# Application of Crack Propagation Simulation of Windshield to Roof Strength Analysis

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## Abstract

*This paper describes a new modeling method to represent the crack propagation of windshield, namely the laminated safety glass. In the roof strength analysis used for vehicle development process, it is not easy to accurately predict crack propagation paths with existing modeling method, e.g., improving material properties. If the windshield cracks in a test using a prototype vehicle, the body deformation in the simulation and that in the test might not match, resulting in a less accurate simulation of force transfer to vehicle frames through the windshield. Therefore, prediction of crack propagation in a windshield is significant in accurately estimating the deformation and improving the accuracy of roof strength simulation results.*

*The new modeling method to represent the crack propagation of the windshield was applied using tied overlapping shell technique, one of the modeling methods for material fracture, which has been developed by Kojima et al. The tied overlapping shell technique consists of element groups made of base elements and overlapping elements which are rotated 45 degrees in the normal direction. The base and the overlapping elements are connected using tied contact. The physical laminated safety glass windshield is constructed by placing an adhesive polyvinyl butyral (PVB) interlayer between two glass panes, outer glass and inner glass. In this study, double overlapping shell parts and a PVB interlayer part were applied to a windshield model to represent the crack propagation of the glass. Consequently the model has three layers with five mesh plates. Each part is modeled with shell elements and positioned corresponding to the neutral location of each layer thickness respectively. Four-point bending tests using specimens cut out of windshield glass were carried out to determine the critical fracture strain of glass considering the loading mode in roof strength analysis. Thereafter, application of the windshield glass model developed in this study to a roof strength analysis model was carried out to validate against test data.*

*This paper summarized the application of new modeling method to represent the crack propagation of windshield glass in a roof strength analysis. It was found that the first two cracks propagation and the maximum force of the roof strength could be simulated. In the model the first two cracks propagated in the same shape as seen in the test. However, the number of crack propagation paths observed in the simulation was just two while there were many crack paths observed in the test. In addition, the difference in the maximum force of the roof strength between in the simulation and in the test was approximately 1%. However, after the cracks occurred, the force dropped more rapidly in the simulation than in the test. With this consideration there may be room for correction of the elimination methods.*

# 1. Introduction

In the last several years, CAE has been used heavily in vehicle development. The objective of the application of crash analysis to vehicle development is a detailed understanding of the deformation and the load transfer of a complex vehicle structure under various loading patterns for safety evaluation.

This paper describes the modeling method to represent the fracture of windshield glass to help predict the stiffness of the vehicle. It has been generally well known that laminated safety glass windshields have a contribution to the overall stiffness of the vehicle. Mao et al.(2005) evaluated a roof crush model has some differences between the simulation and the real test as the windshield model does not offer accurate representation. The laminated safety glass model with three layers (shell/volume/shell) has been developed by Sun et al.(2005). The critical fracture strain of glass was determined from static bending tests. It was found that the fracture load varies depending on the element size of the model simulating the component test.

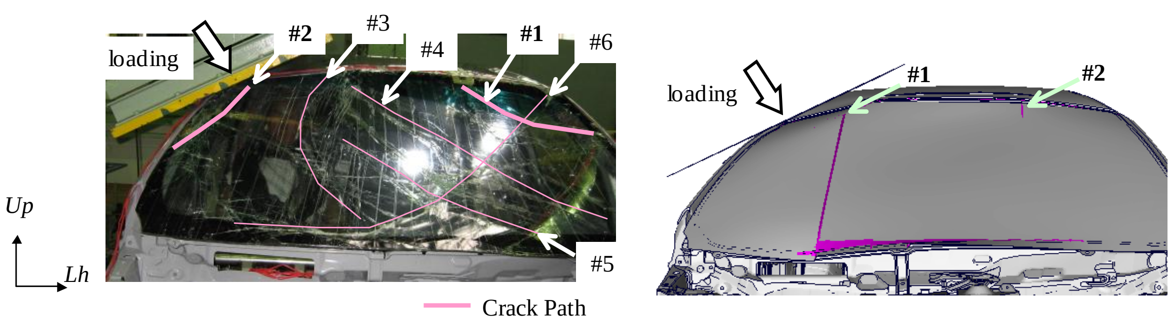
# 2. Motivation of This Study

## 2.1 Technical Issues of Roof Strength Analysis

Two major technical issues are observed in a roof strength analysis using the glass model, which has been previously developed. The practical example used for this study is a mid-size passenger vehicle model. These issues are listed as below:

・Representation of glass crack propagation paths (Fig. 1) .

