

LAMINATED VERSUS TEMPERED LATERAL WINDOWS UNDER HEAD IMPACT: EXPERIMENTAL AND NUMERICAL ANALYSIS

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ABSTRACT

During car accidents leading to roll-overs, 49% of the injured occupants are partially or fully ejected through the side window (Yaniv *et al.*, 1998). In addition head impact against an external structure is often observed under lateral impact. In order to study the risks of car occupant ejections and lateral head impact, an understanding of the side window's mechanical behavior during a head impact is necessary. Typically in car industry two types of side windows are used made either of tempered or laminated glasses. To compare the effectiveness and the advantages of these two types of glasses, experimental and numerical studies of lateral windows behavior under head impact have been carried out.

Keywords: Lateral windows, tempered glasses, laminated glasses, HIC

LATERAL IMPACTS account for 27% of the accidents leading to death, which represents about 10000 deceases every year (Langwieder *et al.*, 1996). In such impacts, the major risk for vehicle occupants is the ejection through windows. Lateral windows with tempered glass are gradually replaced by laminated glass which is composed by two layers of tempered glass separated by a PolyVinylButyral membrane (PVB). This safety glass permits a better protection during accidents due to energy absorption without break. Moreover, it offers a good resistance for breaking and entering as well as for decreasing sun radiations and sound effects. At this time, PVB is the most used material for this reinforced interlayer. It is an adherent material which offers a good breaking strength and provides a large rate strain.

Many different mathematical and numerical models have been developed for modeling laminated glass behavior. Concerning numerical aspects, Mukherjee *et al.* (2000) have studied impacts of road vulnerable users against windscreens. They propose a finite element model of windscreens with the mechanical characteristics of glass and PVB extracted from Haward's study (1975). The authors implemented an isotropic elastic brittle law for the glass and an elastic law for the PVB layer. Du Bois *et al.* in 2003 and then Timmel *et al.* in 2007 have modeled windscreens for crash simulations with a hyperelastic law for PVB, such as Blatz-Ko or Mooney-Rivlin's laws in small deformation range, or Ogden's law for large deformation. The two glass layers with small plastic deformations until rupture have been implemented by a linear plastic law. A validation of the numerical model has been made against experimental testing with a spherical impactor shot against a windscreen. All these models do not consider the plastic behavior of the PVB interlayer and its rupture. Parsa *et al.* (2005) expose an isotropic visco-plastic model for laminated glass behavior in order to study the glass creep forming process.

Laminated lateral windows glazing has not yet been investigated experimentally and numerically under impact conditions. In this study, a lateral window modeling is proposed, based on experimental data, with laminated glazing. In a previous phase, an experimental study is carried out to compare effectiveness and advantages of the two current types of side glazing used, tempered and laminated glasses.

METHODOLOGY

The experimental tests consist of a Hybrid III (HIII) headform which impacts either laminated or tempered glasses side windows. The HIII headform is composed of an aluminum structure covered by a vinyl synthetic skin and its total mass is about 4.6 kg. Experiments are performed on an impact test

bench including a fixed door. This device consists of a propulsion system supplied in compressed air which catapults the headform to the glazing. The headform impacts the inner side of the window at several velocities from 3 m/s to 9.5 m/s. For this experimental study, fifteen side windows are used, ten laminated glasses and five tempered glasses. An illustration of the device is proposed figure 1. The triaxial linear accelerations of the center of gravity of the head, the permanent plastic strain, head ejection as well as cracks and rupture of the glass and PVB interlayer were recorded.

In parallel of these experiments, a finite element model of the lateral laminated glass window has been developed and impacted numerically with a HIII head FE model in order to reproduce experimental tests. Laminated glass is modeled under Radioss code by a three layer composite shell: glass –PVB– glass with thicknesses of 2.1-0.76-2.1 mm respectively. The PVB interlayer is assigned an elastoplastic law with rupture. An elastic brittle law is implemented for the glass layers with mechanical parameters taken from Mukherjee *et al.* (2000). The boundary conditions used for numerical reconstruction are the same as those used for experiments. The lateral window fitting is represented by a simple rubber layer.

