated the energy absorption attributes of polyurethane foam in various forms — flexible high resilience, flexible viscoelastic and semi-rigid — as a function of the overall foam density, based on the load-displacement behaviour of the material under compressive loads.

Taher *et al.* [47] investigated the use of polyurethane foam with a density of 47 kg/m^3 as a core filler of a composite keel beam as a way of preventing global buckling and improving crashworthiness performance in aeroplanes and helicopters. The results obtained by these authors revealed that the energy absorbing mechanism can meet the requirements for the purpose desired together with substantial savings.

Likewise, the behaviour of polyurethane foam filled thin-wall structures was investigated by Ghamarian *et al.* [13] in terms of crashworthiness improvement for the aerospace industry. The quasi-static crushing behaviour and efficiency of empty and foam-filled structures was investigated experimental and numerically and the efficiency and the authors were able to demonstrate that the filled tubes presented higher energy absorption capabilities than that of the combined effect of the empty structured and the foam.

Furthermore, applications of polyurethane foam in explosive blast and ballistic energy absorption applications have also been subject of investigation [51, 52], indicating that this material may be a valuable part of protection systems against both generic types of threats.

Later, Shim *et al.* [45] investigated the two-dimensional behaviour of rigid polyurethane foam under low velocity impact loadings in terms of both the deceleration of the impactor and the overall amount of energy dissipated. These authors also proposed suitable stress-strain relations as well as failure patterns, failure criteria and equations of motion for this cellular material.

The foam used by Shim *et al.* [45] was obtained by blending — Daltofoam and Suprasec — in the presence of a blowing agent, producing a final product with a density of 25.6 kg/m^3. Alike typical cellular materials the uniaxial compressive behaviour of this material can be described, in terms of stress-strain, by three distinct stages [14]. The first stage — the elastic deformation stage — is followed by a plastic constant stress stage (also known as "plateau" region) where most of the energy absorption occurs. Finally, the material exhibits densification. The elastic part of the behaviour of these materials is mostly due to the axial compressive resistance of the cell walls. The plateau region is mainly related to the bending, crushing and eventually fracture, of the cell walls. The material starts to densify when all the cells are crushed and the behaviour approaches the behaviour of a monolithic material [19, 42, 54].

The type of polyurethane foam investigated by Shim *et al.* [45] is adopted for the scope of this study and its stress-strain curve is represented on Figure 1, where the three stages are clearly evident. As the overall behaviour of this material can be divided in three distinct stages, its stress-strain constitutive modelling can be defined by the following set of equations:

$$\sigma = \begin{cases} E\varepsilon & \text{if} \quad \varepsilon \in [0, \varepsilon_y] \quad \text{(elastic behaviour)} \\ E\varepsilon_y & \text{if} \quad \varepsilon \in [\varepsilon_y, \varepsilon_d] \quad \text{(plastic behaviour, plateau)} \\ E\varepsilon_y \exp \dfrac{a(\varepsilon - \varepsilon_d)}{(\varepsilon_l - \varepsilon)^b} & \text{if} \quad \varepsilon \in [\varepsilon_d, \varepsilon_l] \quad \text{(densification)} \end{cases}, \tag{1}$$

where E is the material elastic modulus (considered to be $E = 2.78$ MPa), ε_y is the compressive yield strain ($\varepsilon_y = 0.05$), ε_d is the densification strain ($\varepsilon_d = 0.8$), ε_l is the maximum compressive strain ($\varepsilon_l = 0.95$) and a and b are constants which define the shape of the stress-strain curve in the densification regime.

3. Crashworthiness efficiency of polyurethane foam

In previous investigations the authors used a Finite Element Analysis (FEA) approach to study the behaviour of four distinct cellular materials under impact loading in order to evaluate their relative efficiency in terms of crashworthiness applications [40]. The materials tested within these studies were two polymeric foams: polyurethane foam and IMPAXX™ ; a metallic foam: aluminium foam; and a natural cellular material: micro-agglomerated cork. The most relevant mechanical properties of these materials are listed on Table 1, where ρ^* and E^* are the density and elastic modulus of the cellular material, respectively, and E, σ_y and ν are the

