LATERAL GLAZING CHARACTERIZATION UNDER HEAD IMPACT: EXPERIMENTAL AND NUMERICAL INVESTIGATION

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ABSTRACT

In case of lateral impacts, the most frequent contact source is the side window. This window is also the most frequent aperture through which occupants are partially or fully ejected during a lateral crash. In order to keep occupant within the vehicle during a collision, laminated side glasses have been developed to gradually replace tempered glasses. Three-layered laminated glazing is composed of two glass layers separated by a plastic PolyVinylButyral (PVB) interlayer. The aim of the present work is to improve the understanding of the side window's mechanical behaviour during a head impact. An experimental study is undertaken which consists of an impact of a Hybrid III dummy head on both laminated and tempered side glazing. It appears that at same velocity, impact against laminated glass leads to a significant lower injury head risk than a tempered glass. The principal role of laminated glazing has been preserved as PVB layer never fails. A laminated side glass FE model is then proposed based on experimental validation, with the PVB interlayer implemented by an elastoplastic law with failure criteria. A parametric study is carried out to define the influence of the laminated glass mechanical characteristics on the head response. The parametric study pointed out the importance of the glass layer thickness on head responses in terms of head injury criteria.

INTRODUCTION

In case of lateral car crash, the most frequent contact source is the side window. This side window is also the most frequent (40 %) apertures through which occupants are partially or fully ejected during a crash (Clarke *et* al. 1989, Morris *et* al. 1993, Hassan *et* al. 2001). Occupant ejection from vehicles is often considered to be a contributor to death and serious injury. The head/neck region is the most frequently injured body region of ejected occupants (Hassan *et* al. 2001). In order to keep occupant within the vehicle during a collision, laminated side glass has been developed to gradually replace tempered glasses. This security glass is composed of two layers of heat-strengthened glass (2.1 mm thick) with a plasticised interlayer membrane of PolyVinylButyral or PVB (0.76 mm thick). This enhanced protective glass offers a good resistance for breaking and entering. It can resist an aggressive attack for 20-30 seconds compared to tempered glass which would resist the attack for only 1-2 seconds (Lu *et* al. 2000).

In the late 1980's, Clarke *et* al. conducted rollover tests on vehicle containing bi-layer glazing in the side window openings. The authors demonstrated the potential of glass-plastic glazing to significantly reduce ejections through motor vehicle windows. Clarke provides acceptable neck loads under severe glazing contact conditions. Advanced glazing systems may reduce partial and complete ejections through side window, according to the same authors. In 2002, Sances *et* al. simulated rollover accidents consisting of a Hybrid III dummy test device impacting side windows with three-layered laminated glazing. This glazing contained the dummy assembly. Head-neck biomechanical parameters were below the critical value injury tolerance limits value. The dummy assembly never went through this security glazing. More recently, other authors stated that production laminated side glass is not an efficient barrier to occupant ejection during rollover (Kramer *et* al. 2006, Pierce *et* al. 2007). Evaluations were made against laminated glazing by drop tests on door-glass systems. Rollover accidents typically include multiple impacts and potentially long duration forces on the side glazing. For this reason, some authors (Piziali *et* al. 2007, Luepke *et* al. 2007) do not associate laminated glazing as a suitable candidate for occupant containment during rollovers. However the use of laminated side glazing in automobiles is increasing. To understand the retention characteristics of laminated glazing, several mathematical and numerical models have been developed in order to model the laminated glass behaviour. Concerning numerical aspects, Mukherjee *et* al. studied impacts of pedestrians against windscreens. The authors implemented an isotropic elastic brittle law for the glass and an elastic law for the PVB layer with the mechanical characteristics of glass and PVB extracted from Haward's study in 1975. Du Bois *et* al. in 2003 and more recently Timmel *et* al. 2007 modelled windscreens for crash simulations with a hyperelastic law for PVB, such as Blatz-Ko's, Mooney-Rivlin's or Ogden's laws. The two glass layers with small plastic deformations until rupture have been implemented by a linear plastic law. To represent the three-layered glass behaviour, shell elements were used for glass layers and a membrane for PVB interlayer. Zhao *et* al. (2006) studied impact resistance of laminated glazing under head impact. PVB has been modelled as linear elastic in this study. Dharani *et* al. investigated failure modes of a laminated glass subjected to head impact using a linear viscoelastic material for PVB interlayer. According to Wei (2004), difference in stress obtained by treating the PVB as linear viscoelastic and linear elastic is less than 2 %. Considering the PVB plastic behaviour, Parsa *et* al. (2005) are the only one to suggest an isotropic viscoplastic model for laminated glass to study the glass creep forming process.

All these models are applied to windscreens. Laminated side glazing has not yet been numerically investigated under head impact. In a first step an experimental study was carried out to compare effectiveness and advantages of the two current types of side glazing used, tempered and laminated glasses. In a second step a finite element model of a laminated side window will be proposed and validated against experimental date. Finally a parametric study on four mechanical parameters of the lateral window will be conducted in order to propose a tool for lateral window optimisation against head criteria.

METHODOLOGY

An experimental study is undertaken which consists in impacting a Hybrid III dummy head against both, a laminated and a tempered side glasses. A set of 15 laminated windows and 5 tempered windows were studied. Head impact velocities ranged between 3 and 9.5 m/s, which is a realistic level of real head velocity during side impact crash (Bosch *et* al. 2005).

A laminated side glass FE model is then proposed based on isolated experimental data. Same boundary and initials conditions as for the experimental tests were. A parametric study is carried out to define the influence of the laminated glass mechanical characteristics on the head response.

