Improvement of windshield laminated glass model for finite element simulation of head-to-windshield impacts

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Abstract. The automotive windshield, with which pedestrians come into frequent contact during car accidents, has been identified as one of the main sources for severe pedestrian head injuries. Finite element simulation of head-to-windshield is widely used for the design and evaluation of car safety performance. Most of the windshield models used in the simulations for pedestrian head injury studies are simplified model. However, accurate modelling of windshield mechanical behaviour is necessary for good prediction of head injury during car-to-pedestrian collision. The purpose of this paper is to improve the model of automobile windshield for simulation of a collision between a pedestrian and a car. The laminated glass windshields of various thickness were tested according to UNECE R43. The deformation and crack pattern were recorded for validation of the finite element model. The finite element models of two layers and three layers laminate glass were developed. Element deletion method and share node techniques were employed for crack propagation pattern. Appropriate mesh size and shaped were obtained. The simulation results were compared with the experimental results of ball drop tests. The simulation results of the laminated glass model with two layers, 1mm-triangle mesh shows good agreement with the experimental results. This laminated glass model was then implemented to the windshield of the car. Simulation of headform impact tests according to the EEVC protocol on pedestrian protection were performed. The results in terms of head deceleration, crack pattern and windshield energy absorption were compared with the test results. Good agreement can be seen.

1. Introduction
Almost half of all fatality in the world’s road accident involves motorcyclists, cyclists and pedestrians [1]. The accident of vehicle-pedestrian collisions has been identified as one of the main reasons for severe pedestrian head injuries causing life-long disability or death [2].

Windshield protection and performance under head impact during a collision are legal requirements for the manufacturers. The safety glass for automobile windshields must follow UNECE R43 [3]. It requires a ball drop test and headform impact at various heights, to evaluate penetration, failure resistance and break pattern. The European New Car Assessment Program (Euro NCAP) [4] require headform impact tests to verify that the windshield assembly is less dangerous for pedestrians.

However, the automobile windshield models used in the simulations are all laminated glass components which are complex composite materials consisting of glass, polymer foils and adhesives (Polyvinyl butyral or PVB). Numerical models for windshield are not predictive with respect to
analysing their deformation and failure under impact loading conditions. The windshield model must be able to predict the initial failure of the laminated glass and the crack propagation. For the improvement of the predictability for windshield, the behaviour of glass was studied using finite element modelling. The glass is modelled as a linear elastic material. Once the principle strain reaches a critical value, the glass fails and the interlayer is carried loads. The PVB-interlayer is modelled as a hyper-elastic material [5-7].

The object of the study is to improve predictive capabilities of windshield model by including crack propagation. This is to enhance accuracy of pedestrian-to-car collision simulation. This paper first addresses laminated glass impact tests based on UNECE R43 [3]. The finite element model of laminated glass was developed and compared with experiment tests for validation. The laminated glass model was then employed for headform-to-windshield impact test according to EEVC test protocol [8].

2. Laminated glass impact tests
The laminated glass specimens of 300 mm × 300 mm with two different thicknesses were prepared for rigid ball drop tests as shown in figure 1. The specimen was placed between a steel frame and a rubber frame. The steel box was used as a base structure. The ball/impactor is made of steel with a diameter of 82 mm and has a mass of 2.26 kg in free motion as shown in figure 1. High speed camera was set up to record crack patterns. The test conditions and specimen thickness are illustrated in table 1.

![Figure 1. Ball-laminated glass experiment setup.](image)

| Test number | Drop height (m) | Thickness of layers (mm) | Total | Glass | PVB |
|-------------|----------------|--------------------------|-------|-------|-----|
| 1           | 2              | 6.18                     | 2.90  | 0.38  |
| 2           | 4              | 6.40                     | 2.82  | 0.76  |
| 3           | 2              | 8.14                     | 3.88  | 0.38  |

The glass maximum deflections were measured together with the impact positions. The results of the experiment of the laminated glass-ball impact are shown in the table 2. Test number 1 and 3 were tested at the same drop height but with different specimen thickness. The thicker specimen in test no. 1 reveals larger deflection compared with the one on test no. 3. The ball penetrated the specimens for both tests. Different maximum deflections can be seen for the same thickness specimens but with different drop height as shown in test no. 1 and 2. The ball did not penetrate the specimen in test no. 3 due to the lower drop height. The crack patterns are also shown in table 2. The experimental results will be used to validate the finite element model of laminated glass developed in the next section.
Table 2. Experiment result of the ball impact test.

| Type               | Experiment No. 1 | Experiment No. 2 | Experiment No. 3 |
|--------------------|------------------|------------------|------------------|
| Final crack        | Penetrated       | Penetrated       | Not penetrated   |
| Final condition    |                  |                  |                  |
| Impact position x, y (mm) | 127, 176         | 93, 125          | 174, 165         |
| Maximum deflection (mm) | 34.30            | 39.70            | 22.66            |