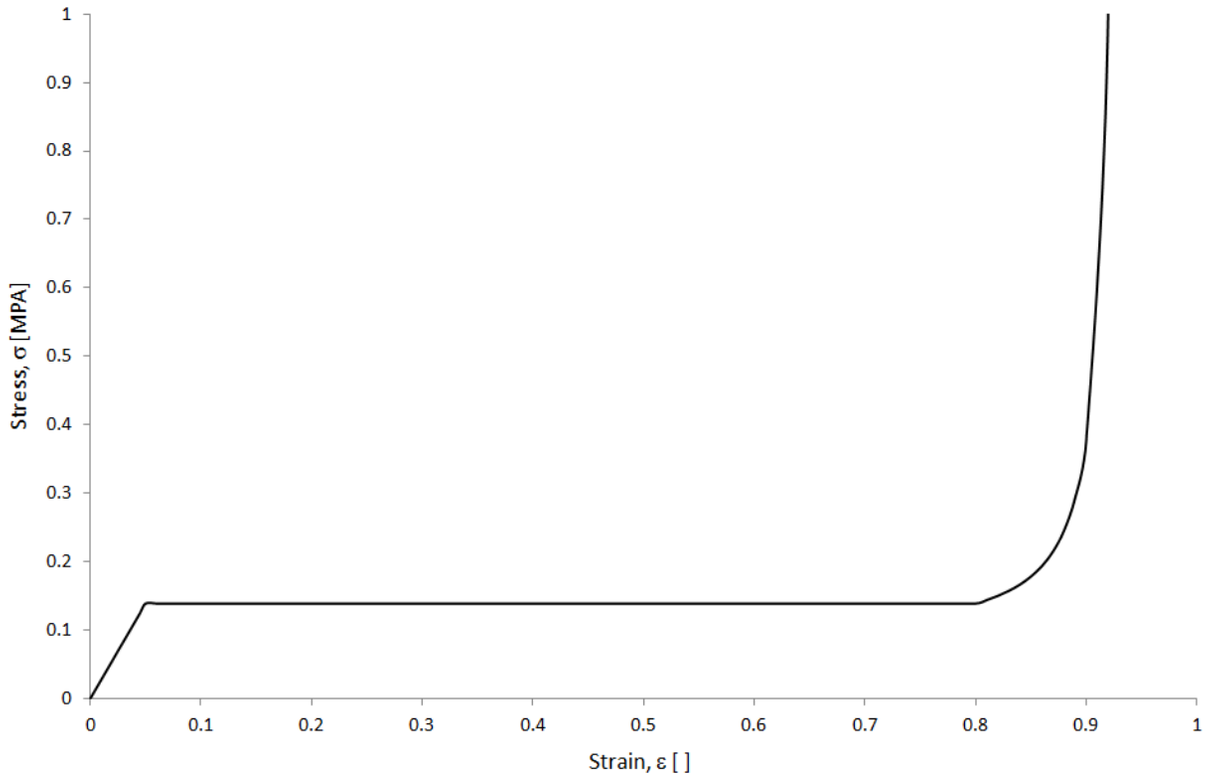


Figure 1. Stress-strain compressive behaviour of rigid polyurethane foam as obtained by [45].

elastic modulus, yield strength and Poisson coefficient of the base material, accordingly. The four materials share great energy absorption capabilities and are used in impact dissipation applications. For this purpose the materials were tested numerically, using a Finite Element Method simulation software, LS-Dyna™ [1], under impact loading in the same conditions and were analysed in terms of acceleration peak and energy absorption.

Mechanical Properties	ρ^* [kg/m^3]	E^* [MPa]	E [MPa]	σ_y [MPa]	ν
Polyurethane Foam [a]	25.6	2.78	1600	127	0.44
Micro-agglomerated Cork [b]	293	15	9000	1	0.30
IMPAXX™	33.661	16.322	3400	80	0.40
Aluminium Foam [c]	470	117	69000	241	0.285

[a] [11]; [b] [23, 45]; [c] [3];
[d] [10, 34].

Table 1. Mechanical properties of the polyurethane foam and of other cellular materials used for comparison purposes.

Paulino and Teixeira-Dias[40] proposed a quantitative procedure that allows a padding or protection system designer to determine the crashworthiness efficiency and performance of specific cellular materials. This procedure assumes that the best method to assess the material

value for automotive safety applications is by evaluating the rate at which it dissipates energy. In vehicle impacts, the ideal would be for energy to be dissipated in a gradual and controlled manner. Bearing this in mind, the authors proposed and tested a performance index, ϕ, as an attempt to quantitatively evaluate the energy absorption rate of a certain cellular material. The analytical expression that better describes the dependency of the absorbed energy with time during an impact can be given by:

$$E = E(\bar{t}) = \bar{E}_c^{\min} + \left(\bar{E}_c^{\max} - \bar{E}_c^{\min}\right)\left[\frac{\exp\left(\lambda \frac{\bar{t}-\bar{t}^{\max}}{\bar{t}^{\min}-\bar{t}^{\max}}\right)-1}{\exp(\lambda)-1}\right] \quad (2)$$

where $E = E(\bar{t})$ is the analytical function of the energy absorption in time, $E_c^{\min}$ is the minimum kinetic energy of an impacting wall and $E_c^{\max}$ is the maximum kinetic energy of the moving wall. $t^{\min}$ and $t^{\max}$ are the minimum and maximum time values considered for the analysis, respectively. The use of the overbar indicates that the respective variable is normalised. λ is a dimensionless parameter that defines the shape of the energy absorption curve. The methodology and interpretation of this performance is explained in more detail by Paulino and Teixeira-Dias [40].

On a first analysis, the research carried out by the authors showed that for all the impact loading cases studied polyurethane foam was actually not the best performing cellular material among the ones tested, as can be observed from the results on Figure 2. The four materials investigated share a tendency of decreasing performance index with the increase of initial impact kinetic energy. For all the levels of energy studied PUF has a better behaviour than IMPAXX™. However, for low values of initial impact energy PUF exhibits relatively high values of performance index, being overtaken only by micro-agglomerated cork or aluminium foam. Nonetheless, in the same study it was also verified that the specific energy absorption results of the rigid polyurethane foam tested was higher than aluminium foam and micro-agglomerated cork. In fact, the former was the material with the lowest density (see Table 1). It is then reasonable to assume that for denser foams the results in terms of total absorbed energy, maximum acceleration, average force or performance index could be similar — or even better — to those obtained when using other cellular materials.

The passive safety system proposed to protect the occupant pelvic area from side-impact collision consists of a padding confined inside the vehicle's lateral doors, positioned in the direction of the occupants pelvic area, as can be seen in Figure 3. This protection padding should result in lower forces transmitted to the occupant and lower maximum accelerations due to the material energy absorption capabilities, as explained previously.

