PEDESTRIAN PROTECTION – PHYSICAL AND NUMERICAL ANALYSIS OF THE PROTECTION OFFERED BY THE WINDSCREEN

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ABSTRACT

Pedestrian head protection is mainly focused on energy absorption when impacting the bonnet. But the technical solutions for mitigating the impact are completely different for the head protection when impacting the windscreen.

Even if regulations do not require an assessment of the protection offered by the windscreen in case of pedestrian impacts, consumerism increased requirements incite us to study in-depth the windscreen, its shape, its boundary conditions and its bonding to optimise adult pedestrian head protection.
Large amount of physical tests were performed with varying all the parameters in order to assess the relative influence of each one.
In parallel, correlation modelling and prediction modelling were performed. Different meshing formulations were also investigated.
The results will be presented showing the effects on the different parameters and the difficulty of modelling them.
This study results in the release of new technical specifications for the windscreen that has to be compatible with the other mechanical and acoustical requirements that need to be fulfilled as well.

INTRODUCTION - AIM OF THE STUDY

Every year, approximately 8,000 pedestrians and cyclists are killed and 300,000 others injured in road accidents in Europe. The accidents are particularly frequent in urban zones. Even when cars are driving at relatively reduced speeds, very severe injuries can occur.
Below a speed of approximately 40 km/h, it is nevertheless possible to considerably reduce the gravity of injury with modifications of the frontal parts of vehicles

So, since 2005, a new European Directive [1] (called "phase 1") requires the car manufacturers to treat their new vehicles for pedestrian protection.

Moreover, the consumerist organization Euro NCAP assesses the pedestrian protection offered by a new car through component tests [2], [3]. The level of pedestrian protection is then ranked by attributing the vehicle a given number of stars.

The assessment of pedestrian protection offered by a vehicle is made through three different and independent component test procedures corresponding to different body segments:

- the first one is related to the assessment of the protection of the leg. The test is called "legform to bumper test"
- the second one is related to the upper leg. The test is called "upper legform to bonnet leading edge"
- the last one is related to the head, adult head impact and child head impact. The tests are called "Adult and Child headforms to bonnet and windscreen test"

Four specific body form impactors are used in these tests. They are propelled against the front part of the vehicle (from the bumper up to the windscreen depending on the type of test) and they are equipped with several sensors in order to measure biomechanical criteria that are used to assess the risk of injuries (see Figure 1).

Because of the increasing requirements on the pedestrian protection performance in the Euro NCAP new rating (overall rating), the performance of head in the windscreen tests becomes more and more sensible.

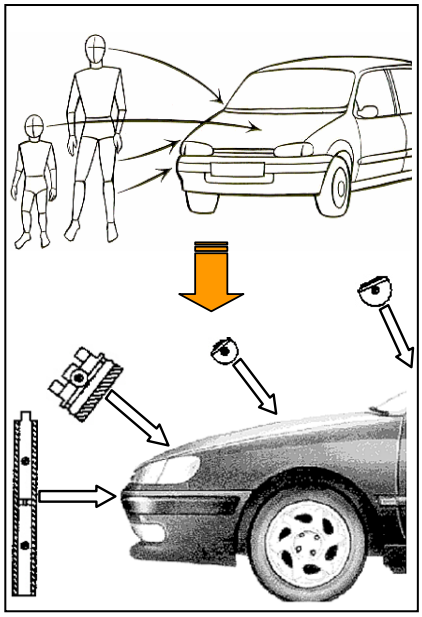

Figure 1. Euro NCAP Pedestrian tests made of body form impactors propelled against the car front-end.

This paper aims to assess the scattering in test and to propose an enhanced numerical model to represent the test of an adult head impactor on the windscreen.

THE ADULT HEAD EURO NCAP TEST PROTOCOL [2]

An adult head impactor is made of a rigid sphere made in Aluminium surrounded by a rubber flesh. The overall radius of the adult head impactor is 82.5 mm, and the mass is 4.5kg.
The test is made by a free flight of the impactor at 40 km/h against the windscreen with an angle of 65° with respect to horizontal (tests can also been performed on the bonnet). The impact zone is defined from wrap around distance measured from the ground.
Pedestrian protection is assed via a total score of 36 points from which 12 points are dedicated to the adult head tests. The adult zone is divided in sixth. Each sixth will have an impact point. Therefore, each sixth will received a maximum score of 2 points.
For these adult head tests, only one biomechanical criterion is computed: the well known Head Injury Criterion (HIC) calculated from the head acceleration.

$$HIC = \max\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,dt\right]^{2.5}(t_2 - t_1)\,with\,(t_2 - t_1) \le 15ms \quad (1)$$

In this paper, unless specified, the tests presented are carried out following Euro NCAP test protocol:

- head impactor mass 4.5 kg (*),
- impact speed: 40km/h,
- impact angle: 65°,
- damped accelerometer.

(*) Some tests were performed with the head impactor of 4.8 kg because it was the Adult head impactor used by Euro NCAP up to 2009.

DESCRIPTION OF THE PROBLEM

As already explained, head impactor test can be carried out on the upper part of the bonnet, or the windscreen. Experience shows that windscreen tests present a very high scattering level which prevents us to be predictive.
In addition to the usual scatterings experienced in the other type of tests (such as the scattering on the impact velocity), other parameters are supposed to influence the results when testing a point on the windscreen:

- the adhesive that glue the windscreen to the car,
- the curved shape of the windscreen,
- the windscreen thickness,
- the supplier,
- the distance to the windscreen pillar,
- the distance to the dashboard.

These different parameters have to be represented in the modelling which makes this modelling more complex.

This paper presents the study of the following parameters in test:

- the windscreen supplier,
- the distance to the windscreen pillar,
- the windscreen thickness,

In addition, the study presents some possible improvements for the modelling of the phenomenon.

DESCRIPTION OF THE ACCELERATION CURVE OF A HEAD IMPACTOR TEST INTO THE WINDSCREEN

Deceleration curves of head impactor test into the windscreen follow the same trend.
As shown in the following example (see Figures 2 and 3), the head impactor first undergoes an increased deceleration representative of the contact between the windscreen and the impactor and of the start of the cracking (from 0 to 5 ms). Then, a second phase of deceleration occurs, which is smaller in magnitude but longer in duration. This second phase is characteristic of the windscreen stiffness (from 7 to 30 ms).

