© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

Relative role of foam thickness and foam density in the design of a car-body pillar and dashboard in order to optimise the HIC index

G. Belingardi[1], R. Duella[2], F. Capello[2]
[1]*Politecnico di Torino, Italy.*
[2]*Tesco TS S.p.a, member of P.C.L group, Torino, Italy.*

Abstract

The FMVSS201 standard prescribes a limit value to the HIC index obtained in experimental impact tests of a human head dummy hitting against any location of the front passenger compartment of a motor car.

In order to satisfy this limit value, automotive designers are considering the possibility of covering the metallic structure with an appropriate layer of foam.

To take advantage from this possibility the designer has to make an appropriate choice of the foam density and of the thickness of the foam layer.

The role of these two fundamental design variables have been studied by means of a number of FEM simulations, that have explored the variable interactions by means of a complete experimental plane.

Results support the designer in making his choice in order to match the regulation prescriptions.

1 Introduction

Safety of the driver and other passengers are of great importance in the design of vehicle, due to the increasing demands of the customers and of the national regulations. In a historical perspective it is well visible the changes in the automotive design and equipment due to the satisfaction of safety regulations.

In this period studies are conducted to prepare solutions for the requirements of the FMVSS201 [1] and the companion European standards. These standards prescribe a limit value to the HIC (Head Injury Criteria) index measured during an laboratory test by means of an instrumented human head dummy that, starting from a stated position relative to the driver or passenger front seats, hits against

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

any structure or object in the passenger compartment. Hence of particular relevance in this type of test is the behaviour of the dashboard, the door structure, the steering wheel and, considering the frame structure, the A and B pillars and the roof rail.

In this paper we deal at first with the problem of head impact against a simple plate of metal sheet (that can represent the upper dash-board structure) in order to understand the role of the design variables, then we pass to deal with the left A pillar that introduce a further complexity in the structural problem due to the large curvature of the beam. The pillar cannot be approximated with a plate, but since its curvature is an important feature, it must be studied as a shell.

One of the possibility to pass the FMVSS201 standard tests is cover these metallic structures with an appropriate layer of crushable foam.

After having chosen the most convenient type of foam, the designer has to define the most appropriate values of the foam density (that means the stress-strain relationship and the energy absorption capability) and the foam layer thickness with the aim of obtaining a HIC value within the admissible limit value.

The first simplified problem (impact of the head against a flat plate) gives the possibility of analysing the relative role of the considered design variables. With this aim a complete factorial plane of numerical experiments has been devised adopting the DOE statistical methodology.

Expanded polypropylene - EPP - foam has been considered, having determined by previous experimental testing the dependence of the foam mechanical characteristic on the density and strain rate values, up to very large strain level.

Simulation has been performed by using the explicit code PAM-CRASH.

Previous numerical tests permitted to chose one of the foam models implemented in the FE code, to calibrate the constants required to describe the material behaviour and to verify that the simulation results are consistent with the experimental data.

2 Description of the problem

Figure 1 show the FEM discretisation used for the first step of our study. It is visible the square steel plate (300x300 mm, 1 mm thick) covered by a foam layer (modelled by brick elements) and the rigid sphere that simulates, in the experimental tests as well as in the numerical model, the human head. The head dummy has a mass of 6.8 kg and a diameter equal to 165 mm by the European standard and a speed of 6.7 m/s at impact as prescribed both by the FMVSS201 and the European standards. The plate is completely clamped along its edge. The head dummy hits the central zone of the plate, the impact movement is directed according to the plate normal orientation.

Figure 2 collects the typical stress-strain curves of a expanded polypropylene foam, as obtained by experimental tests [2,3]. There are four different curves related to four different values of the foam density. This type of material is of large interest for the energy absorption problem in crashworthiness since, as it is

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

well visible in the figure, the mechanical behaviour is characterised by a rather wide compressive stroke where the reaction stress is almost constant. This is a good approximation of the ideal absorber and allows the absorption of a large quantity of energy while the reaction force (that in our case means the head deceleration) remains to a limited, nearly constant value. After that plateau phase there is a rapid growth of the force due to the foam densification (i.e. cells are progressively closed) [4].

