Utilizing a Validated Laminated Glass Model to Simulate Pedestrian Head Impact on a Windshield

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1 Abstract

The authors have previously published a paper characterizing a laminated glass pane to simulate the delamination and fragmentation response of glass in a blast event. In this study, a computational model in LS-DYNA was developed and correlated with physical testing of laminated safety glass panes subjected to blast loads. To generate an accurate model, validation of the component parts including Polyvinyl Butyral (PVB), adhesion and glass that make up the laminated safety glass was completed.

In a new study, the authors using this model undertook several pedestrian head impact tests on a windshield in accordance with the Euro New Car Assessment Program (NCAP) and UN ECE R127 to determine its suitability. Building on this model, the glass material was further refined to correlate with previous physical tests completed with an emphasis to correlate against the head injury criterion (HIC) number as well as match the acceleration vs. time history curve. Following refinement, more physical testing was completed which was compared to the model and showed good agreement between the physical testing and model. Furthermore, when compared to the old approach to simulate pedestrian head impact on a windshield, the new approach demonstrated better membrane action following glass cracking which resulted in better correlation to the acceleration vs. time history curve. The approach and results of the study are presented within this paper.

2 Introduction

Laminated Safety glass (LSG) incorporating a Polyvinyl Butyral (PVB) interlayer is a composite material that combines the durable and visually permeable properties of glass with the benefits of a ductile viscoelastic polymer. LSG is extensively used in both the automotive industry and in architectural applications due to its enhanced impact resistance and ability to retain sharp glass fragments from an otherwise brittle failure mode [1].

LSG is a composite material made up of two parts; an interlayer often PVB, and at least two glass plies either side of the interlayer. LSG when combined form a composite material, which results in a non-linear material. Previous studies have identified that the performance of LSG is dependent on several factors; traditionally these have included the material thickness, glass heat-treatment, pane geometry, and support conditions. LSG is typically formed by placing the glass-PVB layup into an autoclave to allow chemical and mechanical bonds to form between the glass and interlayer. This bonding has been demonstrated to influence the delamination behavior under impact load [1].

The authors have undertaken extensive modelling to validate the components of laminated glass under a blast threat [1]. This includes correlating component testing of PVB dogbone samples, developing material inputs to simulate the bonding between the glass and the PVB and validating the glass inputs. Combining all three components, the material inputs were correlated against four blast tests and demonstrated reasonable correlation for displacements and edge reactions [1-2].

Historically, pedestrian head impact primarily concerned impacts to exterior body panels such as hood and fenders. For the legal UN ECE R127 regulation the windshield was not considered at all, and for Euro NCAP there was an automatic scoring system over the windshield, which depended on the distance the impact was from the windshield ‘frame’. More recently, R127 has adopted a new windshield test zone and Euro NCAP requires full analysis/testing of the adult and cyclist zones, most likely overlapping with the vehicle windshield.

These new updates highlight a growing need for automotive OEMs to have robust and accurate glass models, capable of reproducing the head injuries observed by physical testing.

Several modelling and simulation techniques of laminated safety glass are found in literature. These models range from single multilayer shell models to solid models. Mittelhessen [3] presented a method in which the glass layers are represented by shell elements and the solid layer by PVB. Null-shells and a contact was used to represent the connection between the glass and PVB interlayer. This approach showed somewhat better results than a single multilayer shell model, but still needed further refinement.

Liu [4] used a similar technique and modelled the glass as MAT_MODIFIED_PIECEWISE _LINEAR_PLASTICITY. Once the critical major strain is exceeded, the element is deleted. The conclusion from this study is that the failure of the windshield and its relationship with injury severity needs to be further investigated.

Both studies ignored the influence of adhesion that bonds the glass to the PVB interlayer. In Blast analysis, the adhesion that bonds between the interlayer and the glass itself has been identified as influencing the protective performance of LSG. In this paper, the laminated glass model developed for blast is correlated to multiple pedestrian head impact tests to achieve a similar HIC value to the test as well as a similar force time history.