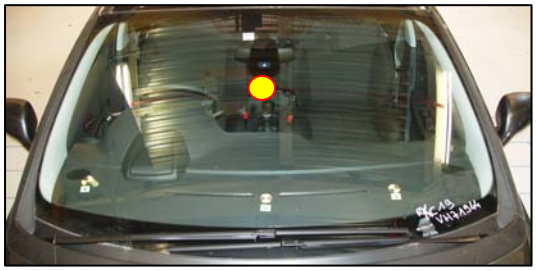

Figure 2. Impact point localisation on the upper part on the windscreen – Car A.

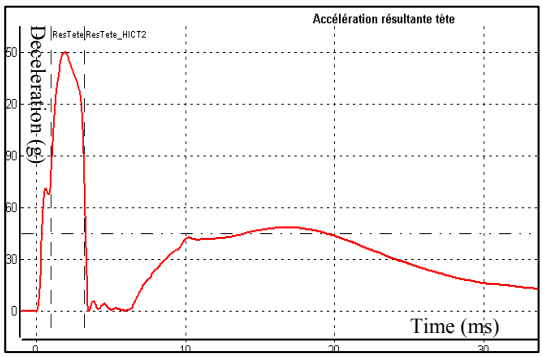

Figure 3. Deceleration curve measured on the impact point as shown in Figure 2.

Sometimes, the first peak is made of several small consecutive peaks.
If the test is made in the lower part of the windscreen, a secondary impact may occur (head impactor to the dashboard) that may overlay the second phase and give a deceleration peak that can be greater than the initial peak ; depending on the dashboard stiffness (see Figures 4 and 5).

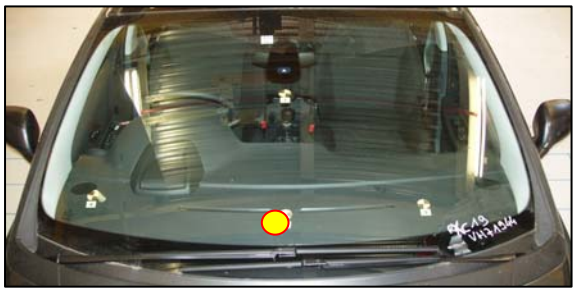

Figure 4. Impact point localisation on the lower part on the windscreen – Car A.

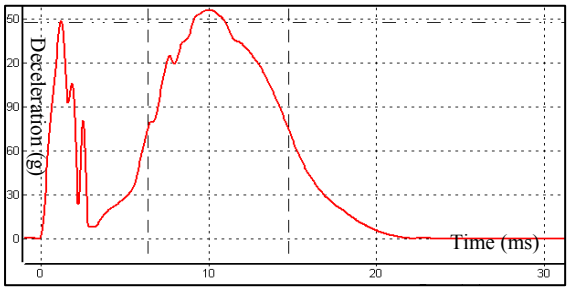

Figure 5. Deceleration curve measured on the impact point as shown in Figure 4.

PHYSICAL STUDY

Influence Of The Windscreen Type

Two types of windscreen have been tested, from two different manufacturers (M-#A and M-#B) with the same test conditions:

- same impact points,
- same windscreen thickness (4.47mm)
- same impactor and test velocity (head impactor of 4.8 kg as used by Euro NCAP up to 2009).

A car model different from the one presented in figure 2 to 5, was used in this test series. It is called "Car B".

Each test point is tested twice: one with a dashboard, the other without (in order to characterise the windscreen behaviour by itself).

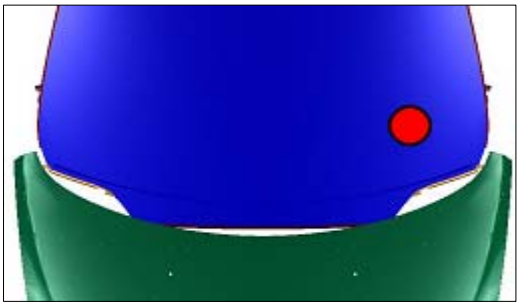

Figure 6. Impact point localisation on the lower part on the windscreen – Car B.

Deceleration curves measured with the windscreen M-#A and M-#B are presented in Figure 7 and 8.

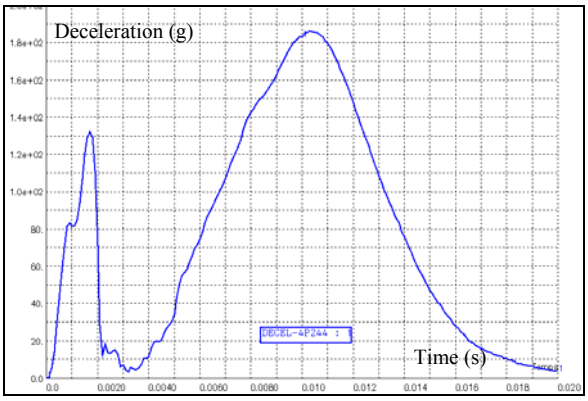

Figure 7. Deceleration curve measured on the impact point as shown in Figure 6 with the M-#A windscreen.

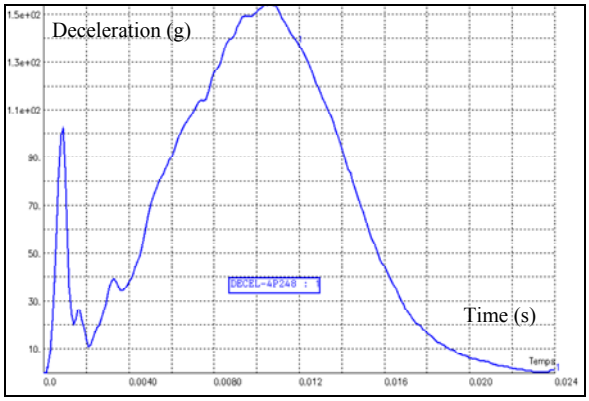

Figure 8. Deceleration curve measured on the impact point as shown in Figure 6 with the M-#B windscreen.