Standard side-impact crash tests should be performed in order to make a correct evaluation of the efficiency of polyurethane foam as a material dedicated to energy absorption specifically to improve passive safety in side-impacts. Given the complexity associated to the numerical simulation of crash tests and consequently due to the highly expensive procedures, a simplified model was used to replicate a vehicle-to-vehicle side-impact as defined by the European New Car Assessment Programme (Euro NCAP) [38]. A schematic representation of this simplified model is shown in Figure 4. Within this scope, a set of finite element analyses

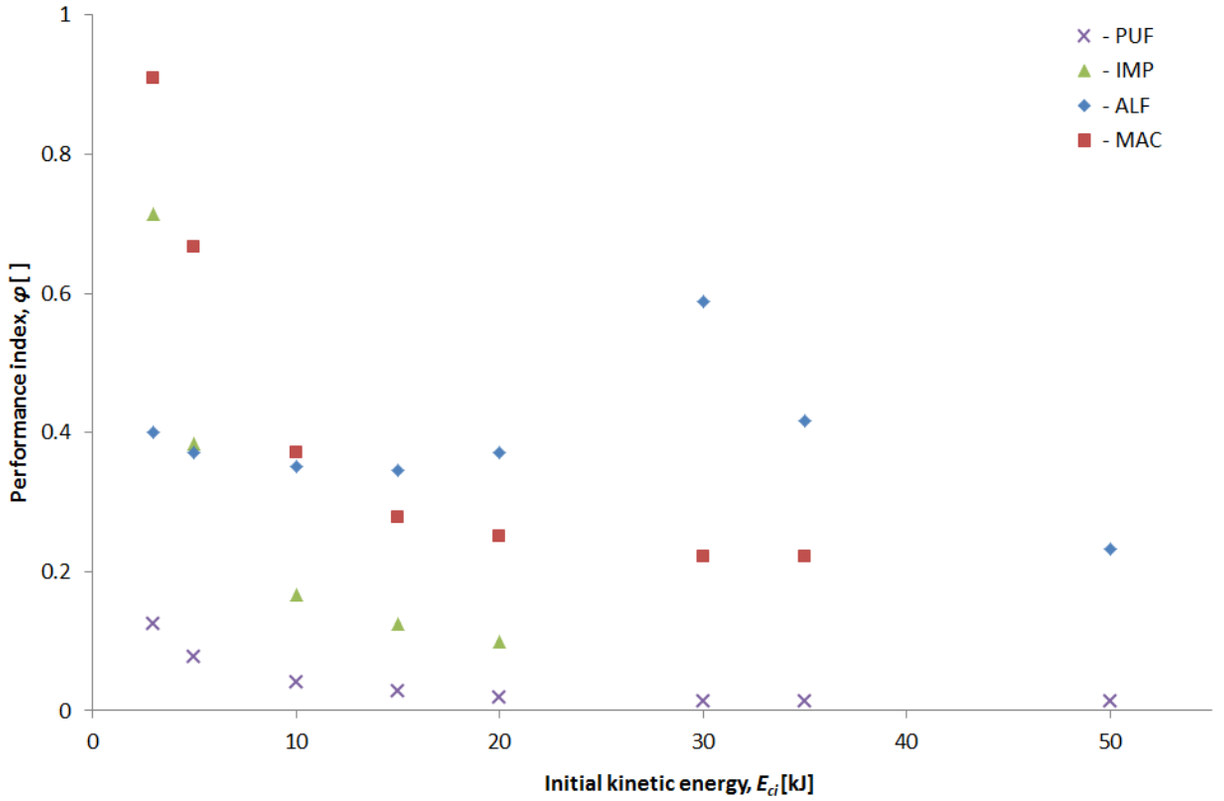


Figure 2. Variation of the performance index ϕ as a function of the initial impact kinetic energy E_{ci} for different cellular materials [40]. PUF: polyurethane foam; IMP: IMPAXX™ ; ALF: aluminium foam; MAC: micro-agglomerated cork.

was performed using LS-Dyna™to assess the benefits of including a padding confined in the vehicle's lateral door and compare the efficiency of different paddings made from different cellular materials, i.e. rigid polyurethane foam (PUF), IMPAXX™ (IMP), micro-agglomerated cork (MAC) and aluminium foam (ALF).

Three key parameters in terms of crashworthiness are defined and analysed, namely the acceleration profiles, the intrusion levels and the loads acting on the vehicle structure.

3.1. Numerical modelling

The use of a simplified model is a common strategy for cost effective preliminary evaluation of crashworthiness situations [9, 12]. Following this line of thought and in the scope of this investigation, an approximate model to crash tests performed by Euro NCAP [38] is developed, implemented and used for the evaluation of the safety performance in vehicle-to-vehicle side-impacts.

The generic vehicle tested in this simplified model consists of a subset of elastic spring elements and the lateral door. The subsets of springs are defined in such a way as to approximately describe the behaviour of the remaining structure of the vehicle. For this purpose, the weight of the vehicle and passengers, the vertical position of the centre of gravity of the car and the friction coefficient between the vehiclet's tires and the asphalt are



Figure 3. Illustration of the inclusion and position of the protection padding, confined in the lateral door of the vehicle.

considered. This schematic description is illustrated on Figure 5. This approach is considered satisfactory given that the deceleration and intrusion behaviour of a vehicle during a collision are mostly influenced by the two following structural properties: (i) its mass and (ii) its global stiffness [36]. With this approach it should be possible to assess the efficiency of a given structural component without modelling the full vehicle and still assure reasonable results and precision.

The springs representing the global structure of the vehicle were modelled within LS-Dyna™ using two-node discrete elements and *MAT_SPRING_ELASTIC stiffness response model. Different material stiffness magnitudes were assigned to the springs in accordance to their relative position to the centre of gravity of the vehicle. The vehicle's lateral door was modelled considering four-node fully integrated shell elements implemented with the Belytschko-Tsay formulation [5].