・Accuracy of the force acting on the loading device at cracks starting time (Fig. 2).




(a) Test (b) Simulation

Figure 1. Comparison of glass crack propagation paths after roof strength test between test and numerical simulation.

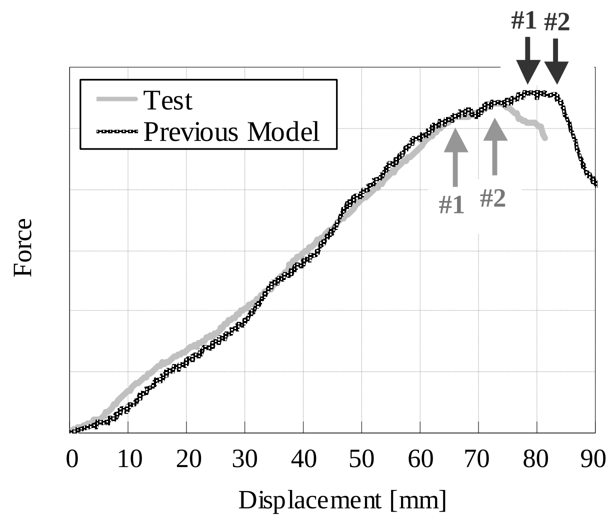



Figure 2. Comparison of force versus displacement during roof strength test between test and numerical simulation.

The laminated safety glass has been modeled using mainly quadrilateral elements with about 5 mm mesh size. The critical fracture strain of the glass was determined from results by means of ring-on-ring tests used extensively for strength measurements on glasses.

## 2.2 Objective of This Study

The objective of this study is twofold considering above issues as follows; (1) to establish a modeling method of laminated safety glass windshield to simulate the crack propagation (2) to improve the accuracy of predicting the roof strength.
A nonlinear dynamic analysis solver LS-DYNA® Ver.971 was used for this study.

# 3. Method

## 3.1 Modeling Method

### 3.1.1 Application of the Tied Overlapping Shell Technique to Windshield

The tied overlapping shell technique, one of the modeling methods for material fracture, has been developed by Kojima et al.(2012). The technique has been suggested in order to decrease mesh pattern dependency in simulating the crack propagation. The tied overlapping shell technique consists of element groups made of base elements and overlapping elements which are rotated 45 degrees around the normal direction as shown in Fig. 3. The base and the overlapping elements are connected with tied contact on one plate.

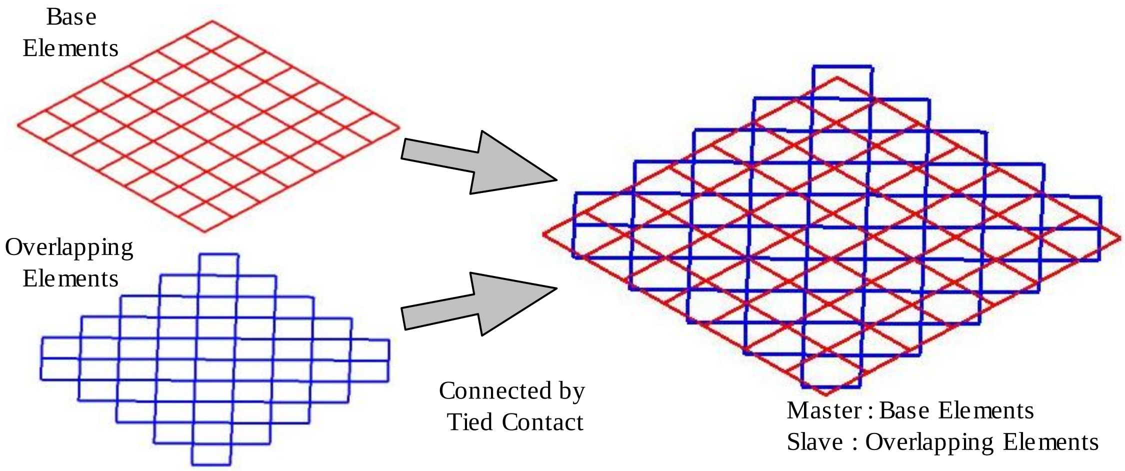



Figure 3. Tied overlapping shell technique.