Pictures presented in Figure 9 and 10 clearly show that the post test deformation and cracks are different between the two windscreens. M-#B breaks into tiny pieces whereas M-#A breaks into bigger pieces.

Figure 9. Post impact picture of test with M-#A windscreen

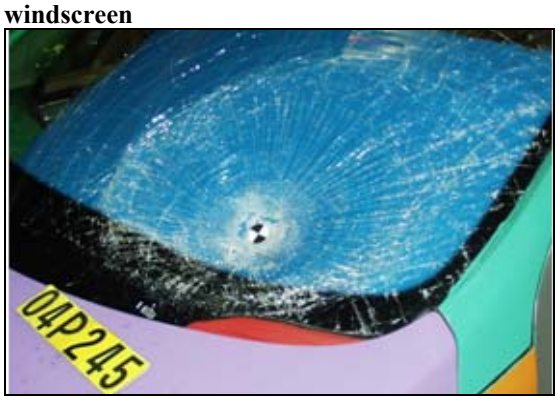

Figure 10. Post impact picture of test with M-#B windscreen

In order to remove the dashboard stiffness influence from the windscreen behaviour, additional tests were performed without the dashboard. The deceleration curves of these tests are presented in Figure 11.

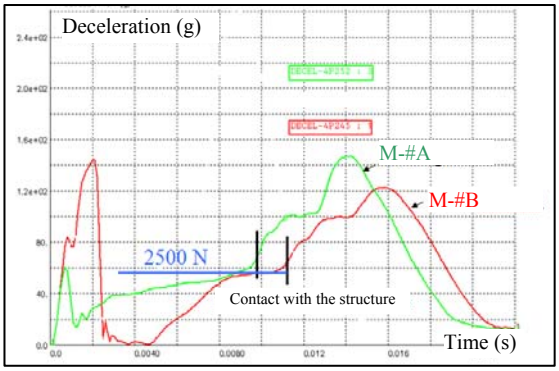

Figure 11. Comparison of the deceleration curves measured on car B without dashboard with the two windscreens.

Although the dashboard was not fitted on the latter tests, a secondary impact is still present (at 10 to 12 ms), because of the impact with structural elements present below the dashboard.

The following curves (Figure 12) show the energy absorbed in function of head displacement into the windscreen with the two windscreens and with and without dashboard.

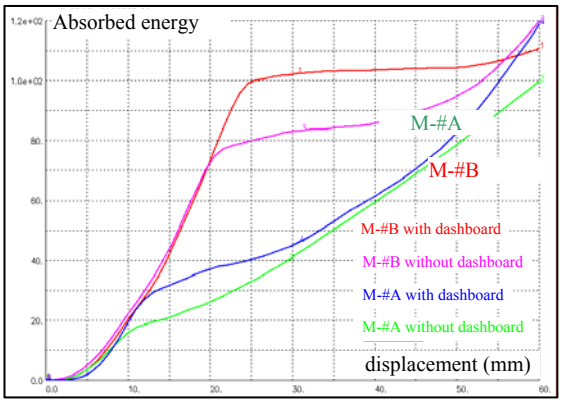

Figure 12. Comparison between the energy absorbed in function of head impactor displacement into the windscreen with the two windscreens and with and without dashboard

The curves shown in Figure 12 highlight the different behaviour between the two types of windscreens, especially during the phase when there is no interaction with the dashboard or its structure below.

The M-#B windscreen dissipate quickly the energy (high initial load peak) then a plateau occurs (from 20 mm to 50 mm of head impactor displacement). Whereas the M-#A windscreen dissipates the energy in a progressive and linear way.

After 50 mm of head impactor displacement the tests with the dashboard evolves in a different way that the test without the dashboard

The windscreen behaviour differs between the manufacturers. The energy dissipated in windscreen M-#B is slightly greater than the M-#A one (up to 50mm displacement).

Moreover, after the first peak, the load crush level are similar (around 2500 N, see figure 11).

In conclusion, if the dashboard is farther than 50 mm from the windscreen, in order to dissipate more energy, M-#B windscreen is to be privileged to minimise the energy to dissipate into the dashboard.

Influence Of The Impact Point Localisation With Respect To The Windscreen Pillar

In order to characterize the windscreen behaviour when impacted close to its pillar, the following tests were performed.

- Car A with M-#B / 4.47mm thickness windscreen
- same impact points at WAD 2100 (in order to avoid a secondary impact to the dashboard),
- same impactor and test velocity
- different distances from the windscreen pillar are tested (80-95-110 mm)

Figure 13 and 14 present the test carried out at 80 mm from the windscreen pillar and its deceleration curve.

Figure 13. Impact point at 80 mm from the windscreen pillar – Car A.

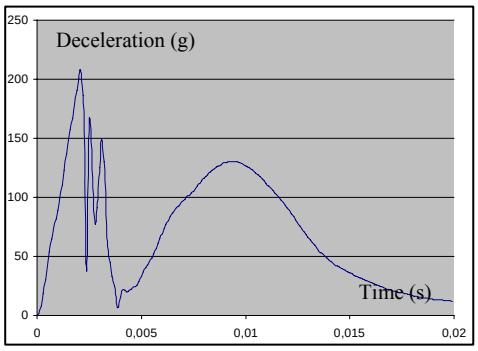

Figure 14. Deceleration curve measured on the 80 mm impact point as shown in Figure 13.

The first peak is 207g, then there is a second phase with a maximum deceleration of 131 g. This gives an HIC of 1111 which corresponds to a score of 1,37 points (out of 2 points). It is important to notice that there is no contact between the head impactor and the windscreen pillar during the test.

Figure 15 and 16 present the test carried out at 110 mm from the windscreen pillar and its deceleration curve.

Figure 15. Impact point at 110 mm from the windscreen pillar – Car A.

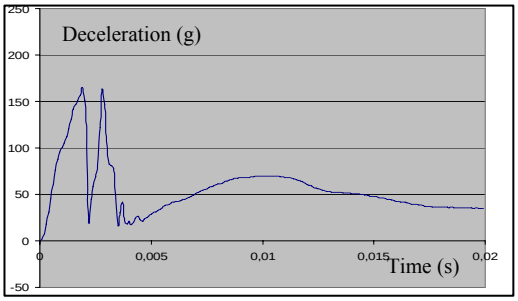

Figure 16. Deceleration curve measured on the 110 mm impact point as shown in Figure 15.