The material considered for the model of the door was DC06 steel, constitutively described with the *MAT_PIECEWISE_LINEAR_PLASTICITY material model, with an elastic modulus $E = 210$ GPa, density $\rho = 7850$ kg/m^3 and Poisson ratio $\nu = 0.3$.

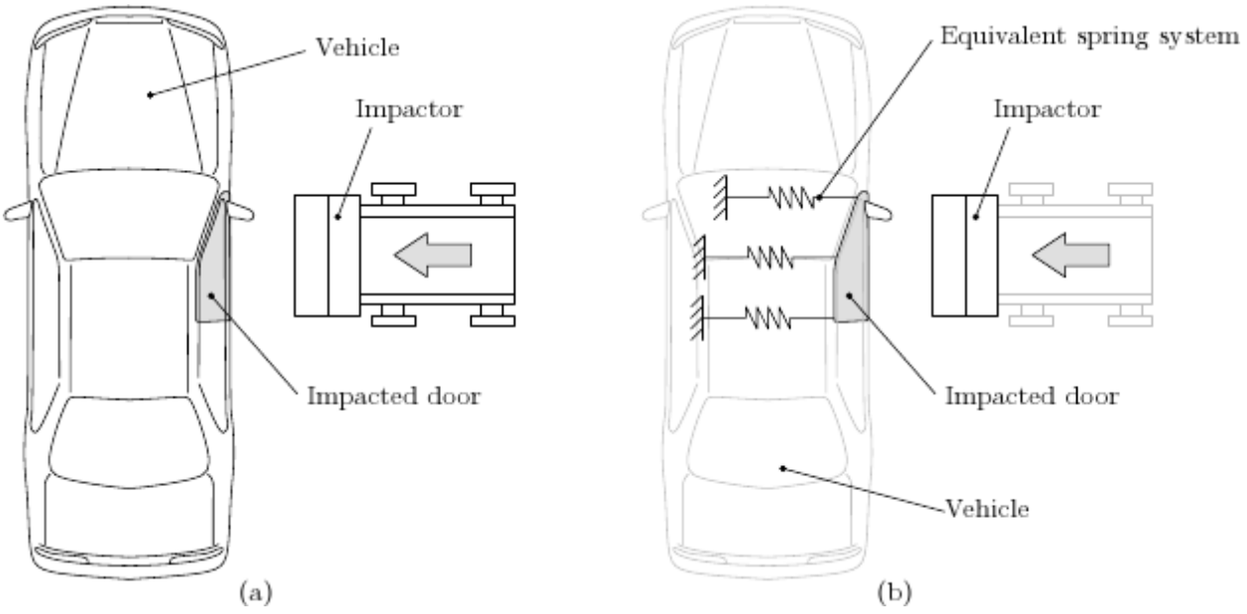


Figure 4. Schematic representation of the simplified model used for finite element implementation of a side-impact crash test according to the EuroNCAP standard [38].

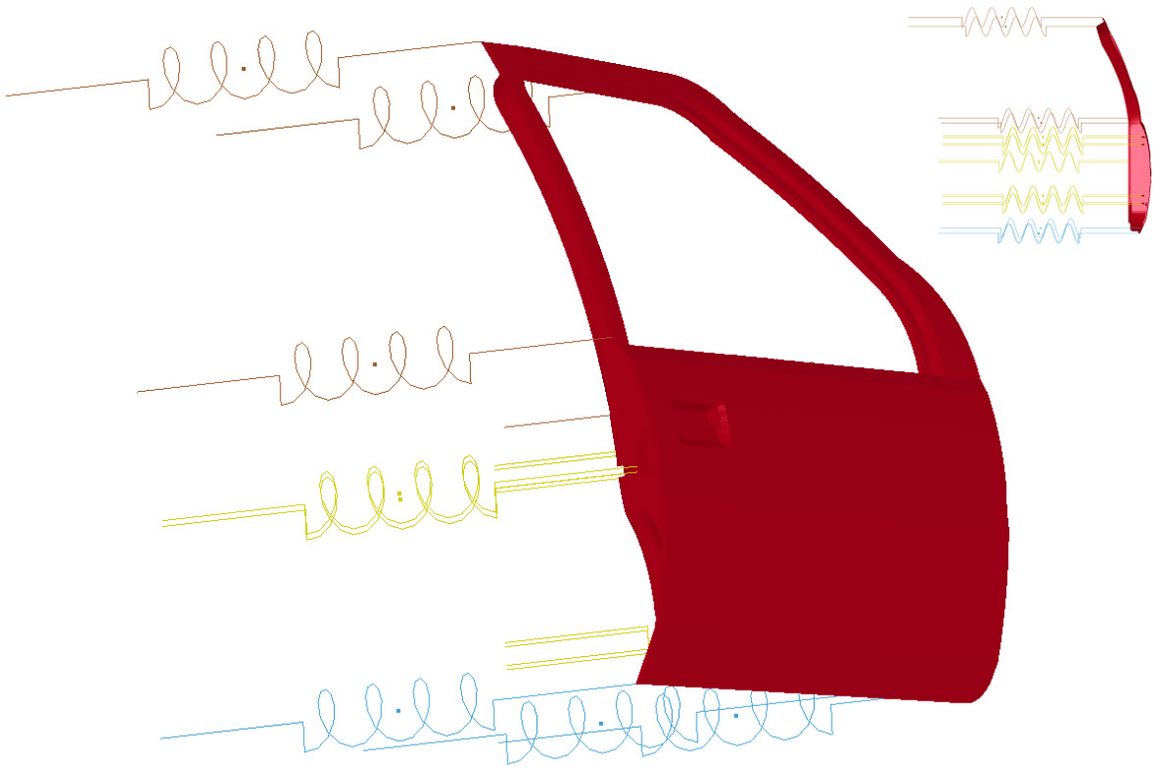


Figure 5. Finite element representation of the simplified model of the vehicle's lateral structure developed and implemented to simulate the side-impact.