3 Material Model Set-Up

The authors through a validation series developed material inputs for PVB, the adhesion interlayer and glass. The various components for the laminate are illustrated in Figure 1

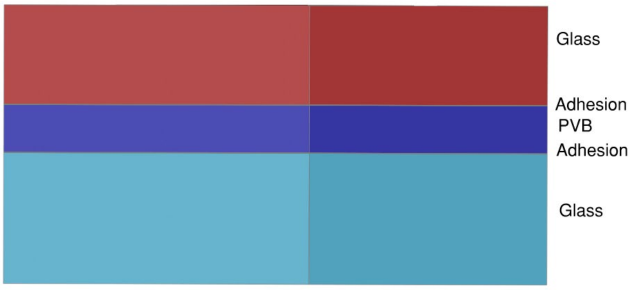

Fig.1: Layup

The PVB inputs are as per those developed in Aggromito et al. [1]. The PVB is represented using MAT_HYPERELASTIC_RUBBER with solid elements. MAT_HYPERELASTIC_RUBBER uses a six-term polynomial to fit the hyper-elastic part of the material. Some of the material inputs are displayed in Table 1.

Table 1: Prony Series Parameters

B (1/s)	Overall fit G_i (MPa)
9080	684.5
10	3.0
11	4.78
2000	0.3

As part of the validation activities, the adhesion that exists between the glass and the PVB was correlated against a series of through cracked tensile tests. The through-cracked tensile test subjects a pre-cracked laminated glass sample to a uniaxial tension load as shown in Figure 2. At the crack interface the PVB interlayer bridges the gap between the adjacent glass edges. During extension, the PVB interlayer progressively de-bonds around the glass edge until the interlayer has completely debonded from the glass or the PVB interlayer reaches its strain limit and ruptures. The force displacement results from the TCT can be used to determine the delamination energy (represented by G in Figure 2) by subtracting the strain energy from the total energy.

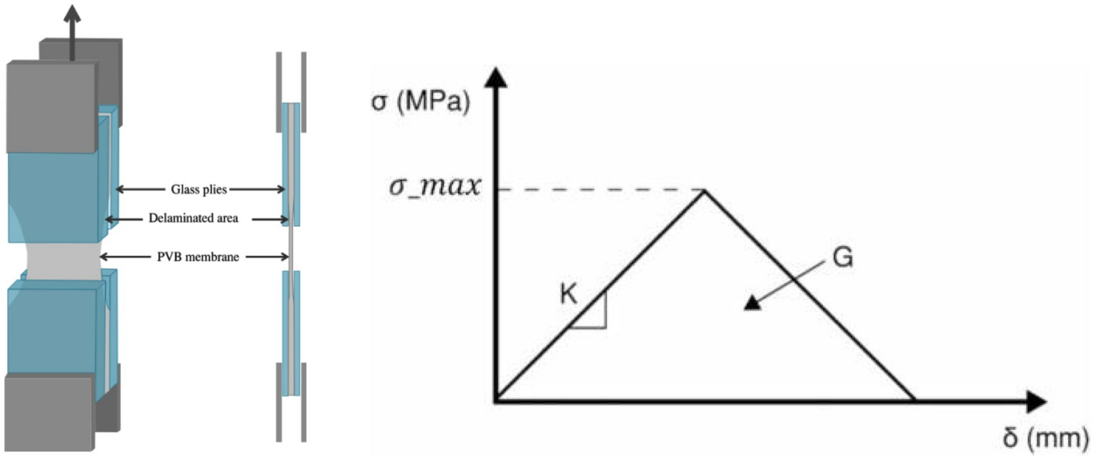

Fig.2: a) Through Cracked Tensile Test b) Traction-Separation Curve

In LS-DYNA the cohesive elements are represented by MAT_COHESIVE_GENERAL with a Bi-Linear Traction Separation Curve. Table 3 provides the inputs for adhesion and are those correlated in Aggromito et al [1]. The cohesive elements are modelled as zero length solid elements with element formulation 19.