In this last test, the first peak is 165g, then, the maximum deceleration of the second phase is 80 g. This gives an HIC of 430 which corresponds to a full score (2 points). For sure, in this test again, there is no contact between the head impactor and the windscreen pillar during the test.

This latter test (110 mm) was reproduced a second time. The second curve is shown in Figure 17.

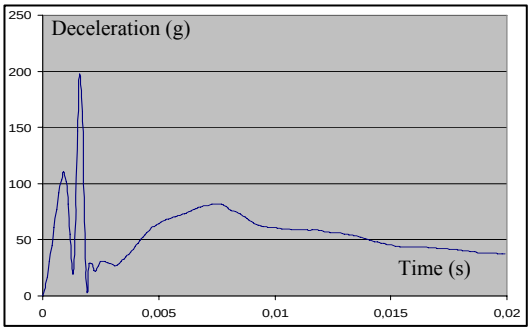

Figure 17. Deceleration curve measured on the 2nd test made at 110 mm.

In this 2nd test, the first peak is 197, then the maximum deceleration of the second phase is 80 g. This gives an HIC of 452 (compared to 430 in the 1st test) which corresponds to a full score (2 points). HIC values are therefore similar even if the first 5 ms of the deceleration curves are different.

By analogy with the adult head impactor size (diameter is 165 mm), we can then conclude that a distance equivalent of the radius of the impactor (82,5 mm) is not sufficient to get 2 points. It is needed to be at 110 mm at least to get the full score at Euro NCAP.

Influence Of The Windscreen Thickness

Another part of the test series was to study the influence of the windscreen thickness. For this purpose, two thicknesses were tested in the same test configurations: 3.96 mm and 4.47mm, with dashboard and M-#B windscreen. Every test configuration is repeated twice.

The impact point is presented in Figure 18.

Figure 18. Impact point for the test of the windscreen thickness influence – Car C.

Deceleration curves of the two tests with the 4.47 mm thickness are presented in Figure 19.

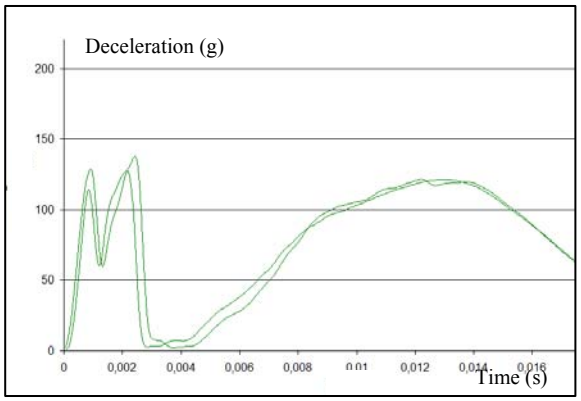

Figure 19. Deceleration curves of the two tests with the 4.47 mm thickness.

Between 0 to 4 ms, two peaks appear on both curves. First peak is 110 to 130 g and 2nd peak is 120 to 140g. Then, there is a drop and a second phase where the deceleration reaches 120 g.

Deceleration curves of the two tests with the 3.96 mm thickness are presented in Figure 20.

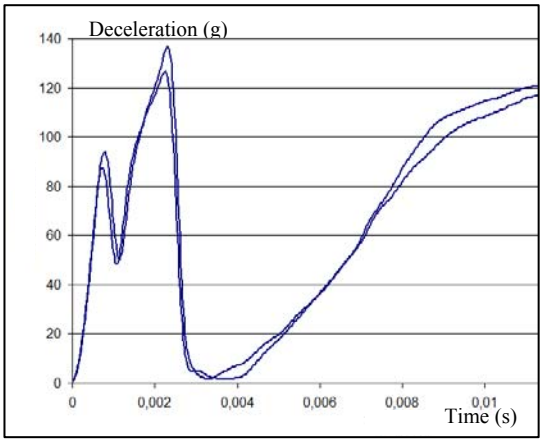

Figure 20. Deceleration curves of the two tests with the 3.96 mm thickness.

Here again, between 0 to 4 ms, the two peaks appear. First peak is 80 to 100 g and the 2nd peak is 120 to 140g. Then, there is a drop and a second phase where the deceleration reaches 120 g.

A comparison between the average curve of the 3.96 mm windscreen and the 4.47 mm one is presented in Figure 21.

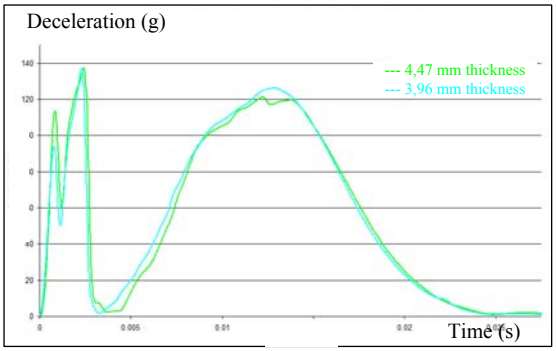

Figure 21. Comparison of the deceleration curves for the two thickness (3.96 mm and 4.47 mm thickness).

Except the magnitude of the first peak, the deceleration curves are very similar between the two thicknesses.
The magnitude of the first peak is lower with the 3.96 mm windscreen because its inertia (its mass) is lower.

In conclusion, theses tests show that the windscreen thickness is not a key parameter for reducing the head to windscreen HIC (for a 12% variation of the thickness). HIC are approximately the same for these four tests: between 1040 and 1140.

But other parameters are important to clearly understand the headform impactor test on the windscreen and they have to be clearly understood. For this reason, an additional study was carried out based on numerical analysis to create an enhanced modelling of the windscreen. This is presented in the following chapter.

NUMERICAL STUDY

Five-Points Flexion Test

The purpose of this test is to validate the modelling of the windscreen without taking into account any other influence, such as the dashboard or the windscreen proximity.
The test configuration chosen, in order to represent a head impactor test into the windscreen, is a five-points flexion test. The load is applied on the centre of the windscreen and the contact with the test trig is made via non-friction balls fixed between two plates attached to the windscreen extremities.