The physical laminated safety glass windshield is constructed by placing an adhesive polyvinyl butyral (PVB) interlayer between two glass panes, outer glass and inner glass. In this study, double overlapping shell parts and a PVB interlayer part were applied to a windshield model. Consequently, the model has three layers with five mesh plates as shown in Fig. 4. Each part is modeled with shell elements considering a strain at fracture as erosion criterion, i.e. failed elements are deleted from further computation. Each part is positioned corresponding to the neutral location of each layer thickness respectively. *CONTACT_TIED_SHELL_EDGE_TO_SURFACE_BEAM_OFFSET is used to connect each part.

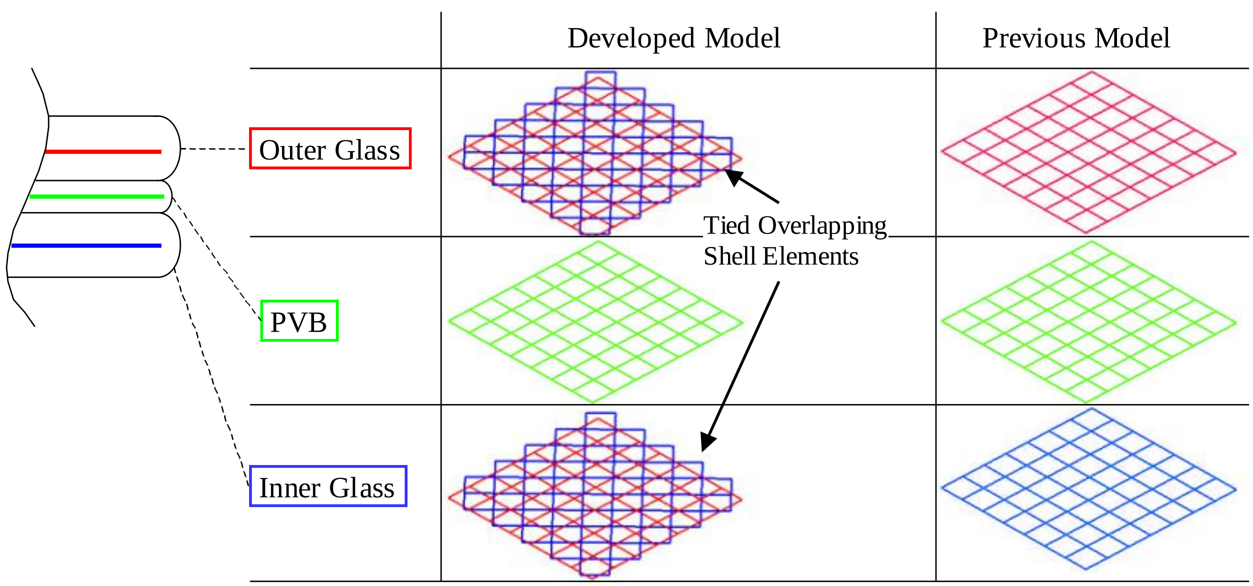



Figure 4. Comparison of laminated safety glass model.

### 3.1.2 Identification of Critical Fracture Strain

In the roof strength test of a mid size passenger vehicle, the moment on the edge of the windshield glass was loaded according to the bending deformation of the front header (Fig. 5). Four-point bending tests shown in Fig. 6(a) were carried out considering the deformation mode during this roof strength test. Specimens were cut out of vehicle windshield glass in 100 mm x 100 mm sizes, and loaded with a speed of 1mm/min by two upper rods. Fig. 7 shows the result of 95 tests with previous results in ring on ring tests (Fig. 6(b)) as comparative reference. The average of these tests was used as the fracture strain in simulations. It was found that the fracture strain in four point bending tests was approximately 40% lower than that in ring on ring tests.