Table 2: Material inputs for MAT_COHESIVE_GENERAL

Parameter	*Input*
σ_{max}	*1.8 MPa*
G	*3000 J/m^2*
K	*5.4E+09*

The glass is modelled with thick shells, element formulation 6 and 5 integration points. Thick shells were used as one node is merged with the adhesion layer and the other node is merged with the adhesive layer back to the vehicle frame. Element deletion was not implemented in the model as the glass does have a limited residual capacity, particularly in compression or in bending, that is paramount to the modelling of post crack performance and predicting the deformed shape of the panel. The softening value applied to the model is 0.2 of the stiffness after failure and 0.15 for the stress after failure, therefore the elastic stiffness at failure is reduced to 20% and the stress is reduced to 15% of its capacity at failure. As there is limited data on the stiffness of laminated glass post fracture these values were chosen through a parametric study to meet the maximum displacements and deflected shape of the full pane tests. The tensile scale factor was set to 2 as values greater than 1 are recommended in the LS-DYNA Manual to capture high impact loading.

4 Windshield Set-up

The windshield set-up is displayed in Figure 3. The head form is modelled with shell elements as MAT_RIGID. The initial velocity and weight of the head-form are massed to meet the required impact energy as per Euro NCAP. The windshield lay-up is as depicted in Figure 1. The windshield is connected to the vehicle frame with an adhesive that is modelled using MAT_PLASTIC_KINEMATIC.

Fig.3: Example Windshield Set-up (some frame components not visible)

5 Results

5.1 Initial Correlation

As presented in Section 3, the material inputs for the PVB and adhesion were taken directly from Aggromito et al [1]. A correlation exercise was undertaken by the authors to tailor the glass inputs for windshield impact testing. As part of this correlation exercise a series of parametric tests were conducted to determine the appropriate inputs for the softening values to achieve the membrane effect of the glass post cracking. An initial analysis was completed with the inputs as provided in Section 3. The results demonstrated less of a membrane effect occurring, recognizing the need for a lower residual strength post glass crack. Figure 4 compares the results of the model validated for blast with the final correlated model inputs for pedestrian impact.

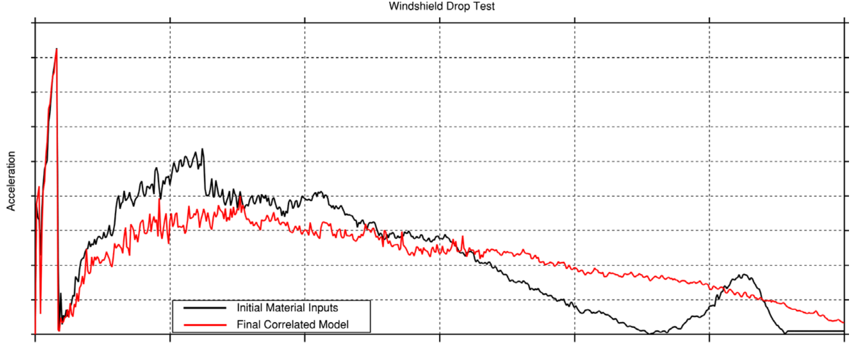

Fig.4: Comparison of the initial inputs for blast with the pedestrian impact inputs

As is demonstrated in Figure 4, post initial cracking, the residual strength is much higher for the “Initial Material Inputs” which leads to less energy absorption as the simulation progresses. In comparison, the “Final Correlated Model” absorbs the impact energy post initial cracking at a steadier rate which correlates well with the test curve in Figure 5. Both stiffness and strength softness values were reduced to achieve the improved correlation.