The designed and proposed padding system was modelled with four-node tetrahedral elements. The material behaviour was described using the *MAT_HONEYCOMB constitutive

approach in order to describe all three different cellular materials. This material is generally adequate for honeycomb and foam materials with anisotropic behaviour [11, 25, 27]. This modelling approach assumes zero value for the Poisson ratio and considers a variable elastic modulus, increasing linearly from the initial value as a function of the relative volume (i.e. the ratio of the actual volume to the initial volume) up to the fully compacted material modulus.

According to the EuroNCAP standards [38] the impacting vehicle (see Figure 4) must be modelled considering deformable 3030 and 5052 aluminium honeycomb blocks. These blocks should be attached to a mobile structure that is to be considered rigid. Within the scope of this work the deformable blocks were modelled using eight-node hexahedral finite elements. The material behaviour was once again described by the `*MAT_HONEYCOMB` constitutive model, for the same reasons stated for the padding materials. The necessary material properties were determined considering both honeycombs [14]. The propeller structure is, however, fairly complex according to EuroNCAP regulations and it is not fully described on the side-impact protocols available. Nonetheless, the total weight of the impactor system is known and, ultimately, the geometry of the impactor moving structure is not significantly relevant for the conditions of the performed tests. For this reason this moving structure was modelled as a moving rigid wall. The most determinant feature is the part of the impactor colliding with the vehicle's lateral door, i.e., the deformable aluminium honeycomb blocks. Hence, mass was added to the impactor's anterior part and the initial velocity of the crash tests ($v_0 = 13.89$ m/s) was assigned to the structure.

4. Results and discussion

Once the full model of the vehicle side-impact is defined and implemented in LS-Dyna™ tests were made considering the vehicle door with the paddings made from PUF, MAC and IMP cellular materials. An additional test was made with the door with no padding, for the sake of comparison. The resultant values of kinetic energy, loads, accelerations and absorbed energy were registered. From these results it is possible to evaluate the relative performance of each material used in the side-impact padding. A detailed discussion of these results is presented in the following paragraphs.

4.1. Load distribution

The evolution of the reaction force on the moving rigid wall (the propellant of the deformable barrier in the impactor vehicle) is computed and its dependence with time is registered and plotted on Figure 6. When the rigid wall first contacts the deformable barrier, a force peak is registered at instants $t \approx 0.5$ ms for all the simulations performed. This occurs in an early stage of the crash test when no intrusion has yet happened, not even contact with the vehicle door. Thus, this event shall not be considered relevant for the analysis and should be considered a side-effect of the modelling approach used. After $t \approx 8$ ms, it can be verified that the the reaction force evolution is, as expected, considerably more unstable for the simulation with no padding in the lateral door than for the remaining tests (using paddings with cellular materials). This fact suggests that there is a significant improvement on the behaviour of the vehicle in terms of protection in side-impact collisions when a lateral padding is applied.

Furthermore, from $t \approx 90$ ms on the load almost goes back to zero on all numerical simulations. This is a consequence of the separation of the rigid wall from the impactor. During this stage, however, the system exhibits rigid body motion and, thus, the results obtained for times $t > 90$ ms are not considered relevant for the scope of this research.

It can also be clearly observed that the average load during the considered time interval is considerably lower ($\approx$ 50kN), one order of magnitude, for all the crash tests including a lateral padding when compared the one observed for the test with no padding ($\approx$ 500kN). This leads to the conclusion that the implementation of a padding, either PUF, MAC, IMP or ALF, leads to a much lower and smoother distribution of the load for the whole duration of the impact. The average force obtained for the simulations with the protection padding was around 85% lower than the ones obtained without padding and the maximum force was up to 79% lower.