The load is applied by a displacement controlled hydraulic jack. The displacement velocity is 50 mm/mn.

Several windscreens were tested up to rupture.

The following measurements were made with a 200 Hz sampling frequency:

- load applied by the jack
- jack displacement
- a total of 36 strain gages glued on the inner part and the outer part of the windscreen (45° set of strain gages)

Figure 22 presents an overall view of the test rig.

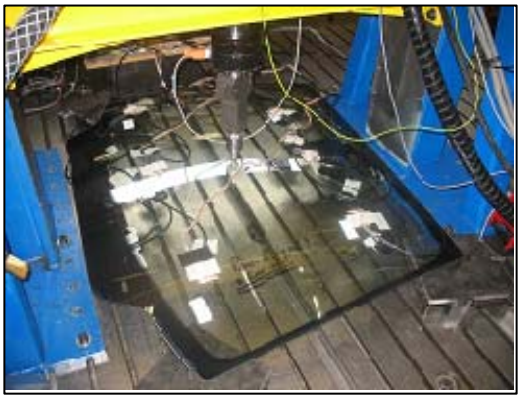

Figure 22. Overview of the test rig used for the windscreen flexion characterisation

Results get from the different tests are presented in Figure 23.

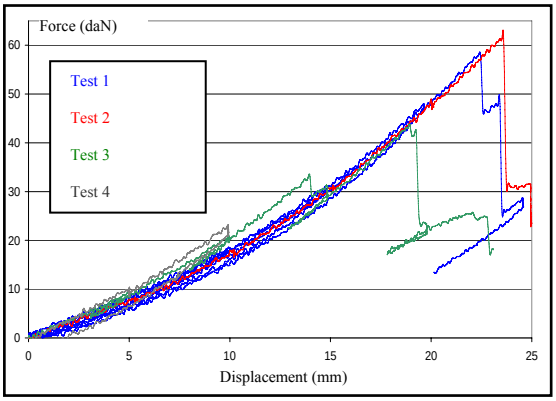

Figure 23. Load vs displacement of the windscreen tested in five-points flexion.

The results in terms of stiffness are very similar and we can state that this test shows good repeatability.
But the level of rupture is significantly scattered, but this can be expected for a fragile material such as glass.

Windscreen Modelling

In the first part of the section, we will present the model formulation used for the windscreen. And the next section, we will present the correlation between physical tests and modelling.

Some glass models with rupture have already been developed and presented to the scientific community [4], but the calculation time is really important which make them difficult to use in the automotive industry, for the development of a project of vehicle.

Indeed, these models request size meshes of 0.1 mm, whereas we are currently using meshes of 5 to 10 mm.

A standard windscreen is made of 3 layers:

- The first layer (external layer) is made of glass. Thickness can be from 1.8 mm to 3.15 mm,
- The second layer is made of “PVB” (Polyvinyl Butyral) of 0.76 mm,
- The third layer (internal layer) is made of glass. Thickness can be from 1.8 mm to 2.1 mm.

The windscreen under study had the following characteristics:

- The external layer had a thickness of 2.1 mm,

- The second layer is 0.76 mm,
- The internal layer had a 1.6 mm of thickness.

Figure 24 describes the 3 layers as modelled via the crash software (Radioss ®).

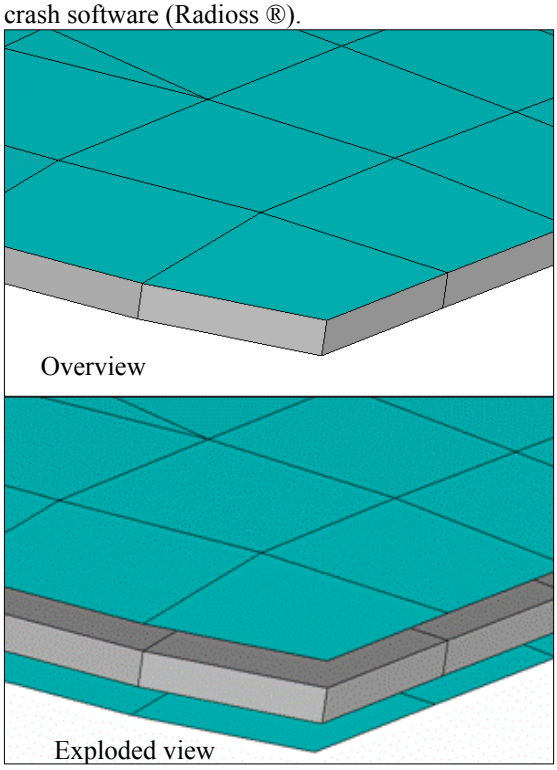

Figure 24. Overview and exploded view of the mesh and model.

The two layers of glass are modelled via a shell formulation with the actual thickness taken into account. The mesh corresponds to the neutral fibre position.
On the other hand, the middle layer (PVB) is modelled by 8 nodes brick elements.
In order to get a consistent mesh, the thickness of PVB has to be modified.

Its mesh thickness is then its own thickness + half the thickness of the internal and external layers.
For this reason, the constitutive law of PVB had to be modified (stiffness and density).

Correlation Between Physical Tests And Modelling

Figure 25 compares physical test and modelling as defined in the previous section.

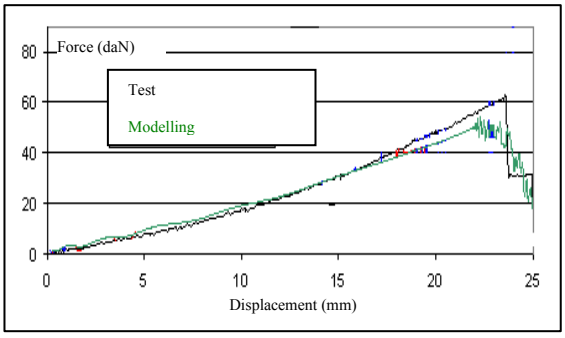

Figure 25. Correlation between test and modelling of the 5-points flexion tests.

In the first model, the constitutive law for the two glass layers was a "fragile elasto-plastic" law with an elastic limit (von Mises stress) of 75 MPa.