Experimental approach

Testing is performed on an impact test bench, which principle scheme is given in Figure 1. This device consists of catapulting a headform against the glazing thanks to a jack supplied in compressed air. This air propels a carriage on which the head is set. The carriage is rapidly stopped letting slip the headform freely before impact. This device enables it to get propulsion velocities in a range of 5 to 10 m/s. Two devices enable to determine head velocity. The first one consists of a photodiode which is blocked up during the carriage passing. The carriage velocity is calculated just before head releasing by the length of the shutter divided by the blocking up time duration. The second device consists of a head tracking from a video obtained by a high-speed camera. The Photron Fastcam Ultima APX records 1000 frames per second at resolution of 1024x1024 pixels. Four targets fixed on the headform surface permit to compute head angular and linear velocity before and during, by tracking methods. Data acquisition system is performed by a PC-based platform PXI-1010 National Instruments with Labview software. Sampling frequency for data recording is set at 10 kHz. The headform is a Hybrid III dummy head developed by Foster *et* al. in 1977. The headform is composed of an aluminium structure covered by a vinyl synthetic skin with a total mass of 4.53 kg. In order to record the head linear acceleration, a triaxial linear accelerometer (Kistler) with a sensitivity of 10 mV/g and a measure range of ± 500 g is set at its centre of gravity. Accelerations data are filtered with a cut-off frequency of 1 kHz. Figure 2 represents Hybrid III headform with the different targets, the accelerometer location in the headform and its reference frame. Finally, in addition to head kinematics, HIC is computed with the linear acceleration data.

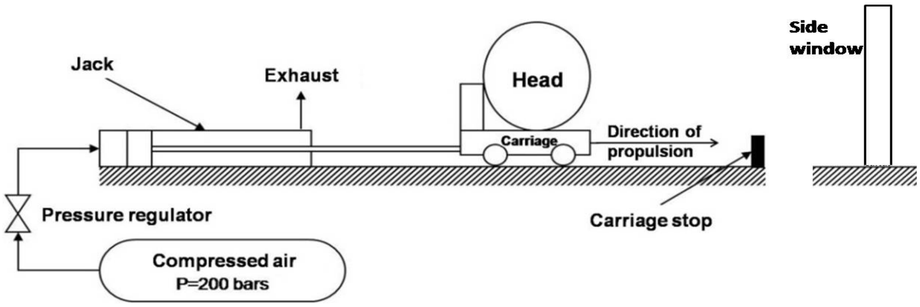
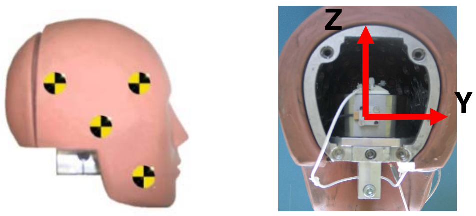


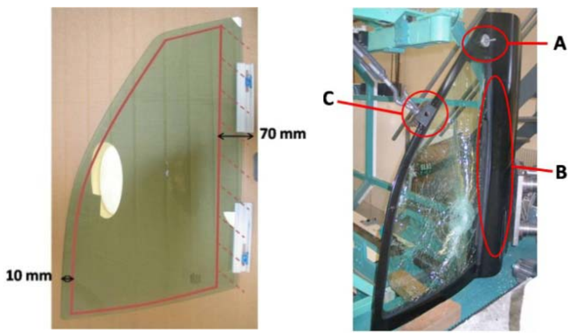
Figure 1. Impact test bench: Principle scheme.



(a) (b)

Figure 2. Hybrid III headform: (a) location of targets, (b) accelerometer location and reference frame.

The windows used in this study are front right side windows of a Volvo S80. In order to respect window boundary condition, the windows are enchased, closed in the lateral door which is fixed thanks to rubber stripes. Figure 3a represents the window setting in the door. The lateral door is hold screwed on the bench at point A, as represented in Figure 3b. Jambs of the door are maintained at points B and C. The door body is maintained on its slopes to avoid translations along impact direction.



(a) (b)

Figure 3. Side window: (a) Window frame in door, (b) Door setting on test bench (screw: A, wedge: B,C).

Tests are performed on 15 laminated glasses and 5 tempered glasses. Table 1 summarizes the different tests with impact velocity and type of glazing used. Nine tests are realised on tempered glazing at impact velocity ranging from 6.6 m/s to 9.4 m/s. A total of fifteen tests are performed on laminated glazing in an impact velocities range of 2.9 m/s and 11.3 m/s.

The description of the different tests results on laminated and tempered glazing will be presented. Results will be then analysed in terms of head response and injury assessment for both type of glazing.

Table 1. Tests realised on both laminated and tempered glasses with impact velocity.

	Test n°	Velocity [m/s]		Test n°	Velocity [m/s]
Laminated glasses	1	2;9	**Tempered glasses**		
	2	3,4			
	3	3,9			
	4	4,0		1	6,6
	5	5,0		2	6,7
	6	6,3		3	7,4
	7	6,4		4	7,5
	8	6,8		5	7,7
	9	7,4		6	7,8
	10	7,4		7	7,9
	11	7,4		8	9,1
	12	7,4		9	9,4
	13	8,5			
	14	8,9			
	15	11,3			

Numerical aspects

The second step of this study is to develop a laminated side glass FE model validated against experimental data.

The side window Finite Element model is presented in Figure 4. This model is based on CAO geometry and is meshed with Hypermesh software. It consists of 16613 shell elements modelling the laminated glazing and 8443 brick elements modelling the rubber band. Glazing is modelled under Radioss code by a three layered composite shell with three different thicknesses: 2.1 mm (glass), 0.76 mm (PVB), 2.1 mm (glass). Glass layers are assigned to an elastic brittle law. An elastoplastic law is implemented for PVB interlayer based on Johnson Cook material for rupture simulation. Rubber band is assigned to an elastic law. Concerning material properties, start point is to consider windscreen properties performed by Mukherjee et al (2000). Young modulus of glass is set at 74000 MPa with a yield stress of 3.8 MPa. PVB is assigned to a Young modulus of 50 MPa, a yield stress of 30 MPa and a failure strain at 0.51. These reference properties will be fitted in order to reproduce mechanical behaviour of laminated glazing during experimental testing.