After first simulations of two occipital impacts with HIII FEM and the developed windscreen under experimental conditions (5 m/s and 7.4 m/s), we proceeded to a parametric study of the windscreen FEM in order to optimize its behavior. All results were analyzed with a principal component analysis (PCA) method. This PCA is used to analyze the influence of windscreen mechanical properties on the HIC values as well as cracks propagation and windscreen strain. Six mechanical parameters have been varied, Young modulus, yield stresses and maximum strain of glass and PVB materials. Each parameter has been set on three different values: a reference value which comes from Mukherjee *et al.* (2000), a high (+30%) and a low (-30%) value. The test used for the parametric study remains an occipital impact of HIII head at 5 m/s initial velocity.

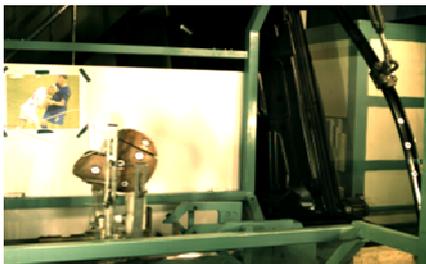


Fig. 1 –Impact test bench with Hybrid III headform

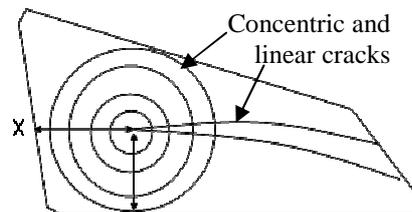


Fig. 2 – Scheme of the window's cracks for laminated glass

RESULTS

Twenty five experimental tests have been carried out; sixteen tests against laminated glass windows, nine tests against tempered glass. All these windows have been impacted by the occipital part of the Hybrid III headform. Impacts were performed for the laminated glasses at velocities ranging from 3 m/s to 9 m/s. The maximum linear acceleration range was respectively from 100 g to 500 g with corresponding HIC values of 250 to 2800. Different linear and concentric cracks were observed at 5 m/s speed for the laminated glasses. The PVB interlayer was never broken. Between 5 and 15 mm plastic deformation were observed

For the tempered glasses, tests were performed at velocities ranging from 6.5 m/s to 9.5 m/s. The maximum linear acceleration range was respectively from 260 g to 590 g with corresponding HIC values from 1200 to 3700. The tempered glasses broke to pieces with head ejection from 7.9 m/s. In all cases, the HIC value stood over a limit of 1000.

To compare laminated and tempered glass, linear accelerations and HIC are resumed at five comparable velocities in Figures 3a and 3b respectively. For most cases, linear acceleration and HIC values are less important with laminated glass than tempered glass. All laminated glasses have broken from 6.37 m/s to 8.51 m/s except the test at 7.43 m/s, which have the greatest HIC value around 1800.

The tempered glazing have never broken from 6.64 m/s to 7.53 m/s with HIC values greater than a limit of 1000, from 1190 to 3350. Tempered glass broke to pieces at 7.90 m/s and thereby has lower acceleration peaks and HIC values, 198 g and 320 respectively.