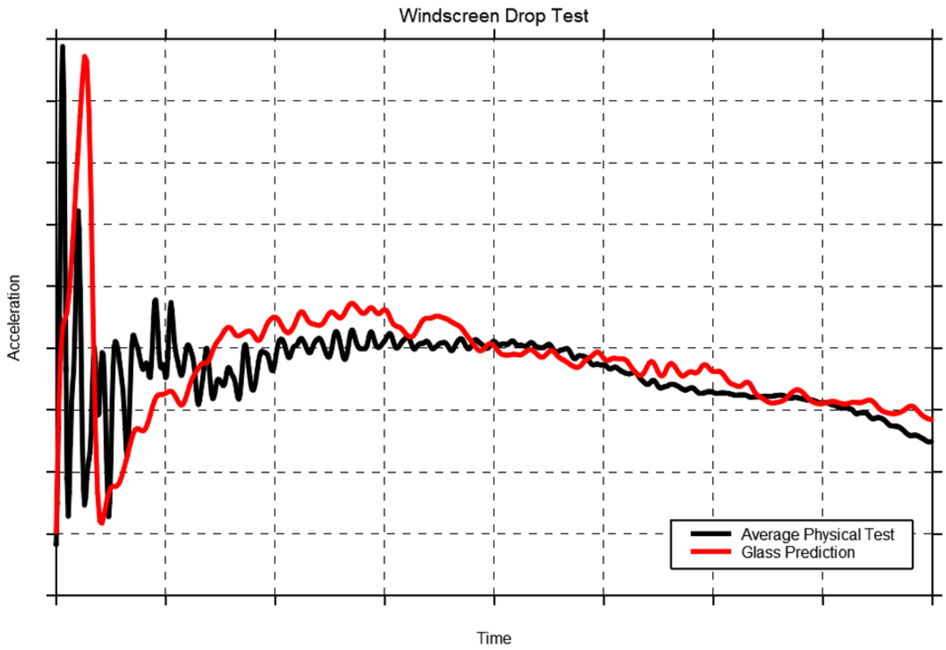

Fig.5: Force Time History Graph for Correlation activities

5.2 Full Vehicle & Deformable Head Testing

Following correlation of the glass material inputs, further testing was completed and compared to the model using a full vehicle and free-flight deformable head form. For such impacts, assuming there is no atypical glass failure, the injury curves often share similar attributes: there will be an initial peak as the head form loads the glass until failure, before dropping steeply back to almost zero, then at larger displacements the membrane effect of the residual glass dominates and a second peak is formed; often of higher magnitude than the first peak, and typically the main driver of the HIC score. Such a curve is sketched in Figure 6.