The mechanical behaviour of the FE lateral laminated window model will be validated against experimental test number five with an initial velocity about 5m/s For this the HIII head FE model was used in simulations. This model consists of shell elements modelling the skull covered by a layer of brick elements. A linear elastic law is implemented for bricks modelling the skin. Mechanical parameters of the HIII FE head model are listed in Table 2 and the total mass of the head model is 4.53 kg.

Equivalent initial conditions and boundary conditions as experimental ones have been applied. These conditions are represented on Figure 5. Interface between window and rubber band is considered as elastic. The validation of the lateral window FEM is made in terms of maximum linear acceleration at the centre of gravity of the head, HIC criterion, glass permanent strain and glass and PVB cracks.

Finally, in order to define the influence of the laminated glass mechanical characteristics on the head response, a parametric study at 5 m/s was undertaken. Four mechanical parameters have been varied: the glass and PVB elastic limit, the thickness of the glass and the PVB interlayer. Each parameter has been set on three different values: a reference value, a high (+ 30 %) and a low (- 30 %) value. The head response was computed in terms of maximum linear acceleration of its center of gravity and HIC value. To analyze and to refine all results, a principal component analysis (PCA) was performed (Volle, 1997) to analyse head response as a function of laminated glass characteristics.

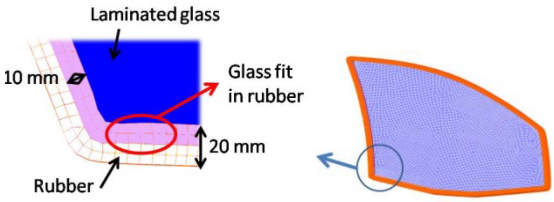


Figure 4. Lateral Window Finite Element Model (16 613 shells, 8 443 bricks).

Table 2. HIII FEM mechanical properties.

component	law	elements	Mechanical properties
skull	Linear elastic	408 shells	ρ = 260 Kg/m3 E = 210 000 MPa ν = 0,29
skin		1224 bricks	ρ = 99 Kg/m3 E = 60 MPa ν = 0,409

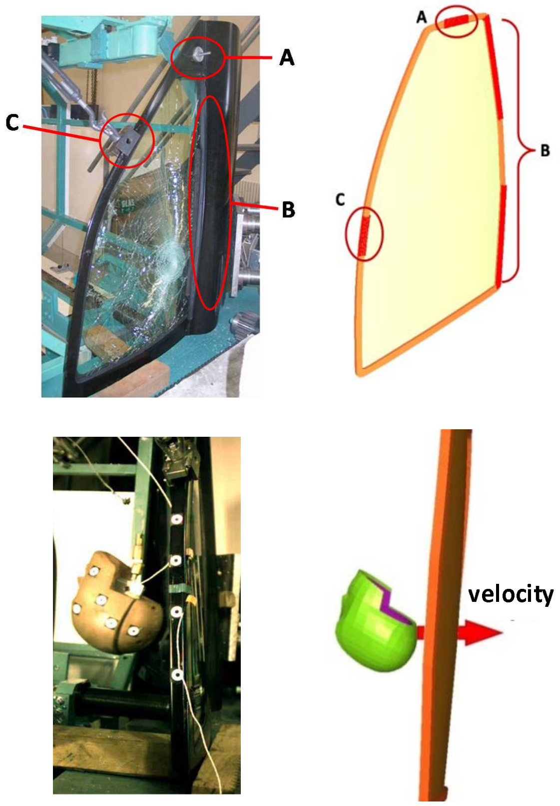


Figure 5. Initial and boundary conditions applied to the window FEM comparing to experimental conditions.

RESULTS

In this section experimental results will be presented by comparing tempered and laminated glass results. Results concerning the FEM of the lateral laminated glass windows validation will be proposed by reproducing test number 5. Finally results concerning the numerical parametric study will be analyzed.

Experimental results

This section presents comparative experimental tempered-versus laminated windows impacts. Tables 3 and 4 lists the different tests performed on tempered and tempered side glazing respectively. These tables report head velocity at impact, maximum linear acceleration at center of gravity of the head and HIC values. Lines in grey represent tests leading to a window failure. Testing was performed on impact test bench at velocity range of 3 to 11 m/s. A pendulum system was used for velocity under 5 m/s on laminated glazing as exposed in the methodology (tests n°1-4).

Table 3. Tests on tempered glazing with maximal linear acceleration and HIC; grey tests led to a glass failure.

Test n°	v [m/s]	γ_{max} [g]	HIC
1	6,6	258	1190
2	6,7	293	1327
3	7,4	525	3347
4	7,5	431	2481
5	7,7	279	1451
6	7,8	356	1646
7	7,9	198	321
8	9,1	357	1772
9	9,4	586	3698

Further observations about broken laminated glasses are detailed in Table 6. In case of failure, cracks appear in both glass layers. An example of coordinates of impact location, cracks after impact and permanent strain is represented in Figure7 for test n° 5.

In the two last presented cases, there was a duplicated impact of head on the window. In only one case (test n°14), PVB interlayer broke. The rupture location corresponds to the nose impact. Window permanent strain go from 5 to 15 mm. One can notice that there is no correlation between window permanent deformation and impact velocity.

Table 4. Tests on laminated glazing with maximal linear acceleration and HIC; grey tests led to a glass failure.