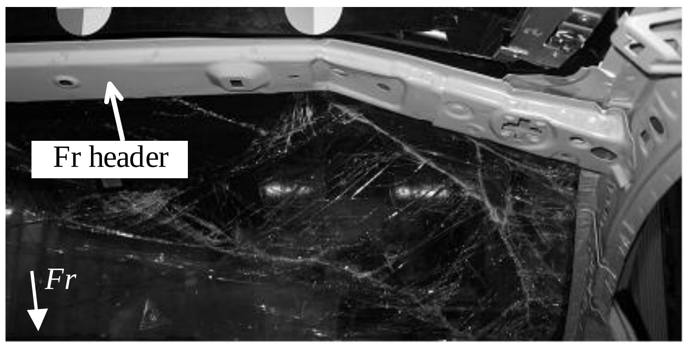
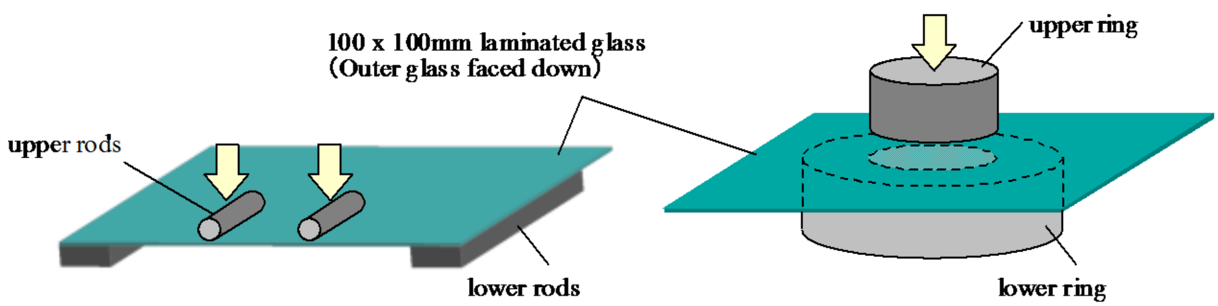



Figure 5. Inside view around front header after test.




(a) Four-point bending test (b) Ring on ring test

Figure 6. Comparison of test methods.

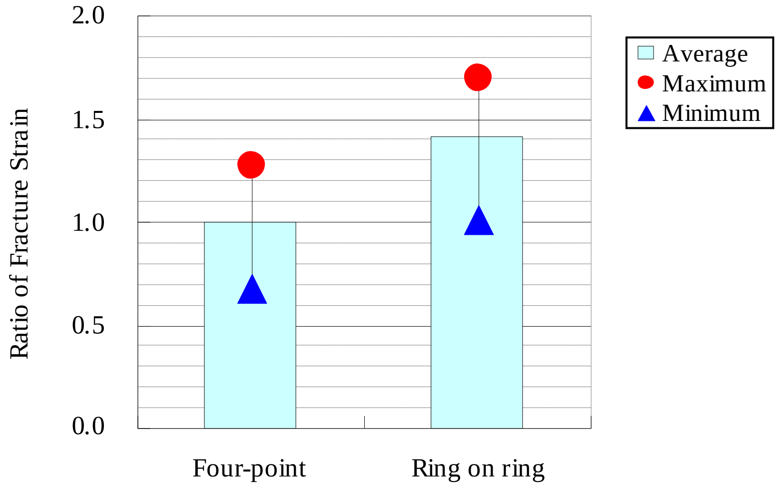



Figure 7. Comparison of fracture strain between edge and in-surface.

## 3.2 Application to Vehicle Model

Application of the windshield glass model developed in this study to a full roof strength analysis model was carried out to validate the glass model. A mid-size passenger vehicle model was used for the validation (Fig. 8). The windshield model was connected to body-in-white with an adhesive solid model using *CONTACT_TIED_SHELL_EDGE_TO_SURFACE_BEAM _OFFSET. Mesh size in this model was about 5 mm. The loading plate was modeled as a rigid wall which loaded the vehicle with a velocity of 1000 mm / sec using *BOUNDARY _PRESCRIBED_MOTION. The other boundary conditions were set up according to FMVSS216 test protocol.