3. Development of laminated glass impact model

Two and three layers laminated glass models were created as shown in figure 2. The two-layer model consisted of Glass-PVB whereas three-layer model consisted of Glass-PVB-Glass. The glass behaviour was modelled using *MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY and PVB behaviour was modelled using *MAT_PIECEWISE_LINEAR_PLASTICITY in LSDYNA [9] with material properties taken from a typical car windshield model [10] as summarized in table 3. Adhesion between glass layer and PVB later was modelled using the shared node technique [11]. This technique assumes that the glass layer and the PVB layer are perfectly bonded to each other and there are no relative displacements between glass and PVB. The crack characteristic was modelled using the Element Deletion Method (EDM) which is also known as the erosion contact method. The basic idea of this method is to remove the mass elements of the global mass matrix to represent the failure of these elements. This method has been implemented in the LS-Dyna software.

![Figure 2. Two- and three-layers shell elements of laminated glass.](image)

Table 3. Material properties [10].

| Part     | Young Modulus (GPa) | Density (kg/m³) | Poisson’s ratio | Plastic Strain at Failure |
|----------|---------------------|-----------------|-----------------|---------------------------|
| Glass    | 70.0                | 2.500           | 0.22            | 0.001                     |
| PVB      | 2.5                 | 1.000           | 0.35            | 2.5                       |

The laminated glass impact test was set up as shown in figure 3. The ball with 2.26 kg mass was model as rigid. Initial impact velocity corresponding to each drop height was assigned to the ball. All degree of freedom at 4 edges of specimen are fixed. The contact between ball and laminated glass was designed with a friction coefficient of 0.
4. Mesh sensitivity study and model validation

The finite element simulations of test no. 2 were conducted with triangular and rectangular mesh. Each shape varied in sizes of 1 mm, 2 mm, 3 mm, 4 mm and 5 mm. In addition, all set up condition were performed for both two-layer and three-layer laminated glass models. The baseline windshield laminate glass model was also simulated for comparison. Total of 22 simulations were performed.

The crack pattern results of different mesh shape and size for two-layer and three-layer model are shown in figure 4 and 5 respectively. The crack characteristic was measured using the circular patterns as shown in figure 4 and 5. The circle diameters, maximum deflection, energy absorption obtained from various mesh sizes and shapes for two-layer and three-layer models are illustrated in table 4.

| Experiment 2 | Triangular mesh 1mm | Triangular mesh 2mm | Triangular mesh 3mm | Triangular mesh 4mm | Triangular mesh 5mm |
|--------------|----------------------|---------------------|---------------------|---------------------|---------------------|
| Benchmark    | Rectangular mesh 1mm | Rectangle mesh 2mm  | Rectangle mesh 3mm  | Rectangle mesh 4mm  | Rectangle mesh 5mm  |

Figure 4. Comparison of crack pattern results between triangular and rectangular shape for two-layer laminated glass model.

| Experiment 2 | Triangle Mesh 1 mm | Triangle Mesh 2 mm | Triangle Mesh 3 mm | Triangle Mesh 4 mm | Triangle Mesh 5 mm |
|--------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| Benchmark    | Rectangle Mesh 1 mm| Rectangle Mesh 2 mm| Rectangle Mesh 3 mm| Rectangle Mesh 4 mm| Rectangle Mesh 6 mm|

Figure 5. Comparison of crack pattern results between triangular and rectangular shape for three-layer laminated glass model.
From the simulation results in table 4, it was found that the triangle mesh gives better comparison with the experiment than the rectangle mesh for both two-layer and three-layer models. Smaller mesh size gives closer deflection and final crack patterns to the experimental results. It is also found that the maximum deflection and crack patterns obtained from the two-layer model compared better with the experimental results for all mesh sizes and shapes. The triangular shape of size 1 mm had the highest validation of 97.45%. Circular pattern of C1 was 96.20%, C2 was 98.21%. The predictive capability of the laminated glass model has been improved when comparing with results from the baseline laminate glass model without crack propagation. 21.5% improved in the maximum deflection. The energy absorption is higher than that obtained from the baseline model.

However, the results from the triangular shape of 1 mm were closest to that of the experiment. Reduction in mesh size resulted in an increase of the number of elements and therefore long simulation time. Triangular shape of 1 mm simulation time was 350 minutes whereas the mesh size of 5 mm took only 5 minutes. This project will select the triangular shape of 5 mm for improving the automobile windshield. This can save duration of simulation by 70 times with an accuracy of 93.97%. The difference in maximum deflection between 1 mm and 5 mm triangular shape is only 3.5%.