Test n°	v [m/s]	γ_{max} [g]	HIC
1	2,9	503	2827
2	3,4	545	4041
3	3,9	429	1015
4	4,0	511	2264
5	5;0	104	101
6	6,3	428	2892
7	6,4	126	148
8	6,8	139	211
9	7,4	483	1893
10	7,4	306	1374
11	7,4	324	1383
12	7,4	402	1177
13	8,5	284	702
14	8,9	98	249
15	11,3*	143	2041

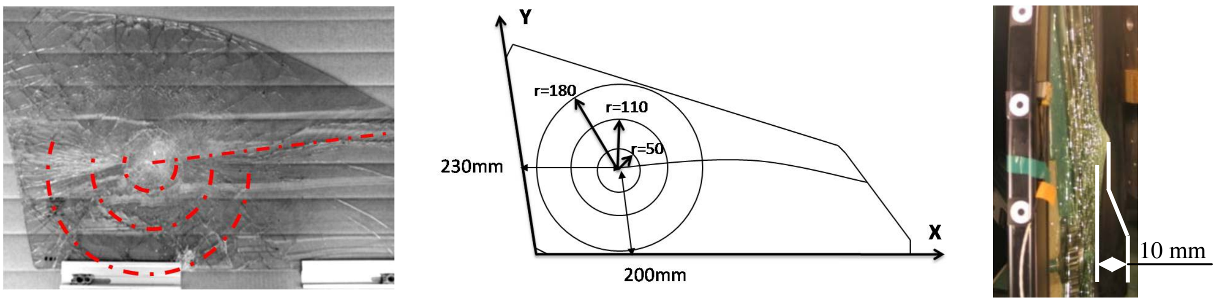


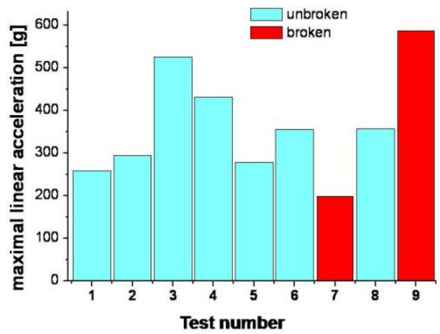
Figure 7. Window condition after impact at test n°5, coordinates of impact location and window permanent strain

Table 6. Observations on broken laminated glasses, permanent strain and impact location.

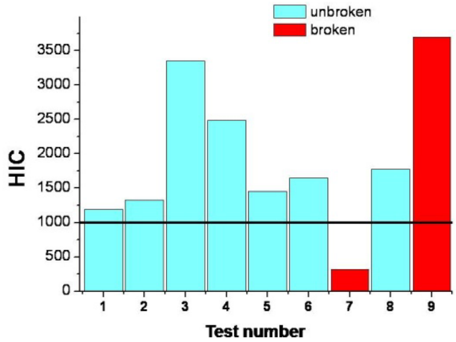
N° Test	Observations	Per. Strain. [mm]	Impact location
5	Window initially cracked Concentric cracks: r=50, 110, 180 mm No PVB rupture	10	X = 230 Y = 200
7	Concentric cracks: r=50, 180mm Linear cracking No PVB rupture	5	X = 210 Y = 200
8	nape impact Concentric cracks: r=50,140, 170, 300 mm No PVB rupture Long linear crack on rear glass layer	13	X = 230 Y = 225
12	Linear cracking No PVB rupture	10	X = 230 Y = 220
13	Linear cracking Concentric cracks : r=30, 70 mm No PVB rupture	10	X = 230 Y = 225
14	duplicated impact : chin (1) and nose (2) Concentric cracks : r=80, 200 mm PVB rupture (2) Long linear crack	13	X1 = 230 Y1 = 225 X2 = 300 Y2 = 250
15	duplicated impact : nape (1) and chin (2) Concentric cracks : r=140, 190, 300 mm Long linear crack	15	X1 = 180 Y1 = 150 X2 = 260 Y2 = 210

Histograms reported in Figure 8 represent maximal linear acceleration at the center of gravity of the head and HIC values for all tests on tempered glazing. Tests are sorted by increasing velocity. Bars in dark grey represent broken windows. Tolerance limit of 1000 is also represented for HIC criterion. Maximal linear accelerations values stand between 198 g to 586 g. In general, all tests on tempered glazing led to HIC values greater than the tolerance limit, with values from 1190 to 3698. For impact n°7 on tempered glass, predated by tests n°3 and 4, it appears a significant decrease in peak linear acceleration and HIC value. This could be associated with an initiation of micro-cracks due to a repetition of impact. Broken windows (in dark grey) appear at impact velocity from 7.9 m/s (test n°7). Histograms on Figure 9 represent respectively maximal linear acceleration at the center of gravity of the head and HIC values for all head impact tests against laminated glazing. Tests are sorted by increasing velocity. Bars in dark grey represent broken windows.

In tests leading to no rupture for laminated glasses, maximal linear accelerations stand around 400 g (bars in light grey) and HIC values stand all over the tolerance limit of 1000. Mostly tests leading to rupture present HIC values lower than the tolerance limit except test n°12 and 15.



(a)



(b)

Figure 8. (a) Maximal linear acceleration and (b) HIC for impact tests on tempered glazing classified by increasing velocity, in light grey for unbroken windows, in dark grey for broken windows.

There appear three distinct areas for laminated glazing as a function of velocity (Figure 9):

- A first area (I) where there is no rupture for laminated glasses, tests n°1-4 at impact velocity lower than 5 m/s.
- the third one (III) include brken windows over an impact velocity of 7,5 m/s for tests n°13 to 15.
- The second area is referring to tests n° 5 to 12 between impact velocity of 5 m/s to 7,4 m/s. These cases led to unpredictable glass rupture.