Two other calculations were made with an elastic limit of 50 and 100 MPa. The consequences can be found on the load at rupture as shown by Figure 26.

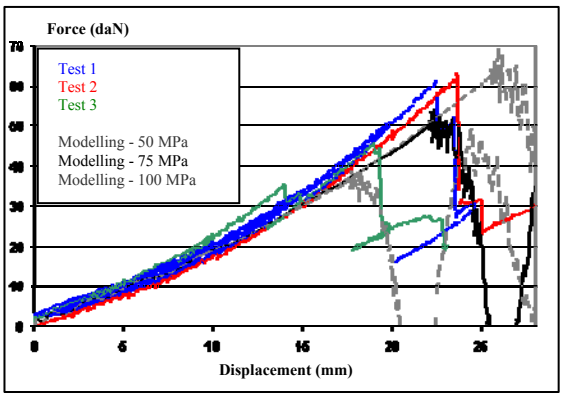

Figure 26. Comparison between test and modelling and influence of the load at rupture.

Following this comparison, it seems that the threshold at 75 MPa is closer to reality than the two other ones.

Modelling Of The Headform Test On The Windscreen

The model correlated thanks to the 5-points flexion tests was used to represent the behaviour of the windscreen when impacted by a 4,8 kg headform impactor at 35 km/h and with an impact angle of 35°.

Test results were X, Y, Z deceleration vs time curves from which we can calculate HIC.

Figures 27 and 28 present the test results.

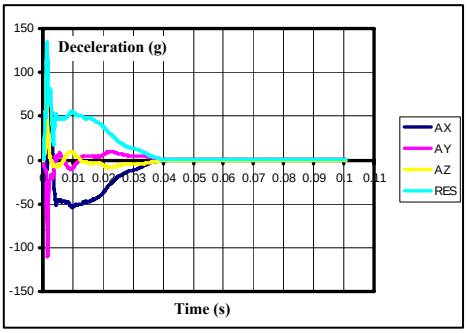

Figure 27. Test results of a head impactor on the windscreen.

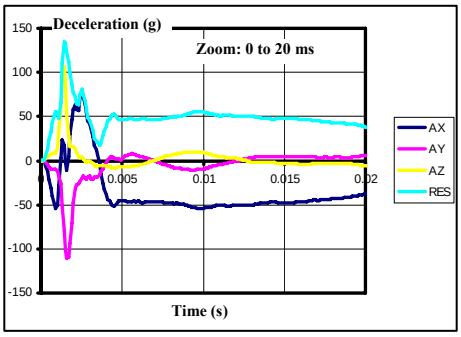

Figure 28. Test results of a head impactor on the windscreen (zoom 0 to 20ms).

As already mentioned, at the very beginning of the test, there is a first peak (135 g at 2 ms in X) which can be described as a dynamic initiation of the glass rupture. Then, the second phase occurs, (longer, at a level of 50 g in X) which can be described as the propagation of the crack in the glass.
In this test, HIC was 360.

Figure 29 presents an overview of a head impactor modelling for a vehicle project.

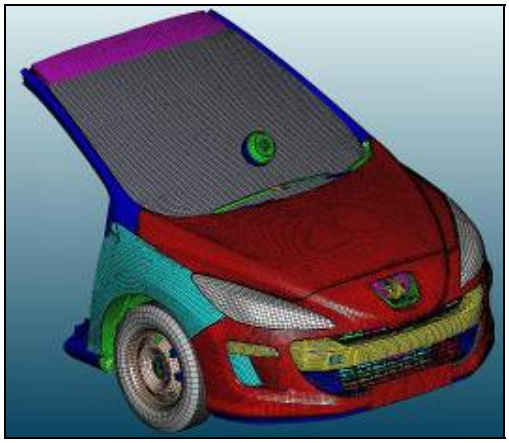

Figure 29. Overview of a head impactor modelling for a vehicle project

As already explained, we used the "shell-brick-shell" modelling for the windscreen. When comparing this model to the physical test, resultant acceleration does not give a good correlation, as shown in Figure 30.

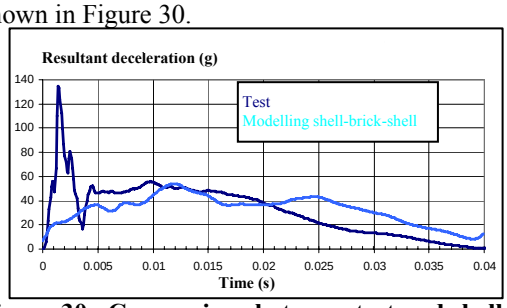

Figure 30. Comparison between test and shell-brick-shell modelling.

The initial peak deceleration is not present in the modelling and the HIC value in the model is 283 (for 352 in the test).

In order to optimise the modelling and enhance the correlation, some numerical and some physical parameters have been studied. Each parameter was studied independently from the others, as presented in the following sections.

Stiffness Of The Adhesive Bead Of The Windscreen

The first parameter under study was the stiffness of the adhesive bead. In order to magnify the influence of this stiffness, we carried out modelling where we artificially increased it by a 100 times with respect to the reference model (see Figure 31).

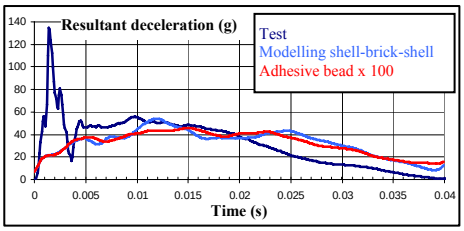

Figure 31. Influence of the windscreen adhesive bead on the head impactor deceleration.

Clearly, the influence of the adhesive bead is not a key parameter to improve the modelling of the headform impactor deceleration.

Stiffness Of The Contact Interface Between Headform Impactor and Windscreen

Another parameter under study was the type of contact defined in the modelling. This is a purely numerical parameter following the "penalty method".
Severals values were tried :1000, 500, 200, 100, 50 (see Figure 32):

- 100 and 50 were used with the headform as the master element of the contact surface.

- For 1000, 500 and 200 values, too much additional and artificial mass was added by the software to keep the calculation stable.