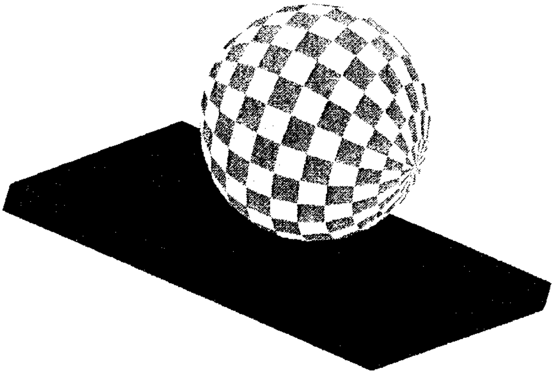

Figure 1: FEM model of the foam covered dashboard and of head dummy.

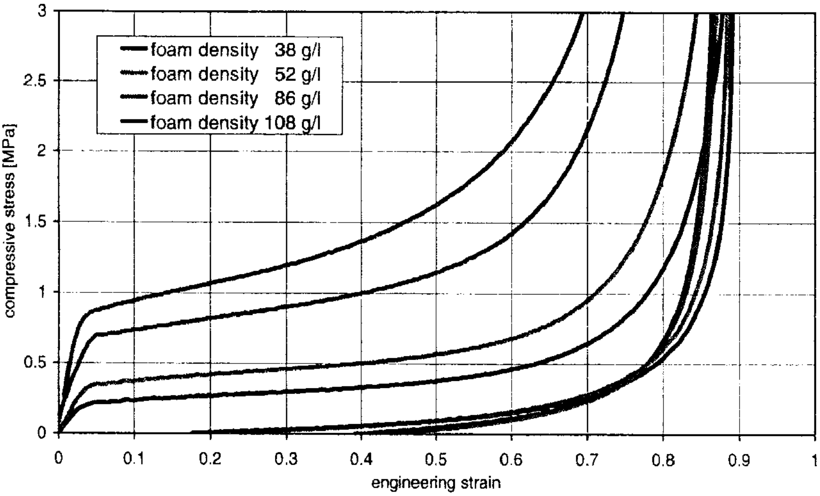

Figure 2: Stress-strain characteristic of EPP foam with different density values.

The figure put also in evidence that it is possible to modify the mechanical characteristic of the foam by simply modify its density: a higher value of the foam density means higher values of the stress and of the absorbed energy.

This foam material has been described appropriately by means of the Pamcrash material model 21 - elastic foam with hysteresis for solids elements [5]. This model is based on a simple coupling of a non-linear spring with a damper; these two elements are in a parallel disposition (*Kelvin-Voigt* model).

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

The spring models the elasto-plastic behaviour, while the viscous damper models the velocity effects, including the strain rate sensitivity. The non-linear behaviour of the spring is described by a piece-wise characteristic.

The metal sheet is made of FeP04 low carbon steel (yield strength 170 MPa (St 12)) typically used for the automotive body constructions. Its strain rate sensitivity is taken into account through the classical Cowper Symonds law [6].

The severity of the head impact against the structure is assessed by the calculation of the HIC index that is defined [1,7] as follows:

$$HIC = \max_{T_0 \le t_1 \le t_2 \le T_E} \left[\left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} R(t)dt \right)^{2.5} (t_2 - t_1) \right] \le 1000$$

where R is the head acceleration expressed as multiple of g, the gravity acceleration, and the maximum width t_2-t_1 of the time range for the integral calculation is 36 ms. The reference limit value for the HIC index is assumed equal to 1000. HIC values equal to 1000 statistically result in human being survival with a 80% of probability, while larger values result in lethal brain lesions with an increasing level of probability.

The HIC index was developed with respect to a human being and the companion dummy with an appropriate level of bio-fidelity, in particular for what concerns the head support and guidance by the neck. In the mentioned test procedure there is not a neck and the associated muscles, this results in a greater severity of the head stress. In order to obtain a meaningful value, comparable with those assessed from the whole human body, a correction - HIC(d) (Dummy Equivalent HIC) - is introduced [1] according to the following formula:

$$HIC(d)=0.75446\ (HIC) + 166.4$$

3 Study of the dashboard problem by FE simulation

A complete plane of experiments has been designed according to the DOE procedure, in order to evaluate the effect of the two considered design variables: the foam density (four density values, namely 38, 52, 86, 108 g/l) and the foam layer thickness (three thickness values, namely 15, 20, 25 mm). Thus a total amount of twelve simulations was done. Of course a thirteenth case was considered: the reference case where no foam was layered on the steel plate, thus simulating the present situation of metal structure without foam cover.