It appears that if the windows failed, the HIC is generally lower than if there is no rupture. It should also be recalled that if the tempered glass break, partial ejection exist which is not the case when laminated glass failed

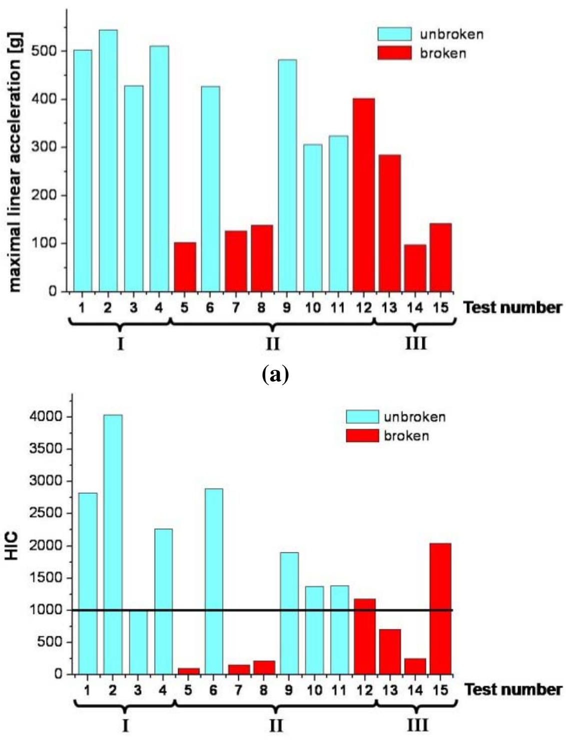


**Figure 9. (a) Maximal linear accelerations and (b) HIC for impact tests on laminated glazing classified by increasing velocity, in light grey for unbroken windows, in dark grey for broken windows.
I: rupture, II: unpredictable rupture, III: no rupture.**

Figure 13 and 14 represent respectively maximal linear acceleration at the center of gravity of the head and HIC criterion for 6 cases of laminated glazing and 6 other cases of tempered glazing. These twelve cases are comparable in terms of head impact velocity.

For laminated glazing, HIC values stand under the limit of 1000 except for test n° 9 at 7.4 m/s and test n°12.

In case n°9 the laminated window did not break. For tempered glazing, HIC values exceed HIC tolerance limit, except for test at impact velocity of 9 m/s where the tempered glass broke.

In most of these cases, maximal linear acceleration and HIC values are lower for laminated glazing. HIC values go from around 200 to 2000 for laminated glazing against 300 to 3500 for tempered glazing. Only one comparison presents the opposing trend. In the fifth comparison (white bars around 9 m/s), values remain greater for laminated glazing (70) than for tempered glazing (321). At this velocity, tempered glass broke and there was a head defenestration. Laminated glazing plays its principal role which is to hold the head inside the car and to fail with HIC value under 1000.

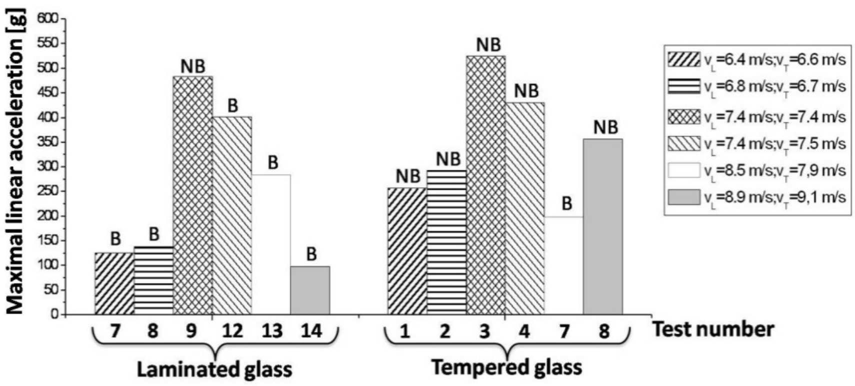


Figure 13. Maximal linear accelerations for tests on laminated and tempered glasses for 12 similar cases (B for broken, NB for not broken), v_L: velocity for Laminated window impact, v_T: velocity for Tempered window impact.

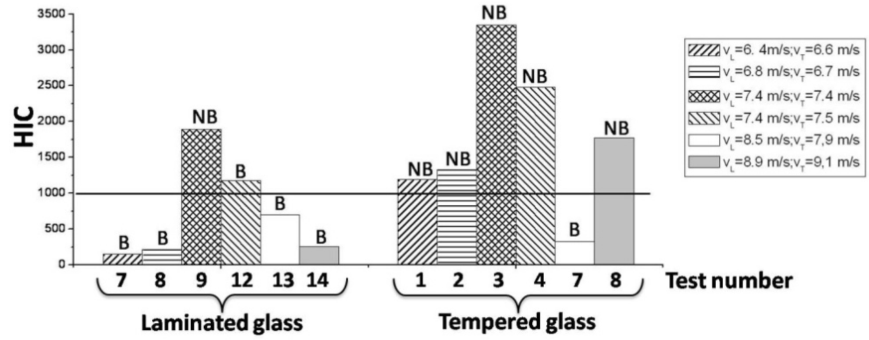


Figure 14. HIC values for tests on laminated and tempered glasses for 12 similar cases (B for broken, NB for not broken), v_L: velocity for Laminated window impact, v_T: velocity for Tempered window impact.

Numerical results

The laminated side window model validation is based on experimental data from test n°5 at 5 m/s. In order to validate laminated behaviour, the mechanical parameters are fitted on both laminated glass and PVB properties.