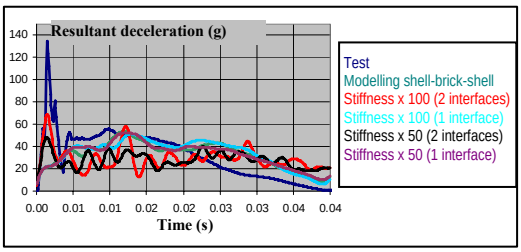

Figure 32. Influence of the stiffness of the head impactor to windscreen interface on the deceleration.

We can see in Figure 32 that the initial peak can be improved (2 interfaces – stiffness 100) but this worsens the rest of the curve.

Rigid Body Model For Headform Impactor and Embedment For Windscreen

In order to see if the initial peak is due to a difference in stiffness between the windscreen and the headform impactor, one idea was to define the headform impactor as a rigid body and the adhesive bead as a complete embedment. The result of this numerical model is shown in Figure 33.

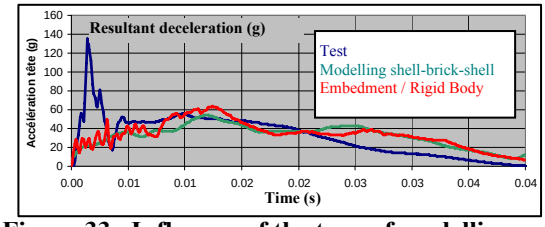

Figure 33. Influence of the type of modelling (rigid body model for headform impactor and embedment for windscreen) on the deceleration.

No significant influence is shown with this type of modelling.

Influence Of The Strain Rate

Radioss software proposes two formulations (ICC 1 and ICC 2) to take into account the influence of the strain rate as shown in Figure 34.

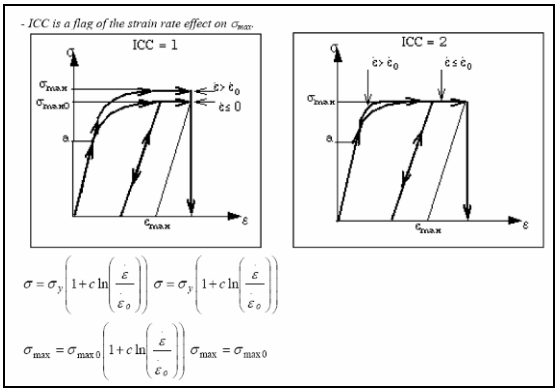

Figure 34. Influence of the strain rate as proposed in the software.

Two strain rate coefficients were tested, with the two Radioss formulation (ICC 1, ICC2) but with little influence, again, as shown in Figure 35.

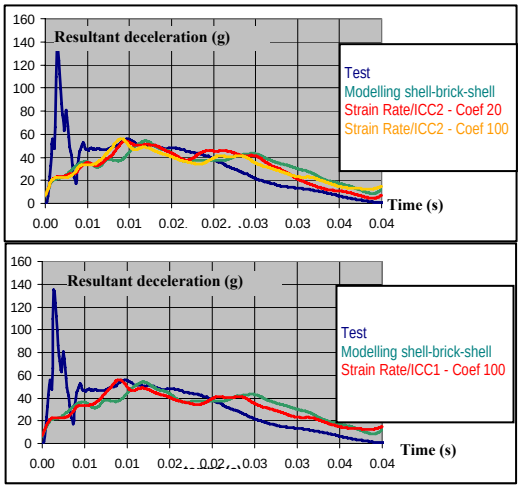

Figure 35. Influence of the strain rate on the headform impactor deceleration using different modelling parameters.

Influence Of The Time Step

Recommendation of modelling experts at PSA Peugeot Citroën is to use a 1 10^{-6} s time step. But we also tried another time step (2 10^{-7} s) as shown in Figure 36 ; unfortunately without any influence.

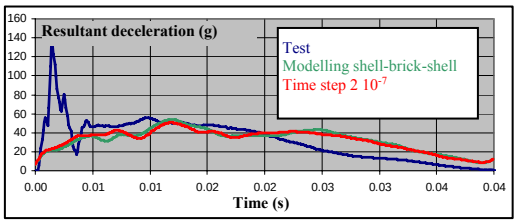

Figure 36. Influence of the time step on the headform impactor deceleration.

Influence Of The Damage Parameters

The glass is modelled via type 27 law in Radioss. The different input parameters of type 27 are shown in Figure 37.

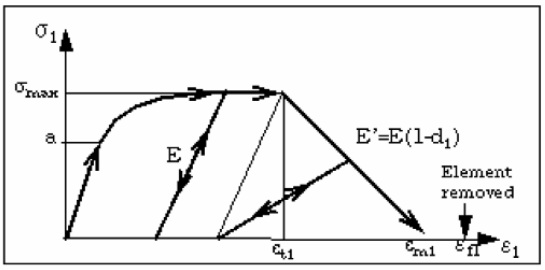

Figure 37. Input parameters of the Type 27 law.

Standard parameters such as σ_{Max}, a, E, ε_{t1} and d_1 are defined in literature. But ε_{m1} et ε_{f1}, characterising the damage undergone by the element, are not well known and not described in literature. Therefore, we studied the influence of these parameters on the headform impactor deceleration.

Influence of ε_{m1} and ε_{f1}.

In the reference model (named shell-brick-shell modelling), ε_{m1} was set at 2.7 10^{-3} and ε_{f1} was set at 2.71 10^{-3}.
Other calculations were made with ε_{m1}set at 5 10^{-3}, 1 10^{-2} and 2 10^{-2}. The results are shown in Figure 38.

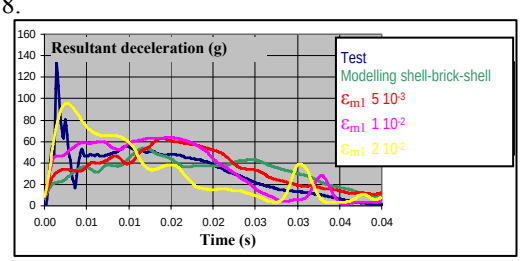

Figure 38. Influence of ε_{m1} on the headform impactor deceleration.

Same philosophy was applied to ε_{f1}set at 5 10^{-2}, 2.7 10^{-2} and 2.7 10^{-1} (see Figure 39).