The completeness of the experiments plane permits to explore not only the role of each single factor but also their interaction so that it would be possible to take advantage from the eventually existing interactions.

Figure 3 shows the typical shape of the curves of the head acceleration during the impact for the case of 52 g/l EPP foam density and a steel sheet thickness of 1 mm, with three different values of the foam layer thickness.

The curve obtained in the case steel plate without the foam layer is also shown for sake of comparison.

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

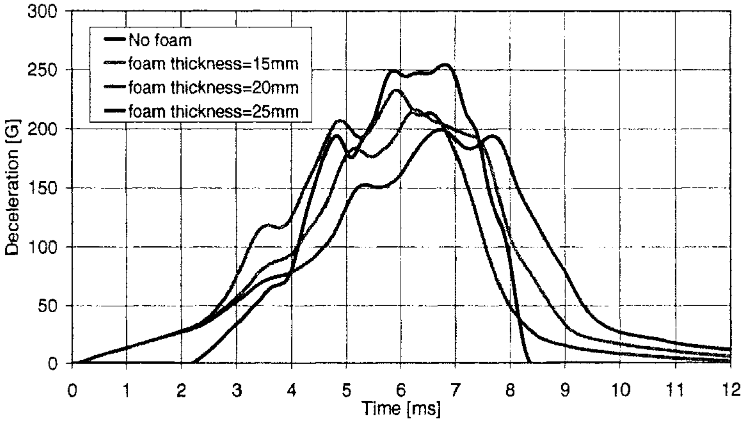

Figure 3:Variation of the peak value of the deceleration with the design variables.

It is well visible the differences induced by the presence of the foam layer, it is also well visible the effect of changes in the foam layer geometry: decreasing the foam layer thickness a higher peak value of the head deceleration is obtained while this maximum is reached in a shorter time. This can be explained considering the densification phase: since we have to absorb a certain amount of energy, the thinner the foam layer the larger the foam maximum deformation, the larger the compressive stress.

The following figures collect the results in a synthetic way, by means of relevant parameters, namely the value of the energy absorbed by the foam layer, the ratio of the energy absorbed by the foam and by the metal sheet, the HIC(d) value. Figure 4 shows the changes in the energy absorbed by the foam layer as a function of the design variables. It is clearly evident from the diagram that the quantity of energy absorbed by the foam layer is increasing with both the design variables.

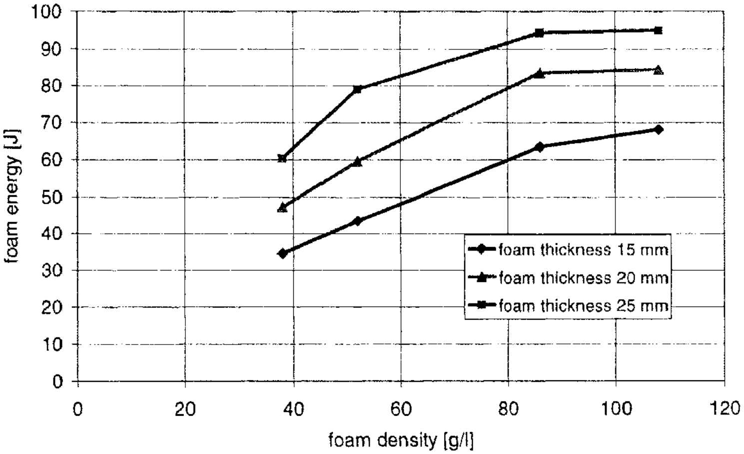

Figure 4: Variation of the energy absorbed by the foam layer with the design variables.

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

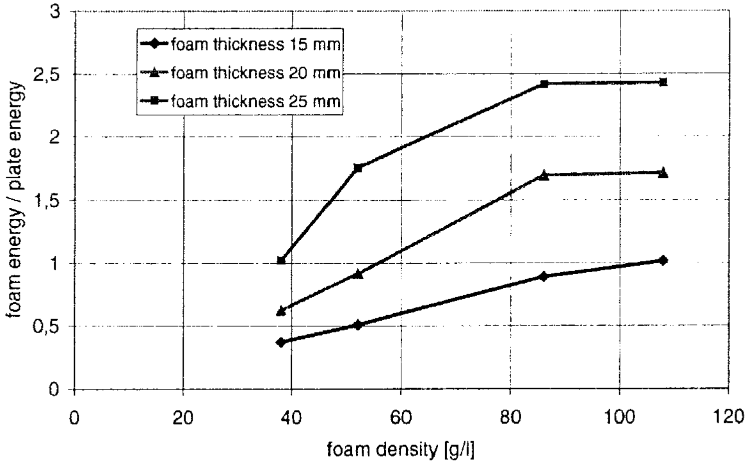

Figure 5: Variation of the absorbed energy ratio with the design variables.