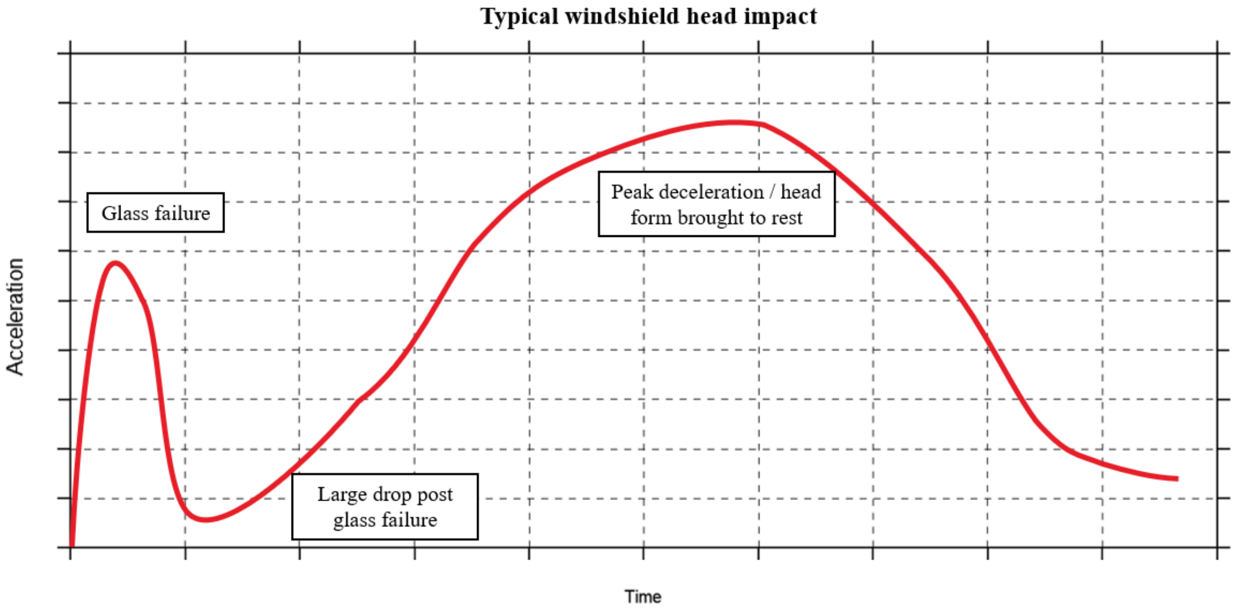

Fig.6: Typical free flight head impact to windshield

By parameterizing the key aspects of the above curve, it is possible to assess the accuracy of the glass model compared to physical test. The following properties were used as shown in Figure 7.

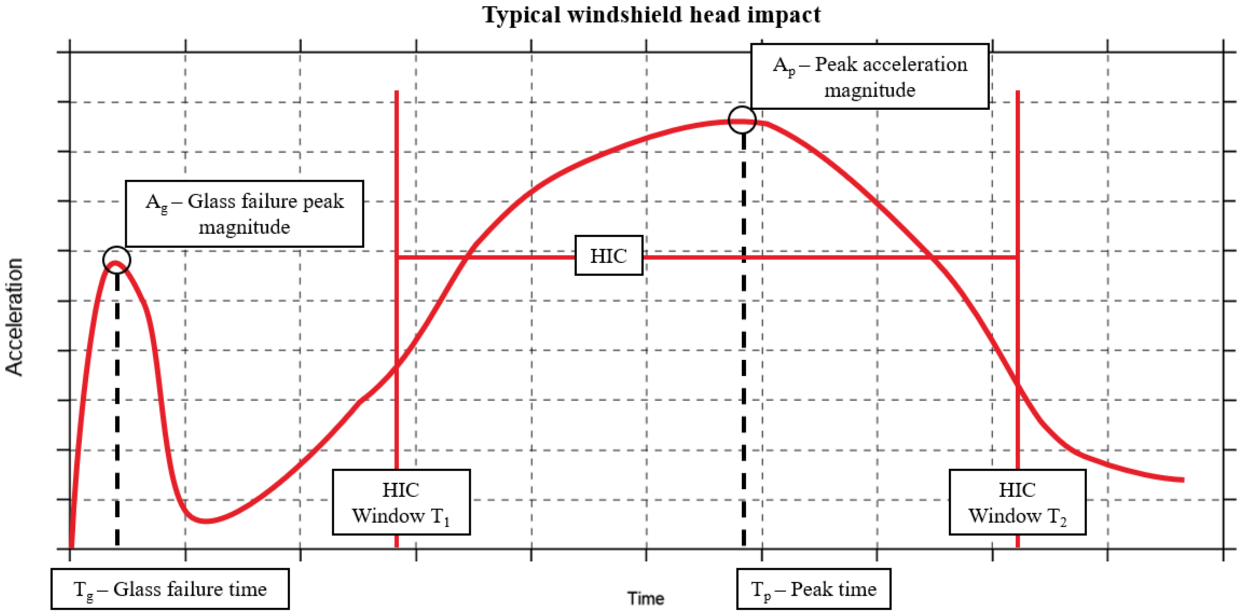

Fig.7: Parameterized head impact injury curve

Table 3 documents the average % difference between LS-DYNA prediction and test for a series of physical tests, impacting different windshield locations and at different test speeds.

