A numerical model on PVB laminated windshield subjected to headform low-speed impact

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Abstract. Polyvinyl butyral (PVB) laminated windshield is one of the most important components in automotive to protect vulnerable road users. First, a windshield finite element (FE) model is set up using a piece of interlayer (PVB) sandwiched by two glass layers. Four parameters which have a critical impact on the simulation results, i.e. glass Young’s modulus, glass plastic failure strain, PVB stress-strain curve and boundary condition, are suggested to measure the influence on the windshield model. Each windshield model is impacted by a standard headform impactor at the speed of 8\text{m/s} based on the LS-DYNA platform and the results are compared with the dynamic experiments of PVB laminated windshield under headform impact to find the most accurate FE model. Furthermore, the most accurate FE windshield model is compacted by the standard headform impactor on various impact velocities (6.6\text{m/s}-11.2\text{m/s}), angles (60°-90°) compared with the parametric dynamic experiments of PVB laminated windshield to verify the windshield finite element model. This paper provides a useful finite element model of windshield for further systematically numerical studies based on the finite element method to explore the ability of the energy absorption and safety design of PVB laminated windshield.

1. Introduction

Polyvinyl butyral (PVB) laminated windshield is a preferred material for current automotive windshield \cite{1} with a certain extent of impact resistance and energy absorption characteristics. Correlation analysis shows that, the collisions between the head and the windshield is the main cause of the casualties of the vulnerable road users \cite{2}.

Several experimental research and numerical studies have been carried out to investigate the behavior of laminated glass under dynamic loading condition. Series of windshield FE models using different modelling techniques have been set up by Pyttel \cite{3}, Sun \cite{4} and Peng \cite{5}, in order to perform the simulation accurately. Meanwhile, some mono material (e.g. soda-lime glass \cite{6}, PVB \cite{7}) property studies have been carried out. Besides, Wingren \cite{8} obtained the mechanical behavior of windshield in the impact of adult head module through impact test. In addition, Xu et al. \cite{9, 10} compared the energy absorption capabilities of two types windshield, PVB and nanoporous energy absorption system (NEAS) interlayers, and carried out a systematic numerical study based on the

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extended finite element method (XFEM), to investigate the effects of material and system variables on the crack pattern.

However, little experimental data of the materials and the corresponding impact test verification are available for previous numerical studies. Any attempt to accurately simulate the behavior of the laminated windshield could only be reached via proper modelling techniques with the experiment data embedded verified by corresponding impact test, which is our fundamental motivation for this research. In this research, windshield model is set up using a triple-layered structure. Afterwards, parametric studies are conducted to investigate the parameters influence on the FE model. Finally, windshield FE model is verified via comparison with the results of the PVB laminated windshield subject to headform impact test.

2. FE model and method

2.1. Head model

The FE model of pedestrian headform impactor is built according to the requirement of Global Technical Regulation (GTR) [11]. The internal structure of the impactor is simplified using the mass and centroid position equivalence method during the finite element modeling process and calibrated. Dynamic calibration test has been done using the software LS-DYNA, and the results meet the requirements.

2.2. Windshield model

The windshield FE model is developed with shell elements. The layered structure of the laminated windshield is modelled using three shell elements with shared nodes at their boundaries: the outside two shell elements representing the glass layers and the inside shell element representing the PVB interlayer. The FE model is meshed using 2 mm quadrilateral elements with the triangular elements in the central region with the convergence study.

A series of simulations are conducted based on the LS-DYNA platform for different conditions in order to obtain the parameters’ influence on the windshield model. The contact form between head model and windshield apply the surface-to-surface contact with the friction coefficient of 0.3 [10, 12]. Firstly, we vary the glass Young’s modulus, glass plastic failure strain and PVB stress-strain curve according to the data listed in Table 1 respectively, meanwhile other conditions are kept at their reference values shown in Table 2. Afterwards, four boundary conditions, i.e. four edges clamped (FC), four edges simply supported (FS), left and right edges clamped while upper and lower edges simply supported (LR), left and right edges simply supported while upper and lower edges clamped (UD), are set up with other simulation conditions at their reference values.

Table 1. The range of the parameters variation.

| Layer | Variable | Values |
|-------|----------|--------|
| Glass | Young’s modulus of glass | 0.7GPa, 7GPa, 70GPa, 350GPa, 700GPa |
|       | Plastic failure strain of glass | 5×10⁻³, 1×10⁻³, 5×10⁻⁴, 1×10⁻⁴, 5×10⁻⁵ |
|       | Strain rate of stress-strain curve of PVB[7, 13] | 4×10⁻³/s, 2×10⁻³/s, 4×10⁻²/s, 8×10⁻²/s, 118/s |

Table 2. Parameters used in the windshield FE model [10, 14].

| Layer | Variables | Reference parameters |
|-------|-----------|----------------------|
| Glass | Density $\rho_{glass}$ | 2500 kg/m³ |
|       | Young’s modulus $E_{glass}$ | 70 GPa |
|       | Poisson’s ratio $\nu_{glass}$ | 0.227 |
|       | Yield stress $\sigma_{y, glass}$ | 0.143 GPa |
|       | Plastic strain to failure $\epsilon_{f, glass}$ | 0.001 |
|       | Thickness $t_{glass}$ | 0.002 m |
| PVB   | Density $\rho_{PVB}$ | 2000 kg/m³ |
|       | Poisson’s ratio $\nu_{PVB}$ | 0.435 |
|       | Strain rate of strain-stress curve | 118/s |

Global settings | Boundary condition | Clamped |
2.3. Model verification

Further simulations are conducted to verify the windshield FE model with the dynamic experiments of PVB laminated windshield under headform impact. The head module impact windshield experimental system consists of seven parts, i.e. pedestrian crash test launcher, the windshield gantry system, high-speed photography system, dual photoelectric speedometer, windshield specimen, adult head module, acceleration sensor and buffer system shown in Figure 1.