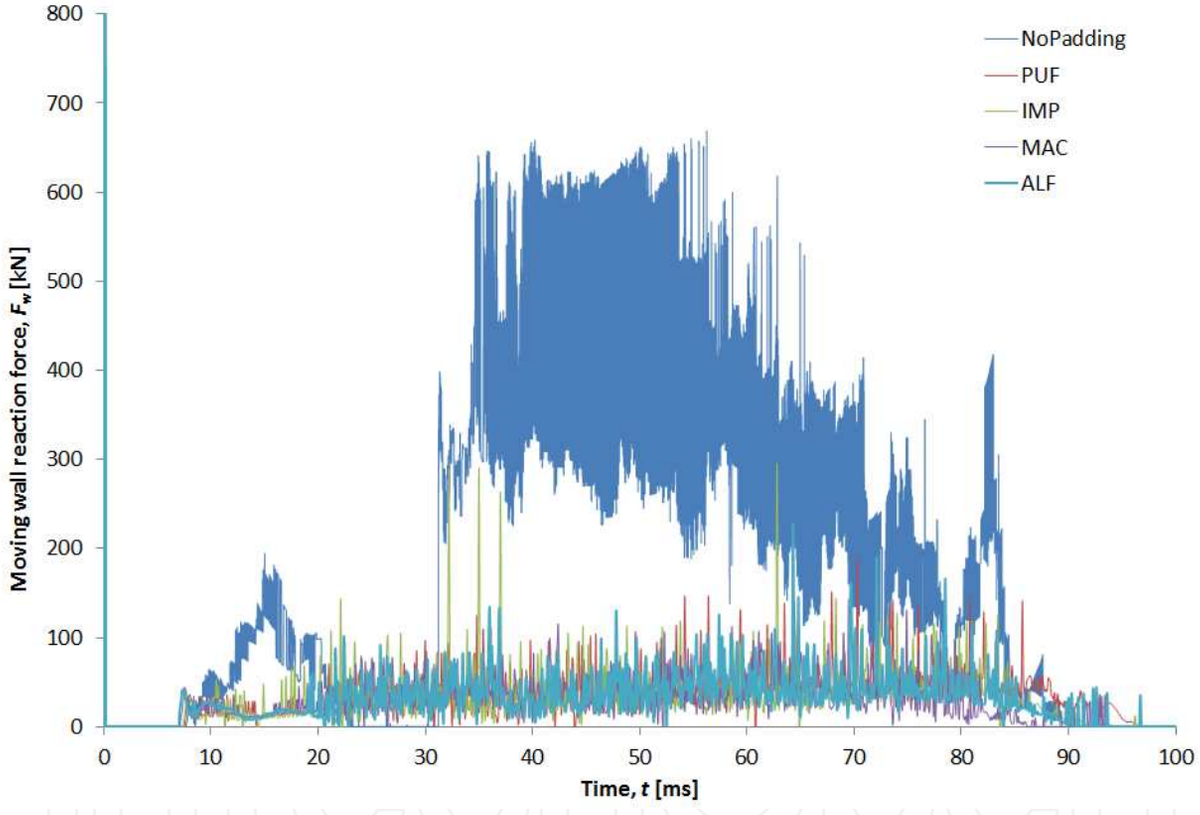


Figure 6. Evolution of the reaction force on the moving rigid wall with time for the simulations of side-impact crash tests.

4.2. Kinetic energy

The evolution of the kinetic energy of the whole system with time is represented on Figure 7. A sudden increase of the kinetic energy can be observed for $t \approx 3$ ms for the crash test with no padding. This corresponds to the instant at which the impactor structure initiates contact with the door of the vehicle. Additionally, for all the simulations performed the curves exhibit an inflection near the final stage of the impact ($t \approx 80$ ms), increasing from this instant until the

end of the numerical simulation. From the visualisation of the kinematic results it is possible to relate this inflection to the beginning of rigid body motion of the door (and vehicle) after impact, where incremental deformation ceases to exist [40]. Hence, for the purpose of this investigation the parameters studied will only consider the instants between these marks (that is $3 < t < t_r$ ms), where t_r is the time when rigid body motion initiates. This time instant will be considered different according to each simulation: (i) $t < t_r \approx 80$ ms for the simulation without padding, (ii) $t < t_r \approx 90$ ms when using the polyurethane foam padding, (iii) $t < t_r \approx 85$ ms when using the IMPAXX™ padding, (iv) $t < t_r \approx 75$ ms for the micro-agglomerated cork padding and (v) $t < t_r \approx 90.5$ ms when using the aluminium foam padding.

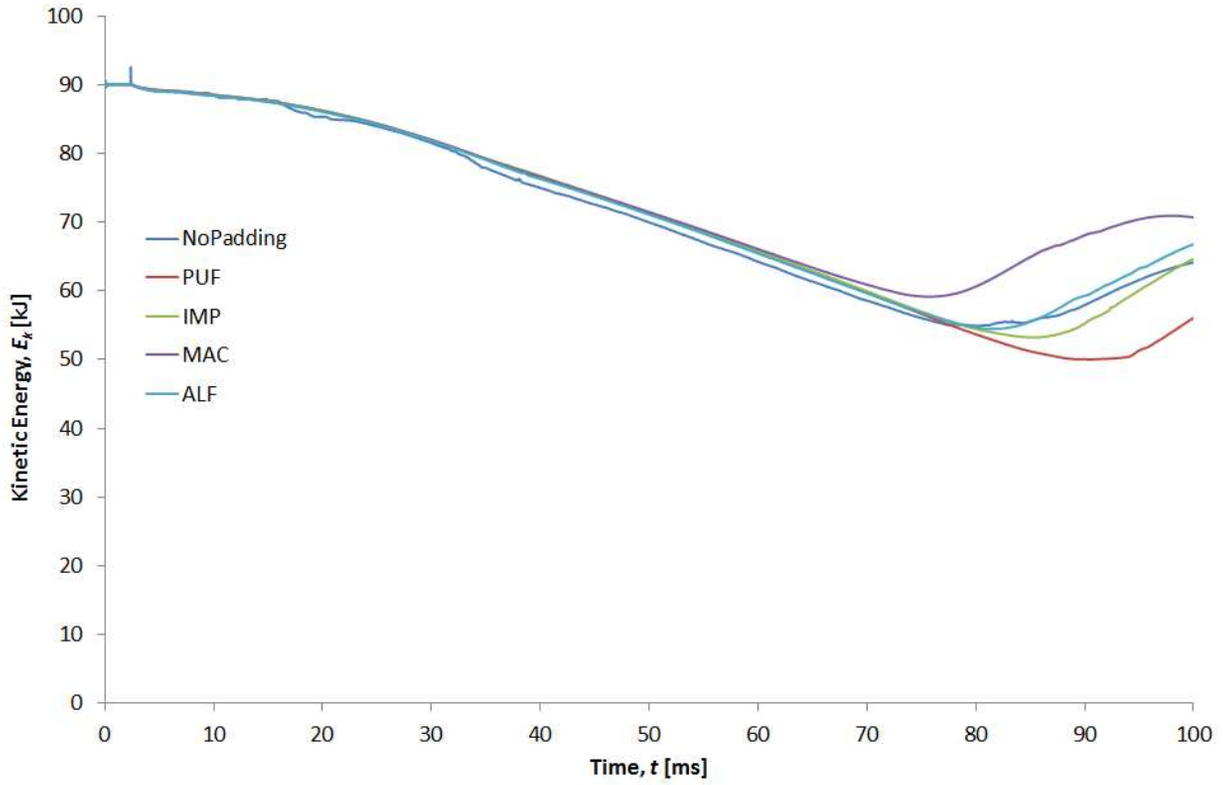


Figure 7. Evolution of the system's kinetic energy with time for the simulations of side-impact crash tests.