Table 3: Comparison of injury curve properties

	Average % Difference	Standard Deviation
A_g	-2%	21%
A_p	-3%	1%
T_g	36%	45%
T_p	-1%	3%
HIC	1%	4%
T_1	-8%	6%
T_2	4%	2%

From the table it can be observed that the model predictions are accurate to +/- 10% for the HIC, HIC timing, peak acceleration and peak acceleration timing. Greater variation was found for the prediction and timing of the glass failure. However, it was observed that while the model produced repeatable predictions the actual physical glass was not as repeatable, with failure strengths varying by as much as 50% test-to-test. Without more repeatable physical behaviour, it is impossible to improve further on the glass failure, and instead correlating to an average target is most appropriate.

5.3 Crack Pattern Comparison

Figure 8 demonstrates a comparison of the crack pattern between the laminated glass model and the test. At the point of impact, significant cracking occurs. As the crack propagates outwards, the model does not fully capture the cracks that propagate at a 45-degree angle out to the 2nd and 3rd rings of cracks, though some mesh independent cracking is observed. It may be possible to improve on this using a cob-web style mesh rather than a quad mesh, however, the model does show good agreement for the circumferential spacing and the extent of cracking. Nevertheless, the crack pattern formed in the windshield when using *MAT_GLASS demonstrates better cracking than if MAT_PLASTIC_KINEMATIC and an erosion criterion is used.

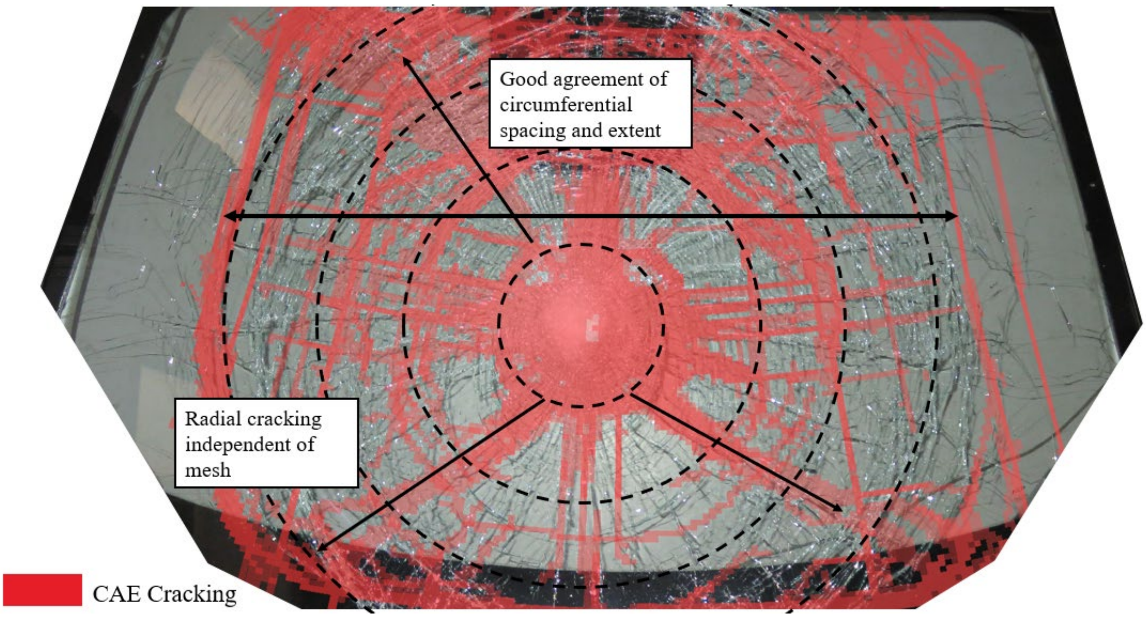

Fig.8: Comparison of Crack Pattern underneath the windshield

6 Conclusion

This paper summarizes the use of a validated laminated glass model for blast to predict pedestrian head impact in accordance with R127 and Euro NCAP. As is demonstrated, with minimal updates, the model shows good agreement with the acceleration time history graphs and can predict the HIC within 10%. Additionally, the model shows reasonable correlation with the crack patterns when compared to the test. Further analysis could be done to refine the model to achieve the cracks that propagate at a 45-degree angle from the center.

7 Literature

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