During this fitting, it appeared that initials conditions in door clumping influenced the model response in a significant way in terms of PVB strain and crack propagation in glass layers. Different ways of clumping were analysed in order to come closer to experimental cracks represented in Figure 7.

In parallel to this clumping analyse, the fit of mechanical parameters have been performed in terms of Young modulus, yield stress and failure strain. The aim of this fitting would be to reproduce cracks in glass layers and strain in PVB interlayer.

Variations in Young modulus of both materials do not influence results. The variation of the yield stress of the two materials combined (glass and PVB) influenced the permanent plastic strain of the laminated glazing. A more accurate optimisation of these mechanical parameters has been made in terms of maximal linear acceleration and HIC criterion.

Final mechanical properties of glass, PVB and rubber listed in Table 7 give the best values compared to experimental results. Results in terms of maximal linear acceleration, HIC criterion and permanent strain are detailed in Table 8 for experimental testing and numerical simulations.

It results for linear acceleration an error of 20 %. HIC values go from 101 in experimental case to 138 in numerical simulation. Figure 15 shows the cracks of window after experimental impact and numerical simulation at impact velocity of 5 m/s. It can be observed two principal concentric cracks at radius equal to 97 mm and 163 mm on numerical picture compared to values equal to 1100 mm and 180 mm on testing window. We also observed a beginning of long linear cracks in accordance with experimental results. The PVB interlayer remains intact in both cases (experimental and numerical results).

Table 7. Final mechanical properties for glass and PVB layers and rubber bands applied to the laminated window FEM.

Constituent	Propriety	Mechanical parameters	Values	Element type	Thickness
Glass	Elastic brittle	Density	2500 $Kg.m^{-3}$	Shell	2.1 mm
		Young Modulus	70000 MPa		
		Poisson's ratio	0.2		
		Yield stress	50 MPa		
		Maximum strain	0.0007		
PVB	Elastoplastic with rupture	Density	950 $Kg.m^{-3}$	Shell	0.76 mm
		Young modulus	50 MPa		
		Poisson's ratio	0.4		
		Yield stress (a)	20 MPa		
		Hardening modulus (b)	20		
		Hardening exponent (n)	0.9		
		Failure strain	1,2		
Rubber	Elastic	Density	1052 $Kg.m^{-3}$	Bricks	5 mm
		Young Modulus	3.91 MPa		
		Poisson's ratio	0.4		

Table 8. Experimental and numerical results for impact at 5 m/s on laminated glass.

Parameter	Experimental	Numerical	Error %
Impact velocity [m/s]	5	5	0
Maximum linear acceleration [g]	103,82	125	20
HIC	101	138	37
Window permanent strain [mm]	10	12	20

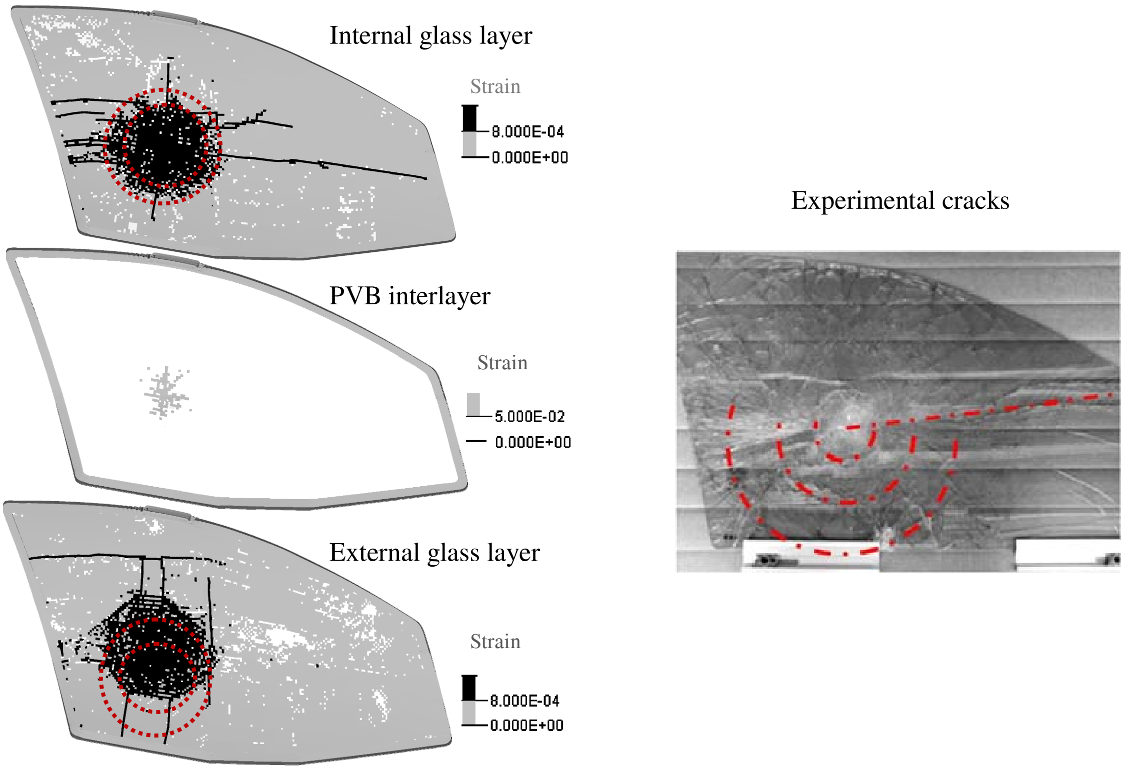


Figure 15. Cracks on laminated side window for impact at 5 m/s with HIII headform, comparison of experimental and numerical simulation.