Figure 5 shows the changes in the ratio of the energy absorbed by the foam to the energy absorbed by the metal sheet as a function of the design variables. It is a measure of the relative contribution the two constituents of the structure.

It is clearly visible from the diagram that the quantity of energy absorbed by the foam layer is increasing with both the design variables: however with the lower value of the foam thickness the metal sheet is the constituent that absorbs the most of the energy, while with the higher value of the foam thickness the foam layer is the constituent that absorbs the most of the energy.

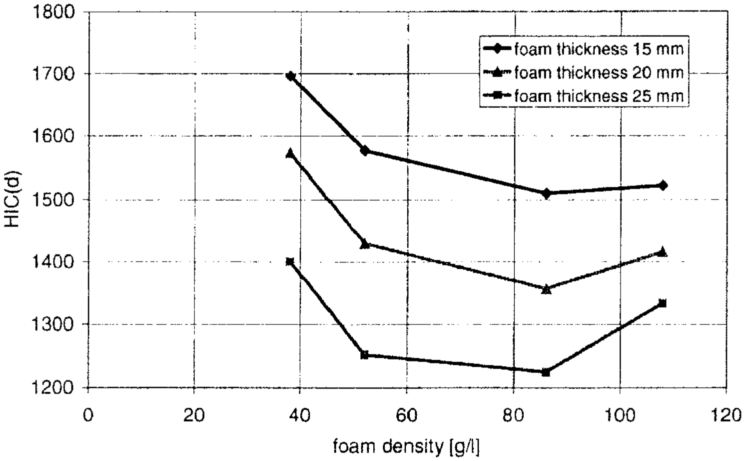

Figure 6: Variation of the HIC (d) value with the design variables.

Finally figure 6 shows the changes in the HIC(d) value as a function of the design variables. It is well visible that the HIC value is decreasing with the thickness of the foam layer: a larger amount of energy can be absorbed by the

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

foam (see figure 4) with a limited value of the reaction force (a proportionally longer plateau phase takes place before the densification phase, that is accompanied by a sharp stiffening effect, is reached).

The effect of the foam density variable is non-linear, a second order parabolic shape can be identified, with a HIC minimum in the range between 60 and 80 g/l.

The HIC value is larger than the limit value 1000, but a design strategy has been identified and a further increment of the foam layer thickness, eventually together with a slight reduction of the steel sheet thickness, can lead to the requested solution.

4 Study of the A pillar problem by FE simulations

Figure 7 shows the geometrical configuration of a typical A pillar, the adopted FE discretisation is also shown.

The pillar is, as usual, made by FeP04 steel sheet, previously submitted to a deep drawing forming in order to obtain the appropriate section shape. Although the forming operation changes the wall thickness of the pillar (the actual thickness value is variable from point to point and generally less than the nominal one) and leaves a residual stress distribution, in this first stage of the research these effects have been neglected. So the wall thickness is uniform and equal to the nominal one (1 mm).

The steel sheet parts have been modelled by shell elements, while the foam cover has been modelled by brick elements.

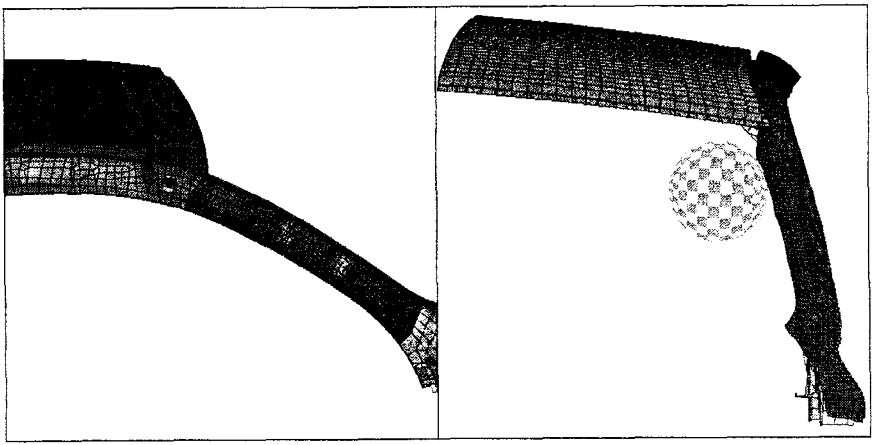

Figure 7: Typical configuration of the A pillar and its discretisation by FE.