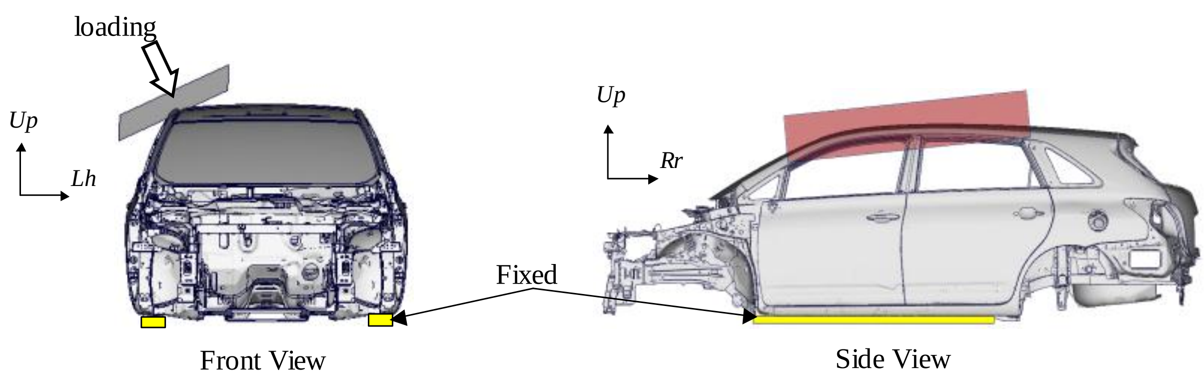
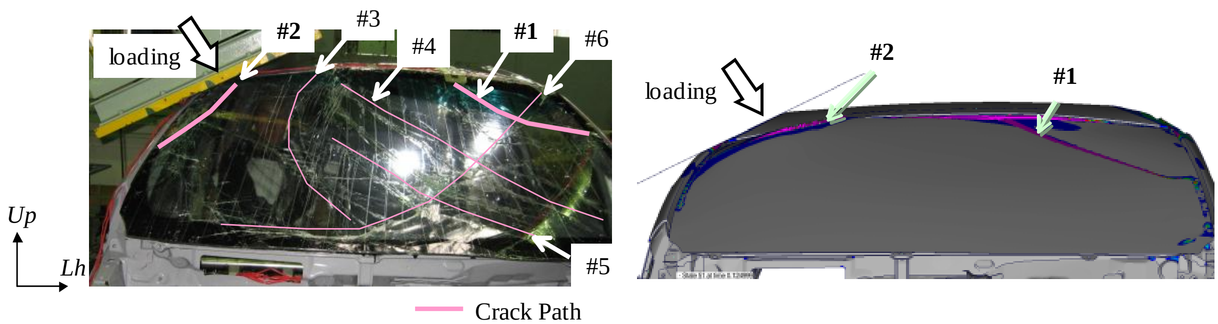



Figure 8. Roof strength model boundary condition.

# 4. Results

## 4.1 Comparison of Crack Propagation Paths in Windshield

Initially, the crack propagation paths in this windshield glass model were validated in comparison with experimental results. The first crack path #1 occurred at 65 mm of platen displacement corresponding to the timing that bending deformations of the front header began, and the second crack path #2 occurred at 73 mm of platen displacement. These cracks continued propagating in the model following the same shape as the test (Fig. 9). However, the number of crack propagation paths in the simulation was just two while there were many crack paths observed in the test.




(a) Test (b) Simulation

Figure 9. Comparison of glass crack propagation paths after roof strength test between test and numerical simulation.

## 4.2 Comparison of Force-Displacement Curves

In Fig. 10, the resulting force acting on the loading plate is plotted versus displacement for the simulation and the test in the same conditions. For this load case, the difference in the maximum force between the two is approximately 1%, and both curves follow the same shape until 73 mm displacement. After cracks #1 & #2 occur, the force dropped more rapidly in the simulation than in the test.

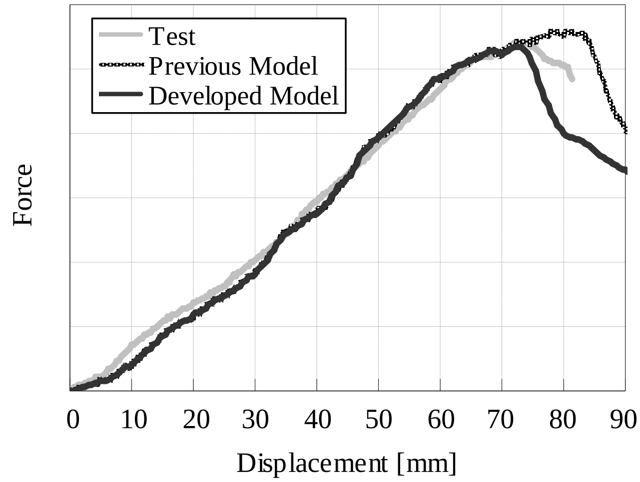



Figure 10. Comparison of force versus displacement during roof strength test between test and numerical simulation.

## 5. Discussion

As described in section 4, the crack path #1 at 65 mm and the crack path #2 at 73mm could be successfully replicated by the use of the laminated safety glass windshield model developed in this study. Moreover, the maximum force at 73 mm in roof strength analysis could be closely predicted. However, the additional crack paths were not represented in the simulation. In addition, after 73 mm displacement, the device force drops more rapidly in the simulation than the test. In Fig. 11, the windshield force is plotted versus displacement for the simulation. It was found that the windshield force drops rapidly, also. These reasons are described in the following.