### Table 4. FE simulation results of mesh sensitivity.

| Type and size of mesh       | Maximum deflection (mm) | Energy absorption (J) | Circular Diameter of 2L (mm) | Circular Diameter of 3L (mm) |
|-----------------------------|-------------------------|-----------------------|-----------------------------|-----------------------------|
|                             | 2L<sup>a</sup> | 3L<sup>b</sup> | 2L | 3L | C1<sup>c</sup> | C2<sup>d</sup> | C1 | C2 |
| Experiment 2                | - | 39.70 | - | - | - | - | 71.00 | 123.00 |
| Benchmark                   | 30.37 | 25.02 | 137.21 | 119.05 | - | - | - | - |
| Triangle Mesh 1 mm          | 38.69 | 36.71 | 170.87 | 162.18 | 73.70 | 125.20 | 76.35 | 148.00 |
| Triangle Mesh 2 mm          | 38.08 | 34.58 | 172.81 | 162.47 | 64.08 | 143.46 | 74.71 | 148.10 |
| Triangle Mesh 3 mm          | 37.70 | 33.91 | 168.37 | 158.62 | 73.60 | 119.50 | 48.72 | 141.70 |
| Triangle Mesh 4 mm          | 37.60 | 32.22 | 164.89 | 154.24 | 59.45 | 117.60 | 65.00 | 136.10 |
| Triangle Mesh 5 mm          | 37.31 | 32.86 | 160.71 | 156.36 | 69.60 | 124.40 | 54.40 | 155.60 |
| Rectangle Mesh 1 mm         | 36.56 | 33.51 | 159.35 | 143.44 | 66.34 | - | 71.08 | - |
| Rectangle Mesh 2 mm         | 35.15 | 31.17 | 148.54 | 134.66 | 66.00 | 126.58 | 50.65 | 109.47 |
| Rectangle Mesh 3 mm         | 35.17 | 31.22 | 143.30 | 134.81 | 71.10 | - | 64.47 | - |
| Rectangle Mesh 4 mm         | 35.78 | 30.36 | 142.58 | 132.22 | 89.52 | - | 73.00 | - |
| Rectangle Mesh 5 mm         | 36.69 | 30.76 | 140.20 | 131.95 | 58.50 | 120.55 | 72.75 | - |

<sup>a</sup>2L is 2 layers  
<sup>b</sup>3L is 3 layers  
<sup>c</sup>C1 for the first circular pattern  
<sup>d</sup>C2 for the second circular pattern

The laminate glass model with 5 mm triangle mesh was also validated with experiment test no. 1 and no. 3. Comparisons of maximum deflection and crack patterns are shown in table 5. Reasonable agreement can be seen.
Table 5. FE simulation two layer of triangular 5 mm result

| Experiment | Final crack | Maximum deflection (mm) |
|------------|-------------|-------------------------|
|            | Test        | Simulation              |
| No. 1      | 34.30       | 32.69                   |
| No. 3      | 22.66       | 28.03                   |

5. Development of headform-to-windshield impact test

5.1. Headform-to-windshield impact model set-up

The two-layer laminated glass model with triangle mesh of 5 mm validated in the previous section was adopted to model the car windshield. The headform of 4.8 kg mass was modelled according to EEVC test protocol [5]. An accelerometer was attached at the C.G. of the headform to measure the linear acceleration. Figure 6 shows the setup of headform-to-windshield impact simulation. All edges of windshield were fixed in all direction. Headform initial velocity was 11.1 m/s. It impacted at the middle of the windshield.

Figure 6. Windshield-headform impact simulation setup.

5.2. Validation results

The comparison of final crack pattern between the test [12] and the simulation are shown in figure 7. The result in term of headform’s linear acceleration between the simulation and the test is presented in graph shown in figure 8. Overall, the results of the simulation showed good agreement with the result from the test. When the headform impacted the windshield in the centre position, the maximum value of headform’s linear acceleration from the simulation was lower than the test results. The value in the test was 1,190 m/s² and the simulation was 1,100 m/s² with a validation of 92.44%. The overall picture’s trend also showed good agreement with the test result.
Figure 7. Final crack pattern of windshield between (a) test and (b) simulation.

Figure 8. Comparison of headform’s linear acceleration between the test and simulation.

6. Conclusion
Laminated glass models were set up in combinations of glass and PVB with different mesh shapes, mesh sizes and number of layers based on the LS-DYNA code. Adhesion between glass and PVB was modelled using shared node technique. Element deletion method was employed to include crack behaviour. Mesh sensitivity analysis was conducted. The results indicated that the triangular shape, size 1 mm model is the most accurate in representing a laminated glass. The laminated glass impact simulation shows good agreement with experimental result. Laminated glass model was employed for headform impact test. The simulation result was compared with experimental results. Good agreement of the head acceleration and crack pattern is revealed. Based on these results, vehicle designers should consider the design of the windshield for improvement in pedestrian protection.

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