Parametric study

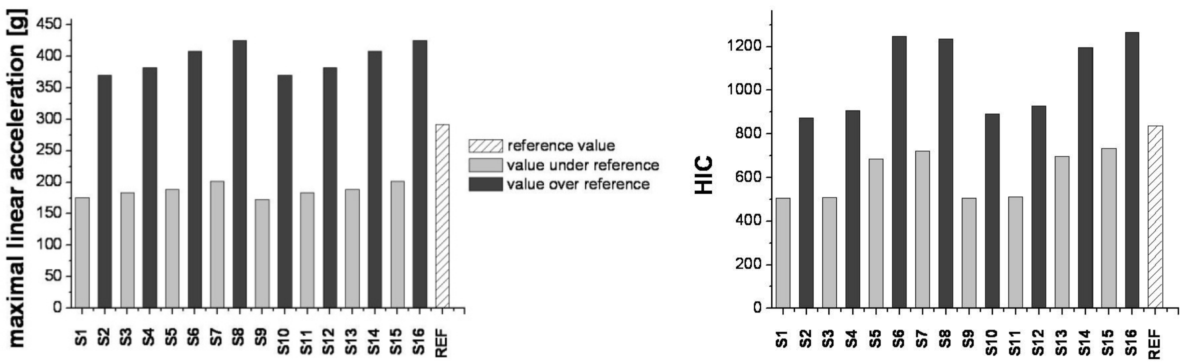
Four mechanical parameters have been varied: the glass and PVB elastic limit (C and D), the thickness of the glass (A) and the PVB interlayer (B). Each parameter has been set on three different values: the reference value used in the model validation, a high (+ 30 %) and a low (- 30 %) value. The tests used for the parametric study remain in the same boundary conditions at 10 m/s reference velocity for normative impacts. Head response for a given simulation was calculated in terms of maximum linear acceleration at the center of gravity of the head and HIC value. A total of 16 simulations were run with a simulation protocol illustrated on Table 9.

Histograms shown in Figure 16a and b represent respectively the maximum linear acceleration at the center of gravity of the head and HIC values calculated for each simulation. While the reference value in term of maximum linear acceleration reaches 292 g, one of two results stand around a value of 180 g, the others around a value of 400 g. This variation corresponds to the A parameter. We can already conclude that the glass thickness influences head response in terms of linear acceleration. The same trend is observed concerning HIC values.

The principle of the PCA is to research the best data representation with the less possible dimensions to reduce the number of variables or the initial space dimension number. This consequently allows to explain and to display data with a reduced number of axes in order to facilitate the interpretation of synoptic results. The first result is the correlation matrix reported in Table 10. From this we can observe that some of the variables are highly correlated which means that they move together (boxes in dark grey). We can mention for example that input variables B and D have less correlation with output variables. On the other hand, the glass thickness (A), as observed before, is highly correlated with head responses, maximum linear acceleration (0.98) and HIC (0.85). The variable C is moderately correlated with HIC criterion (0.5). Finally maximum linear acceleration and HIC values are naturally correlated (0.92).

Table 9. Simulation protocol indicating for each of the 17 simulations, the window characteristics retained: +/- stand +30% or -30% of the reference window properties values.

	REF	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16
A (Glass thickness - mm)	2,1	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+
B (PVB thickness - mm)	0,76	-	-	+	+	-	-	+	+	-	-	+	+	-	-	+	+
C (Glass elastic limit - MPa)	50	-	-	-	-	+	+	+	+	-	-	-	-	+	+	+	+
D (PVB elastic limit - MPa)	20	-	-	-	-	-	-	-	-	+	+	+	+	+	+	+	+



(a) (b)

Figure 16. Maximal linear acceleration (a) and HIC values (b) calculated for each simulation.

The next step is then to calculate the principal components. Here the correlation matrix (Table 10) is considered in a mathematical point of view. For this symmetric matrix (6x6) the eigenvalues and eigenvectors are then determined. These eigenvalues reflect the quality of the projection from the N-dimensional initial table (N=6 in this study) to a lower number of dimensions. Each eigenvalue corresponds to a factor which is a linear combination of the initial variables, and all the factors are un-correlated (r=0). The eigenvector associated with the largest eigenvalue has the same direction as the first principal component. The eigenvector associated with the second largest eigenvalue determines the direction of the second principal component. These axes are defined by linear forms (1) and (2).

Ideally the first two or three eigenvalues will correspond to a high percentage of the variance, ensuring us that the maps based on the first two or three factors are a good quality projection of the initial multi-dimensional table. In this study, the first two factors allow us to represent 66.6 % of the initial variability of the data.