![Figure 1. The experimental system schematic diagram.](image)

The headform impact velocities and angles are set to be 6.6m/s-11.2m/s and 60°-90° respectively according to real-world vehicle pedestrian accidents in Tsinghua University traffic accident cases database. A total of 8 experiments are conducted shown in Table 3. The simulations using the most accurate windshield model above-obtained are conducted according to the settings in Table 3 to verify the windshield FE model.

| NO. | Impact angle (°) | Impact velocity (m/s) |
|-----|------------------|-----------------------|
| 1   | 90               | 6.6                   |
| 2   | 90               | 8.1                   |
| 3   | 90               | 8.8                   |
| 4   | 90               | 11.2                  |
| 5   | 90               | 8.1                   |
| 6   | 80               | 8.2                   |
| 7   | 71               | 8.2                   |
| 8   | 59               | 8.2                   |

3. Results and discussions

3.1. Effect of glass Young’s modulus
Figure 2 shows the acceleration-time curves of different glass Young’s modulus compared with the corresponding test results. When the glass Young’s modulus is set to 700MPa and 7GPa, the windshield does not crack and the acceleration trends are different from the experimental results. Once the glass Young’s modulus rises beyond 70GPa, the cracks initiated and the crack intensity becomes higher with the Young’s modulus. When the glass Young’s modulus is set to 70GPa, simulation and experimental results of acceleration curve are closer. Regardless of cracks, head model acceleration increases with increasing glass Young’s modulus.

With the glass Young's modulus increasing, the windshield becomes stiffer, so the peak acceleration becomes larger correspondingly. Since the yield stress and plastic failure strain fixed, the failure strain becomes smaller and cracks easier to generate with the increasing glass Yield stress.

3.2. Effect of plastic failure strain
Figure 3 shows the acceleration-time curves of different plastic failure strain compared with the corresponding test results. With the plastic failure strain increasing, the acceleration does not change...
obviously. As the plastic failure strain decreasing, the cracks become more intensive. When the plastic failure strain is set to $1 \times 10^{-3}$ and $5 \times 10^{-4}$, simulation and experimental results agree better.

Due to the yield stress and the Young’s modulus fixed, the failure stress becomes smaller with the plastic failure strain decreasing. The cracks become more intensive for the cracks initiation being more easily.

3.3. Effect of PVB stress-strain curve
Figure 4 shows the acceleration-time curves of different PVB stress-strain curves compared with the corresponding test results. Compared with the application of dynamic stress-strain curve, the second acceleration peak is not obvious when the quasi-static stress-strain curves are employed. When we apply quasi-static stress-strain curves with different strain rate, the obtained acceleration curves are not very different. Besides, simulation and experimental results of acceleration curve are closer when we apply the dynamic stress-strain curve.

From the quasi-static and dynamic tensile test results of the specimens, we can see that the PVB materials exhibit different tensile characteristics in dynamic and quasi-static loads [7]. Besides, the impact process itself is a dynamic process. Therefore, the results obtained by the application of dynamic tensile test curve are more in line with the actual situation.

3.4. Effect of boundary condition
Figure 5 shows the acceleration-time curves under different boundary conditions compared with the corresponding test results. With FC and FS boundary conditions, the obtained acceleration curves are almost the same. However, the second acceleration peak is not stable with LR and UD boundary conditions. This shows that, boundary conditions only have little influence. So the FC boundary condition is selected in line with the real situation.
3.5. Model verification

Figure 6 shows the obtained acceleration-time curves from the simulations according to Table 3 compared with the corresponding results for further verification. We can see that the peak values as well as the entire time course of the simulation fit well with the corresponding impact test results with different impact velocities and impact angles.

Figure 6. Acceleration-time curves of different impact velocities and angles compared with the corresponding test results for further verification.

Figure 7 shows the comparison of crack propagation patterns for the simulation results and the test results with the velocity of 8 m/s at the vertical impact. The crack propagation patterns obtained from the impact test are captured by high-speed cameras [15]. In the beginning of the impact, radial cracks first appear on the windshield panel to release the hoop stress, for the hoop stress is much larger than the radial stress [16]. Circular cracks begin to appear approximately within 1 second and expand from the inside outward consistent with the initial propagation direction of the stress wave concurred with the literature findings [17, 18]. The simulation results are in good agreement with the experimental results.

Figure 7. Comparison of crack propagation patterns for the simulation results and the test results with the velocity of 8 m/s at the vertical impact.

4. Conclusion

In this paper, windshield with laminated structure is setup and a series of simulations under different conditions are conducted to obtain the parameter’s influence on the windshield model such that a finite element model is suggested with proper parameter settings. Values of parameters in Table 2 can best predict the test acceleration curve. This study provides a solid step for systematic numerical studies on windshield dynamics subject to head impact in the future.
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