4.3. Maximum acceleration

An anthropomorphic dummy was not considered or modelled during the finite element analyses carried out during this research because of the added complexity and Central Processing Unit Time (CPU) time it would bring. Hence, for the purpose of evaluating the maximum acceleration (or maximum deceleration) resulting from the impact felt on the passenger's pelvis area, as well the intrusion level in the passenger compartment, numerical results on nodes on the pelvis direction, on the inner side of the vehicle door, were analysed and are discussed herein.

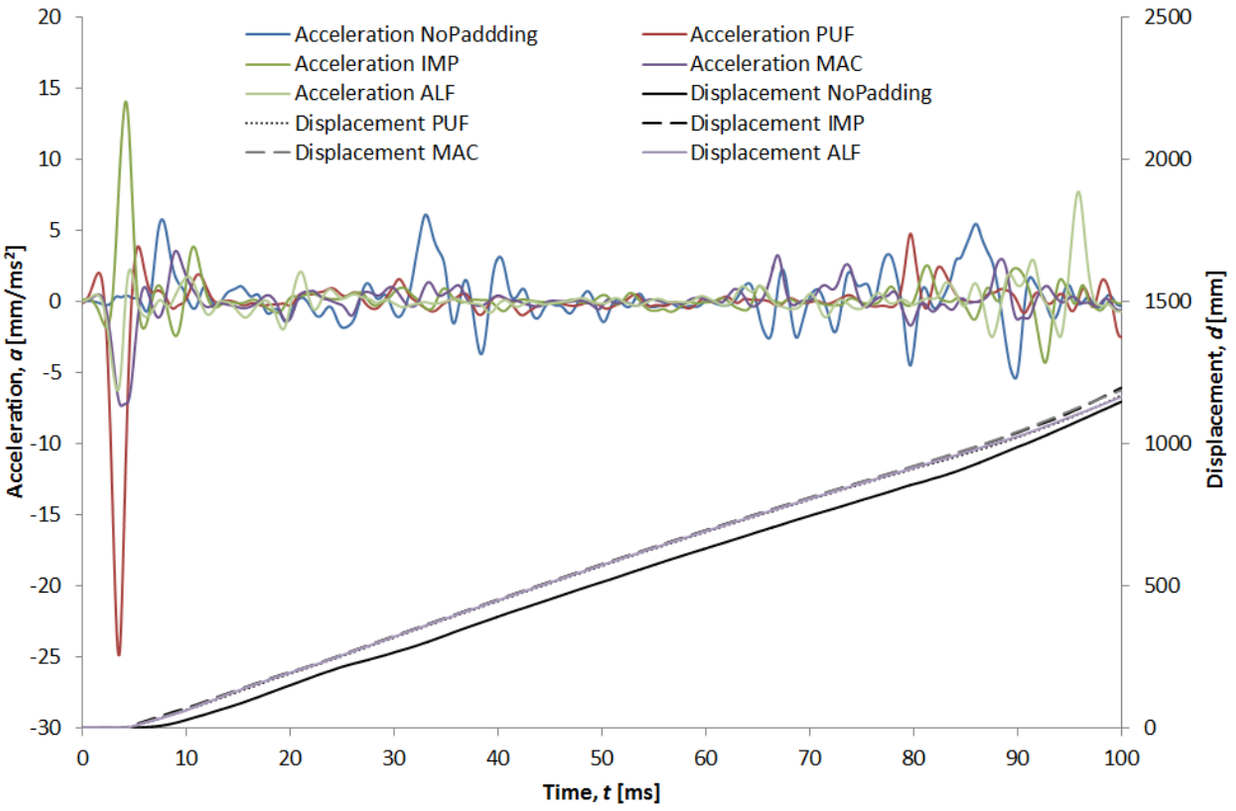


Figure 8. Dependence with time of the acceleration and displacement of the the door's interior structure in the direction of the occupant's pelvic area, obtained from the numerical simulations of the side-impact crash tests.

The resulting evolution in time of the acceleration and displacement measured on the internal structure of the lateral vehicle's door, in the direction of the pelvic area of the occupant, is shown on Figure 8. A SAE-180 filter was used to refine the acceleration results as advised by the protocols used by EuroNCAP [38] for acceleration measurements on the occupants' pelvic area. Very high maximum values of acceleration can be observed at the initial instants of the simulation for all the tests that included a padding, as opposed to the ones observed for the simulations with no padding. This fact is most probably due to the added stiffness of the padding on the first instants of the crash. However, this happens for the early stages of the impact when the displacement of the lateral door's interior is still inexistent and, consequently, there is no contact between the door and the occupant. Thus, the maximum acceleration values were determined only starting from the moment when the displacement of the door initiates.

The results obtained prove that the use of an interior padding can lead to a significant decrease in the maximum acceleration felt by the occupants. This decrease can be as high as 59%. While the maximum acceleration value for the simulations with no padding is $a_0 = 6.1$ mm/ms^2, acceleration peaks of $a_{PUF} = 4.8$ mm/ms^2, $a_{IMP} = 3.9$ mm/ms^2, $a_{MAC} = 3.5$ mm/ms^2 and $a_{ALF} = 2.5$ mm/ms^2 were observed for the crash tests with PUF, IMP, MAC and ALF padding, respectively. Thus, the inclusion of a polyurethane foam padding results in a reduction of roughly 20% even though it is not the best performing material among the ones investigated.