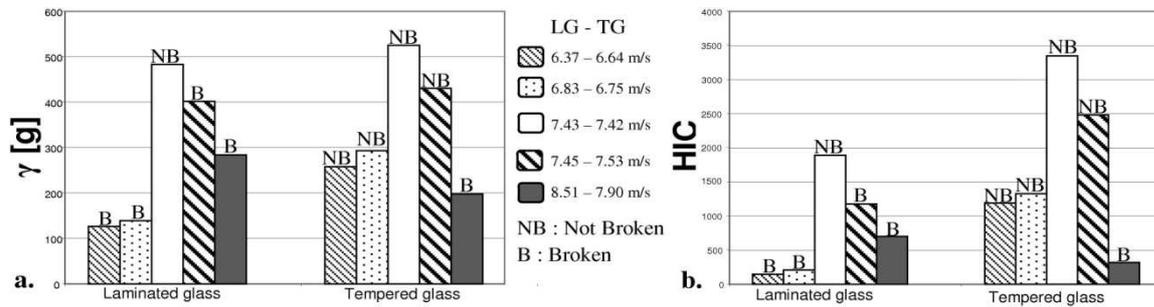


Fig. 3 – Maximum linear accelerations (a.) and HIC values (b.) for laminated (LG) and tempered glass (TG) at same range of velocity

Concerning the numerical parametric study of the windscreen, the statistic PCA method led to the conclusion that the yield stress of the glass is highly correlated with HIC and cracks propagation. To reduce the HIC value, yield stress of the glass need to be decreased. The decrease of the yield stress of the glass leads to more concentric cracks. The variation of the yield stress of the two materials combined (glass and PVB) influenced the permanent plastic strain of the laminated glazing. The two Young modulus did not have a great influence on the model response.

Figure 4 represents the window cracks in experimental test and numerical simulation at 5 m/s. The lines in dark color represent cracks which appear at a maximum strain of $7E^{-04}$ and 1.2 for glass and PVB respectively. The mechanical properties for the glass and PVB that have given the best results are listed in the Table 1. The numerical results with these mechanical properties at 5m/s has given a maximum linear acceleration for the center of gravity of the head, HIC and permanent plastic strain of the window equals to 125 g, 138 and 12 mm respectively against values of 104 g, 101 and 10 mm for the experimental test.

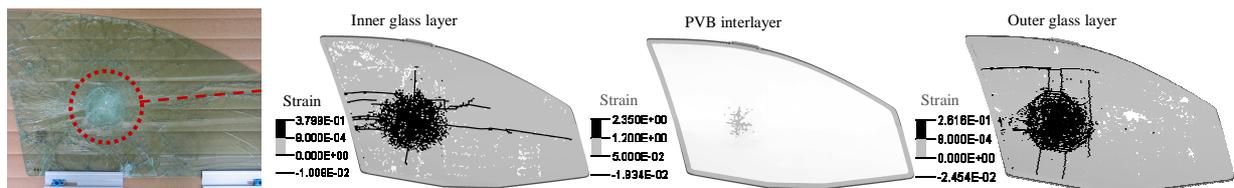


Fig. 4 – Laminated glass cracks after impact at 5 m/s, experiment and numerical simulation

Table 1. Mechanical characteristics for the glass and the PVB layers

Constituent	Propriety	Mechanical parameters	Values	Element type	Thickness
Glass	Elastic brittle	Density	2500 Kg.m ⁻³	Shell	2.1mm
		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	0.76mm
		Young modulus	50 MPa		
		Poisson's ratio	0.4		
		Yield stress (a)	20 MPa		
		Hardening modulus	20		
		Hardening exponent	0.9		
Failure strain	1.2				

DISCUSSION

This study shows that lateral windows with laminated glazing are safer than tempered glazing. For the same velocity, laminated glass windows broke whereas tempered glass did not, and thereby decreased head injury risks in case of impact. 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. Laminated glass avoids ejection.

The developed model even if validated against experimental results need further investigation for the optimization of its behavior against both HIC and more biofidelic head injury criteria based on human head FE modeling.

The limitation of this experimental study is the range velocity. The used device was not made for lower and greater velocities. In the numerical impact reconstructions, the window vibrations were not considered. Some difficulties have appeared during the experimental testing, mainly in the velocity fitting and in the control of head rotation at the impact, which lead to minor errors in linear acceleration peaks.

CONCLUSION AND 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 behavior of the window (cracks, rupture, plastic strain), linear acceleration and HIC. 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. In parallel of these experiments, a finite element model of both lateral windows have been developed and validated.

In order to ensure the validation of the lateral 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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