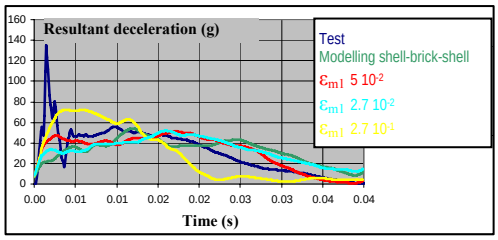

Figure 39. Influence of ε_{f1} on the headform impactor deceleration

A final modelling was made by changing the two parameters at the same time (see Figure 40).

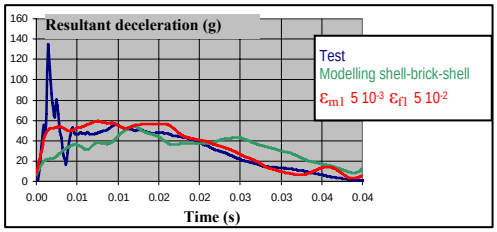

Figure 40. Combined influence of ε_{m1} and ε_{f1} on the headform impactor deceleration.

The corresponding HIC are 352 for test, 283 for the reference modelling and 410 for the combined influence.

Here again, no significant improvement is shown by this parameter study.

Influence of the mesh size

The size of the mesh in the reference modelling is 14 x 14 mm² for the windscreen.
In order to highlight any influence of the mesh size, we decided to divide the mesh size by two in the windscreen; except for the number of element in the middle layer (PVB).
The consequence on the headform impactor deceleration is presented in Figure 41.
Unfortunately, here again, no significant improvement is found whereas the time step decreased from 1 10^{-6} to 0.2 10^{-6} s.

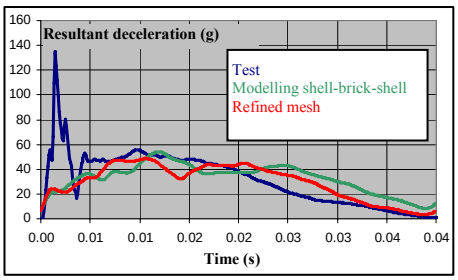

Figure 41. Influence of the mesh size on the headform impactor deceleration.

Another combination was carried out with a refined mesh and the damage parameters. The consequence on the headform impactor deceleration is presented in Figure 42.

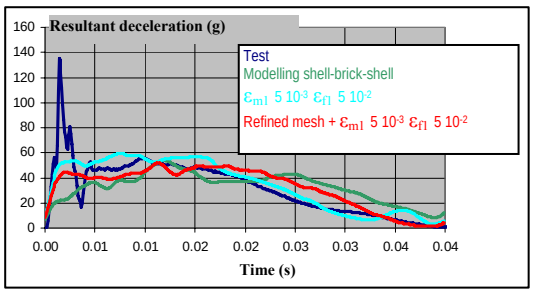

Figure 42. Combined influence of ε_{m1} + ε_{f1} and mesh size on the headform impactor deceleration

A final mesh refinement was made by dividing the initial mesh by 4 in order to have a mesh size of 3.5 x 3.5 mm². This could be done with the same time step as previously presented (0.2 10^{-6} s). And this last change helped to approximate accurately the test results (see Figure 43).

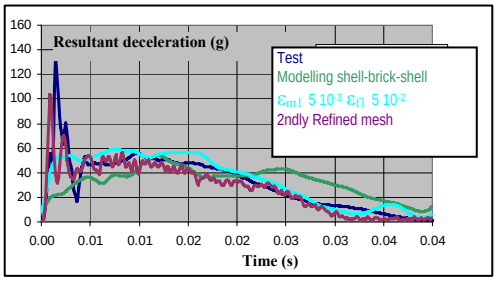

Figure 43. Combined influence of $\varepsilon_{m1} + \varepsilon_{f1}$ and mesh size on the headform impactor deceleration.

The corresponding HIC are 352 for test, 283 for the reference modelling, 410 for the combined influence of damage parameter and first mesh refinement (mesh size divided by 2 with respect to the reference modelling), and finally HIC is 271 for the secondly refinement (mesh size divided by 4 with respect to the reference modelling).

Conclusion of the numerical modelling

The modelling correlated with static test is therefore not able to represent the dynamic impact of the headform to the windscreen.
We have highlighted that the size of the mesh needs to be strongly refined to represent the dynamic impact that last only a few milliseconds. Otherwise the load peaks with short duration are not "catched" by the mesh.
Moreover, because of the fragile behaviour of the glass, predicting the windscreen rupture is a very difficult task without doing a large number of tests.
Finally, the parameters of the constitutive law used to represent the glass behaviour can have a strong influence on the correlation between test and modelling.

CONCLUSION

As shown in the first part of the study, the biomechanical results of a headform impactor into the windscreen are influenced by several parameters and present a high scattering.

Energy absorption depends on the type (manufacturer) of the windscreen and this implies a different risk of head impact to the dashboard. Moreover, impact point proximity with the windscreen pillar strongly increases the biomechanical values and a distance of 110 mm is needed to get HIC below 1000.
Finally, biomechanical results are not strongly influenced by the thickness of the glass layers. Head deceleration over time and HIC values are very similar even with an increase of 12% in the thickness. The only change is seen in the first peak of deceleration.

In the second part of the study, we highlighted the high difficulty to model the windscreen and reproduce its dynamic behaviour.
The mesh size needs to be very small (smaller that the usual mesh size recommendation for an overall car model calculation) to be able to reproduce the first peak of deceleration. But this has a strong influence in the time step and therefore the running time of calculation.
Finally, some other parameters, not analysed in this study, may have a strong influence on the modelling, such as windscreen curvature and adhesive properties of the bonding. These parameters will be part of a future study.

REFERENCES

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[2] Euro NCAP Pedestrian Testing Protocol - Version 4.3 and 5.2

[3] Euro NCAP Assessment Protocol And Biomechanical Limits - Version 4.3 and 5.0

[4] M. Timmel, S. Kolling, P. Osterrieder, P.A. Du Bois - 'A finite element model for impact simulation with laminated glass'- International Journal of Impact Engineering 34-2007 -1465–1478

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