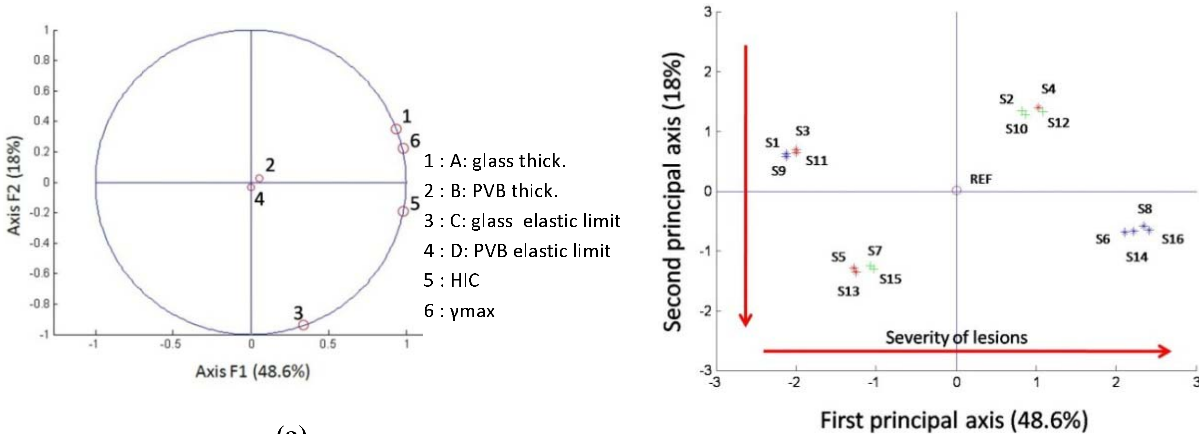
The correlation circle represented in Figure 17a is useful in interpreting the meaning of the axes. It shows a projection of the initial variables in the factors space. In this study, the horizontal axis which represents 48.6 % of the variability is linked with the glass thickness (0.552), HIC criterion (0.573) and maximum linear acceleration (0.575). Along F2 which describes 18 % of the variability, the main important parameter is the glass elastic limit (-0.910).Figure 17 b is the ultimate goal of the PCA. It permits to look at the data on a two-dimensional map, and to identify trends. We can see that simulations are classified from the left (less value) to the right (high value) along the first axis from S1 to S16; S17 represents the simulation of reference. We can note that the best simulations in terms of HIC criterion and maximum linear acceleration are localized in the portion of space described by F1≤0 and more accurately by F2≥0. The space described by F1≤0 corresponds to the influence of glass thickness. The refinement in space corresponds to glass elastic limit.

Table 10. Correlation matrix between the N=6 variables.

	A	B	C	D	HIC	γ_{max}
A (Glass thickness)	1	0	0	0	0,85	0,98
B (PVB thickness)	0	1	0	0	0,04	0,06
C (Glass elastic limit)	0	0	1	0	0,50	0,13
D (PVB elastic limit)	0	0	0	1	0,01	-0,001
HIC	0,85	0,04	0,50	0,01	1	0,92
γ_{max}	0,98	0,06	0,13	-0,001	0,92	1

$$\text{AxisF1} = 0.552\ A + 0.032\ B + 0.190\ C + 0.003\ D + 0.573\ HIC + 0.575\ \gamma_{max} \quad (1)$$

$$\text{AxisF2} = 0.314\ A + 0.027\ B - 0.910\ C - 0.030\ D - 0.189\ HIC + 0.188\ \gamma_{max} \quad (2)$$



(a) (b)

Figure 17. PCA correlation circle of the 6 variables (a), factorial plane (b).

DISCUSSION & LIMITATIONS

This study shows that side windows with laminated glazing are safer than tempered glazing. For the same velocity, laminated glass windows broke and thereby decreased head injury risks in case of impact, whereas tempered glass did not. At an impact velocity from 6 m/s to 9 m/s against tempered glass windows, HIC values stood over a limit of 1000, which is the normalized value for pedestrian head impact at 10 m/s (Directive 2003/102/EC). The PVB interlayer has never broken at impact velocities of 3 m/s to 9 m/s, contrary to tempered glass. Therefore, laminated glass avoids partial ejection. The developed model even if validated against experimental results need further investigation for the optimization of its behaviour against both HIC and more biofidelic head injury criteria based on human head FE modelling (Marjoux *et* al. 2006, Deck *et* al. 2008).

The parametric study pointed out the prevailing part of the glass layer thickness (A parameter) on head responses in terms of maximal linear acceleration at the center of gravity of the head and HIC criterion. The thicker the glass is the more critical HIC criterion becomes. Therefore head injury risks increases. Yield stress of glass has a lesser influence on maximal linear acceleration and HIC. The PVB thickness and its yield stress have no influence on head response. These findings follow the results from Zhao *et* al. (2006). Glass ply thickness plays a very critical role however the PVB interlayer thickness has no significant effect on the impact resistance of a laminated glass. Simulations which give the less injury risk in term of HIC criterion require a lower glass thickness and a lower glass yield stress.

A main limitation resides in reproducibility of experimental testing. Mode of transport, production line and stochastic nature of glass are parameters not controlled. Only new laminated and tempered glasses were used in this study. Each test involves a change in boundary conditions of the window, a manual repositioning of the head on the carriage. Some difficulties appeared also during the experimental testing, mainly in the velocity fitting and in the control of head rotation at the time of impact, which lead to minor errors in linear acceleration peaks. In the numerical impact reconstructions, the window vibrations due to the framing and the changes of windows were not considered. The limitation of this experimental study is the range of velocity. The propulsion system does not allow lower and greater impact velocities and could not reproduce same velocities.

CONCLUSIONS & PERSPECTIVES

The experimental tests consisted of a Hybrid III headform which impacts either laminated or tempered glasses side windows. Characteristics of the impact were investigated: velocity of the head, mechanical behaviour of the window (cracks, rupture, and plastic strain), linear acceleration at the center of gravity of the head and HIC criterion. The different tests were performed within a velocity range of 3 m/s to 9.5 m/s. A comparison between the laminated and tempered glass was performed. At same velocity, impact against laminated glass lead to less injury risk than a tempered glass with lower HIC values. The principal role of laminated glazing has been preserved; PVB layer never broke and laminated glazing led to lower injury risks. Laminated glass broke from 5 m/s and tempered glass broke from 8 m/s. In parallel of these experiments, a finite element model of laminated side window has been developed, validated and improved by a parametric study.

In order to ensure the validation of the side window FE model in a large range of impact velocity more experiments with smaller speed increment must be conducted. In a further step the boundary condition of the head at neck level should be considered as this weak point is important in case of glazing braking and partial ejection.

Finally in deep investigation of head injury risk and realistic laminated glass optimization should be conducted by coupling the windows model to a human head FE model.

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