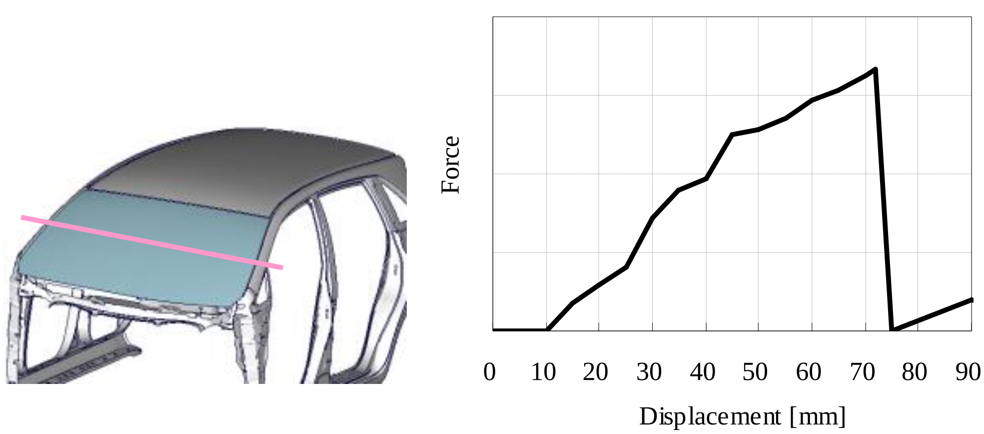



Figure 11. Windshield force versus displacement (simulation).

The cross sections of windshield under bending in three states: initial state, critical state, and after crack state, are schematically illustrated in Fig.12. The stress level in the glass is represented by color levels. In the initial and critical states, stress levels are similar between test and numerical simulation. However, after crack initiation, the calculated stress level around the crack area may be different from that in test. The stress level does not decrease dramatically in test because the fractured pieces of glass become in contact with the surrounding glass. On the other hand, in the numerical simulation the stress level decreases because fracture elements are eliminated. Based on these mechanisms, there could be a difference in the number of glass crack propagation paths and force level after cracks occur. Therefore, to simulate the subsequent cracks, further modeling study is necessary.

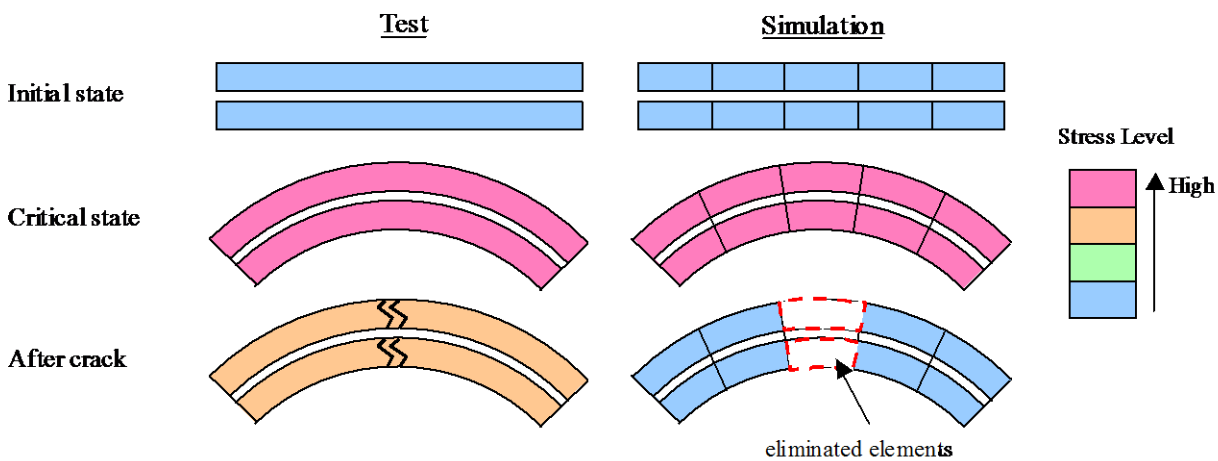



Figure 12. Schematic cross section of windshield under bending in three states.

## 6. Conclusion

The tied overlapping shell technique was applied to the windshield model in roof strength analysis. The critical fracture strain of windshield element was determined using results of many glass bending tests considering scatter. The model with the technique could simulate the crack initiation and the maximum force. The calculated force after crack in simulation, however, is lower than in the test. There may be room for correction in elimination methods.

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