Once again a number of FE simulations have been executed. At this stage there is a strong constraint on the overall transverse dimension of the pillar since there are some regulation requirements concerning the external visibility from the driver seat. Therefore the foam layer thickness (first design variable) was limited to 15 and 20 mm, while the EPP foam density (second design variable) has been allowed to vary in the whole previously considered range.

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

Figure 8 shows the shape of the head dummy deceleration time-histories for five cases: the four cases based on the four different values of the foam density (the foam thickness is at its lower value, 15 mm) and the reference case of the pillar without any foam cover.

In Figure 8 it is well visible the effect of the foam layer: its presence causes a general decrease of the magnitude of the deceleration.

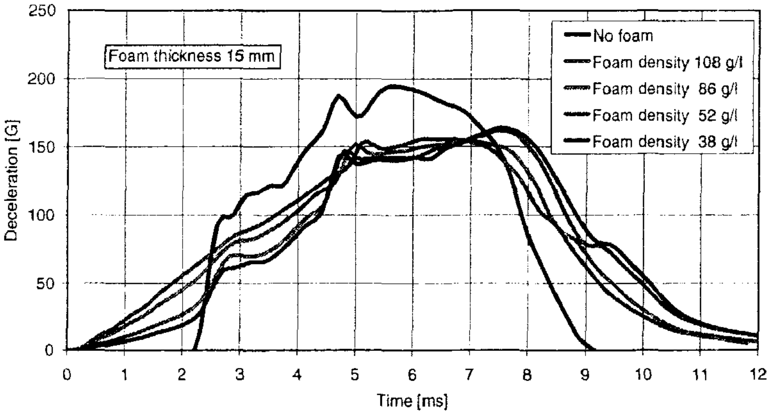

Figure 8: Variation of the deceleration history with the design variables.

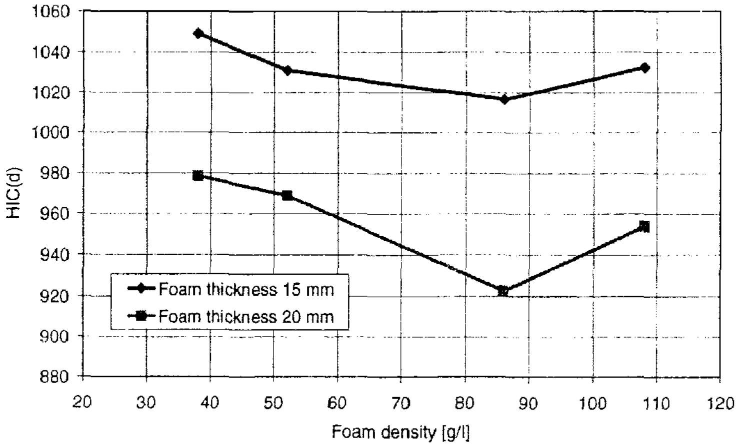

Figure 9: Variation of the HIC(d) value with the design variables.

The time histories can be subdivided in three parts: a first one with an increasing shape, a second one with a nearly constant value, a third one with a decreasing shape. In figure 8 it is well visible that the intermediate constant value is almost the same independently from the foam density value. The two larger values of the foam density give the higher curves in the first part, while the two lower values of the foam density give the higher curves in the third part, together with the higher deceleration maximum values.

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

Finally figure 9 collects the resulting values of the HIC(d) index. It should be noted that the HIC(d) value for the without foam case is equal to 1450.

It is evident that the presence of the foam leads to a large reduction of the HIC value and therefore to the criticality of the head impact against the pillar. Furthermore the HIC(d) value is reduced in a relevant way by the increment of the foam layer thickness, although this trend is influenced by the thickness of the metallic part.

Once again the effect of the foam density variable is non-linear, a second order parabolic shape can be identified, with a HIC minimum in the range between 70 and 80 g/l for the layer thickness equal to 15 mm and in the range between 80 and 90 g/l for the layer thickness equal to 20 mm.