4.4. Energy absorption

The dependence of time of the energy absorbed by the structure of the vehicle is plotted on Figure 9. Analysing these results, it becomes clear that the inclusion of a polyurethane foam padding inside the door structure is the best way to increase the capability to absorb impact energy during a side-impact, when compared to both the crash test numerical simulations with no padding and those using paddings made from other cellular materials. The energy absorbed by the structure with the PUF padding exhibits a higher dissipation capability, leading to an increase in energy absorption of approximately 13% when compared to the structure to no padding.

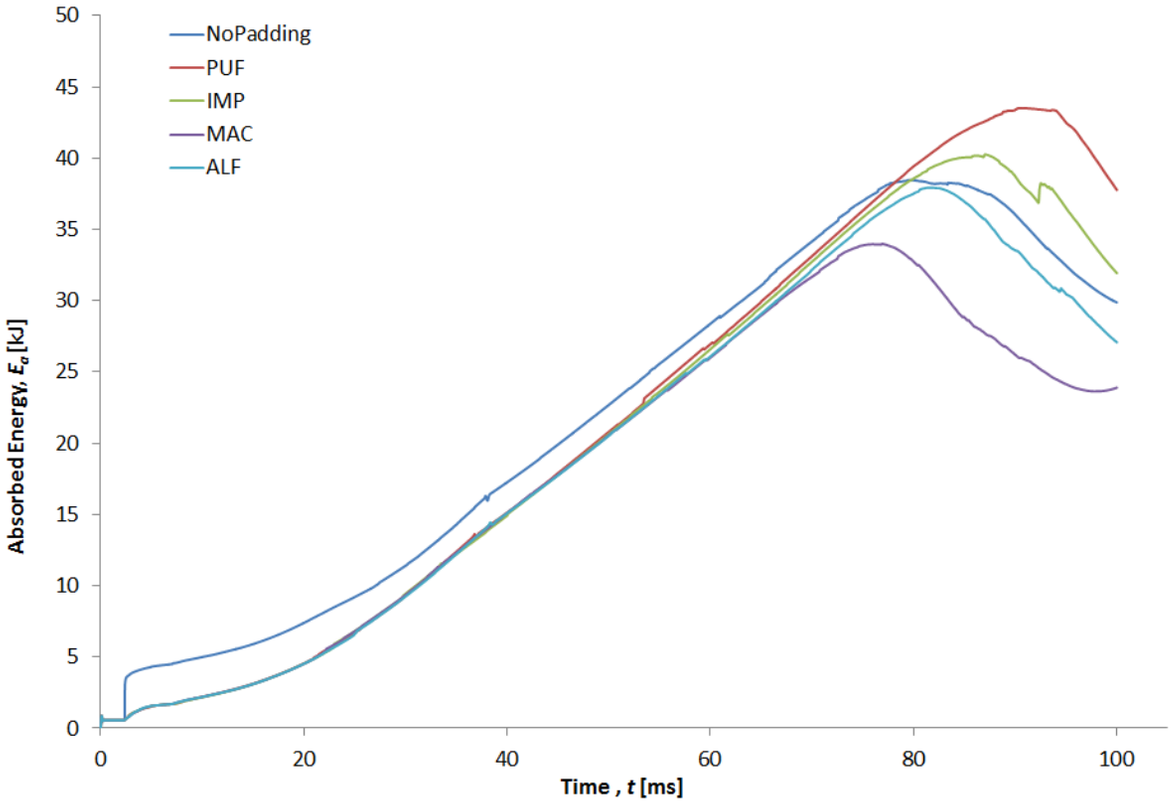


Figure 9. Variation with time of the energy absorbed by the structure of the vehicle during the side-impact crash tests.

5. Conclusions

The introduction of a structural padding made from cellular materials inside the lateral doors of common vehicles is suggested as a passive safety mechanism in side-impact vehicle-to-vehicle collisions. In order to evaluate the viability and efficiency of this safety mechanism crash tests were performed using finite element analysis software LS-Dyna™. The EuroNCAP [38] standards and definitions were considered when the defining and implementing the crash-test models. Rigid polyurethane foam, IMPAXX™ , micro-agglomerated cork and aluminium foam paddings were tested and their performance

as energy absorbers was confronted with the results with no padding. The results obtained show that the implementation of a foam like material — a cellular material — as a padding for energy dissipation in lateral doors can, in fact, lead to considerable improvements, mainly in terms of maximum values of deceleration (the direct consequence leading to injury levels) and loads transmitted to the occupants of the vehicle.

Reductions as high as 59% in terms of maximum acceleration values can be observed when comparing the results obtained with and without padding. This reduction was achieved by implementing an aluminium foam padding. This was followed by a cork micro-agglomerate padding, with an improvement of 43%, and IMPAXX™ with 36%. A padding of rigid polyurethane foam, even though it is the one leading to a smaller reduction, can result in maximum accelerations 21% lower when compared to tests without padding.

The average loads in the crash tests with padding are more than 85% lower than the ones from the tests with no padding and its distribution is more balanced. Additionally, the maximum load could also be reduced by up to 79% when including a protective padding, being the best results obtained with cork micro-agglomerate. Polyurethane foam padding enclosed inside the vehicle's lateral door resulted in reductions of 83 and 73% in terms of average and maximum load, respectively.

Furthermore, in terms of energy absorbed by the vehicle's global structure, polyurethane foam was the material exhibiting the best behaviour. The inclusion of this padding, as well as micro-agglomerated cork padding, resulted in improvements of approximately 13%.

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