With the lower value of the foam thickness the HIC value is still larger than the limit value 1000 although very near to the target, while with the larger value of the foam thickness is well below the regulation limit.

However a design strategy has been identified and a further iteration of the performed analysis with an intermediate value of the foam layer thickness can lead to an optimised solution that match the requested regulation limit.

5 Conclusions

The FMVSS201 standard deals with the vehicle passenger safety in case of accident, with particular reference to a possible impact of the head against the passenger compartment interior structure.

With the aim of matching the limit value stated by this standard, the metallic part could be covered with a foam layer, since structural foam are able to absorb a large amount of energy with a relative little value of the reaction force.

Some expanded polypropylene foams (EPP) have been experimentally characterised in order to get information on their particular mechanical properties, also with reference to their strain-rate sensitivity.

At the end of this first stage of the research we obtained:

- experimental mechanical characteristic of the EPP foam with particular attention to their energy absorption capability and to the dependence of these characteristics on the foam density;
- the validation of the Pamcrash material model of the structural foam (a *Kelvin-Voigt* model) by comparison of the FE numerical results with the experimental ones.

Afterwards a number of FE numerical simulations have performed of the impact of the standard head dummy against, at first, a flat plate (that can represent the dash-board structure) and, finally, against an A pillar. The obtained results allow to draw the following conclusions:

- the use of the foam layer leads to a relevant reduction of the deceleration peak values both through an increment of the foam layer thickness and an appropriate choice of the foam density;
- the HIC(d) values results to be non-linear function of the considered design variable (the foam layer thickness and the foam density); the HIC response

© 2002 WIT Press, Ashurst Lodge, Southampton, SO40 7AA, UK. All rights reserved.
Web: www.witpress.com Email witpress@witpress.com
Paper from: *Structures Under Shock and Impact VII*, N Jones, CA Brebbia and AM Rajendran (Editors).
ISBN 1-85312-911-9

surface has been explored against these design variables by a complete plane of experiments;

- the obtained response surfaces have a minimum in the admissible solutions space; this minimum leads the designer to identify the optimal set of the design parameters in order to match the HIC(d) regulation requirement;
- by the use of the optimal foam layer to cover the metallic A pillar the limit value of the FVMSS Standard 201 can be satisfied and a 20% reduction of the peak value of the head deceleration can be obtained.
- the appropriate choice of the foam layer design parameters is not unique but depends strongly on the impact stiffness of the underlying metallic structure.

The outlined design procedure has proved to be robust and effective in leading to the appropriate choice of the design variables with the objective of matching the regulation requirements.

Acknowledgements

The research work done in the Mechanical Engineering Dept. of the Politecnico di Torino has been financially supported by the Italian CNR (National Research Council) through the research contract 00.00655.PF34 within the frame of the Progetto finalizzato "Materiali Speciali per Tecnologie Avanzate 2".

Thanks are also due to Ing. Alberto Caminiti for his help in performing the foam experimental characterisation tests.

References

[1] *Standard No. 201: Occupant protection in interior impact*, 49 CFR, Ch. V, Parts 571.201, Federal Motor Vehicle Safety Standards, National Highway Traffic Safety Administration, Dept. of Transportation, October 1998

[2] Avalle M., Belingardi G., Montanini R., Mangino E. - "Energy absorption characteristic of polymeric structural foams for passive safety applications", proc. of 6th Int. Conf. Florence ATA 1999 - Firenze, 17-19 November 1999

[3] Avalle M., Belingardi G., Montanini M. - "Characterisation of polymeric structural foams under compressive impact loading by means of energy-absorption diagram", Int. J. of Impact Engineering, vol.25, pp. 455-472, 2001

[4] Gibson L. J., Ashby M. F., "*Cellular Solids: structure and properties*", 2 ed., Cambridge (UK), Cambridge University Press, 1997

[5] *Pam-Crash Reference Manual*, version 2000

[6] Avalle M., Belingardi G., Vadori R., Masciocco G. - "Characterisation of the strain rate sensibility in the dynamic bending behaviour of mild steel plates", proc. of EUROMAT 2000, Tours (F), November 2000, pp. 505-510

[7] Clifford C.C., Nyquist G.W. – "Analytical studies of the Head Injury Criterion (HIC)", SAE paper 740082, 1974