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# Study of the Dynamic Response of Human Skull Impact on Laminated Automotive Glazing

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# Study of the Dynamic Response of Human Skull Impact on Laminated Automotive Glazing

## ABSTRACT

During vehicle accident, occupants head impacting on windshield or side window is commonly observed. It is estimated that over 40,000 people are killed annually in vehicle related accidents in the United States. Use of laminated glass which consists of two soda lime glass plies adhered by a polyvinyl butyryl (PVB) interlayer on automotive windshields and side windows can reduce the possibility of body injury and property damage caused by flying glass fragments. Most of the previous work on laminated glass under head impact has primarily concerned the dynamic response of head rather than the laminated glazing. Any attempt to design glazing that minimizes injury to and death of occupants during a vehicle accident requires a thorough understanding of the mechanical behavior of automotive glazing subjected to head impact loads.

A 3-D nonlinear dynamic finite element model is developed to study the dynamic response of a laminated glazing subjected to simulated head impact. An analytical solution based on the large-deflection plate theory is presented to compare with the FEA result. The crack initiation time and location are determined using a finite element method based on the energy release rate criterion ($J$-integral criterion). A constitutive model based on the continuum damage mechanics (CDM) is employed and implemented into the finite element model to study the failure and impact resistance of laminated automotive glazing. The damage patterns and zone size are predicted. The CDM based constitutive model has been extended to investigate the failure behavior of a laminated architectural glazing subjected to blast loading.

## Notations:

| | |
|---|---|
| a | glass panel length (m) |
| b | glass panel width (m) |
| E | Young's modulus (MPa) |
| Go | Short time shear modulus (MPa) |
| Gω | long time shear modulus (MPa) |
| G(t) | Stress relaxation modulus (MPa) |
| h | total thickness of glass panel (m) |
| hi | impact side glass ply thickness (m) |
| ho | non-impact side glass ply thickness (m) |
| hp | PVB thickness (m) |
| hs | skin thickness (m) |
| K | bulk modulus (MPa) |
| Ks | spring constant for the plate |
| P(t) | surface pressure (MPa) |
| P | contact force (N) |
| Po | maximum contact force (N) |
| Ro | maximum radius of contact area (m) |
| R | radius of aluminum skull (m) |
| T | time (s) |
| 2to | impact duration (s) |
| Vo | initial impact velocity (m/s) |
| w | plate bending deformation (m) |
| wo | plate maximum bending deformation (m) |
| β | decay factor (s-1) |
| v | poisson's ratio |
| ρ | density (kg/m3) |

## Introduction:

In 1995, The National Highway Traffic Safety Administration (NHTSA) documented research establishing the problem size and the potential benefits of preventing occupant ejection through front side windows during accidents. A prototype system made of a modified door and glazing materials was built and tested for this research. This research was primarily concerned with the dynamic response of the head during impact.
Further study was conducted at the University of Missouri-Rolla in this subject which is mentioned in detail in this report. 3-d models were simulated using finite element software (ABAQUS) and results were obtained on different simulated specimens.

## Finite Element model:

Dr. Dharani and Ji developed a 2-D axisymmetric model to simulate the human head, in which a solid aluminum sphere (skull) is covered with a viscoelastic skin. The skull density is 2150 kg/m3 and comparable to that of aluminum which is 2700 kg/m3. So the skull is modeled as aluminum. In this paper, a three dimensional featureless headform model is developed to simulate the occupant's head impacting on the automotive glazing.

Same two-phase headform model is used in which the solid aluminum sphere representing the skull is covered with a viscoelastic skin. Both the skull and skin are deformable. The viscoelastic parameters of the skin used by Dr. Dharani and Ji are also used in the present work. A typical three layer glazing system, consisting of two soda lime glass plies separated by PVB interlayer glazing system, consisting of two soda lime glass plies separated by a PVB interlayer is considered. The interlayer bond is assumed to be perfect with no slipping between the layers during impact. The idealized impact problem under consideration is one where ho is the non-impact side glass ply thickness, hi is the impact side glass ply thickness, hp is the thickness of PVB interlayer, a is the length of the plate and b is the width of the plate. R is the radius of the aluminum skull, hs is the thickness of viscoelastic skin on the skull Vo is the initial velocity of impact. The laminated glass plate is simply supported along its entire perimeter to simulate the service condition. The impact problem is solved by using dynamic nonlinear finite element package ABAQUS.

The glass plies and aluminum sphere are modeled as linear elastic materials. The skin is modeled as linear viscoelastic material the stress relaxation modulus G(t) is assumed to be of the form

$G(t) = G\omega + (Go - G\omega)e^{-\beta t}$

Where e is the base of the natural logarithm, Gω is the long time shear modulus, Go is the short time shear modulus, β determines how fast G(t) decays from Go to Gω.

In the previous study, the PVB interlayer was modeled as a linear viscoelastic material. The impact duration is in range of milliseconds, the stress relaxation modulus G (t) of PVB changes very little during this short duration. In this short time, PVB behaves like a glass solid. PVB could be modeled as a linear elastic material. This assumption would not only make the problem amenable for a close-form solution but also results in significant reduction in computing time. Therefore, PVB is modeled as linear elastic in the present study with a shear modulus Go and with bulk modulus K. The elastic modulus E and poisson's ratio v are given by:

$$E = (9KGo/(3K+Go)) \qquad (1)$$
$$V=((3K-2Go)/(6K+2Go)) \qquad (2)$$

## Objective:

This study was based on the dynamic response of a laminated glazing subjected to simulated head impact. Using 3-d nonlinear dynamic final models to response of a laminated glazing subjected to simulated head impact, results were procured and have been presented in this report. Tests were conducted on three different cases – 2D head impact, 3D head impact with a monolithic glass and a 3D head impact with a laminated glass.

## Designing the model:

Using the finite element analysis software, the model was designed. It was split into two parts – the head and the laminated glass. Alternatively, the head was modeled out of a hollow sphere, not taking into account the brains of the specimen since that is not of primary concern in this report. The head was modeled out of two layers – the outer layer comprising the skin and the inner layer being the skull itself.

The laminated glass had three parts to it, the outer and innermost layers being the laminated glass itself and a layer of polyvinyl butyryl (PVB) in between them.

**Assembly:**

The head was modeled out of a solid revolution part the skin and the skull was assigned a "tie" constraint to each other. This way the software would treat both parts as one and would react as one single unit while performing the finite element analysis. Similarly, the three glass layers (in case of a laminated glass setup) were tied to one another for the same reason. In case of a monolithic glass setup, there was only one glass layer and hence there was no need of assigning a tie constraint to the glass setup. The head is place atop the glass setup and tests are run on this assembly.

**Results and Discussions:**

A baseline case representing a typical automotive glazing impact situation was set. Various parameters were varied from the baseline value (while holding all the other parameters fixed) to determine their effectiveness in reducing the magnitude of stress in the laminate.
The tensile strength of common glass objects (bulk glass) is relatively low and varies from 20 to 100 Mpa. But the compressive strength is substantially higher, by almost a factor of 10 or even more. The tensile strength of car windows can be increased from 300-500 MPa with special processes involving thermal or chemical toughening. The duration of stress during impact loading is normally $10^{-2}$ to $10^{-5}$ s. The glass strength under these conditions is increased by a factor of 2. The tensile strength of the laminated automotive glazing under head impact loading conditions could be as high as 1 GPa.

Laminated glass vs. monolithic glass
The thickness of monolithic panel was the same as that of a laminated panel which is 4.76 mm. All these parameters have been described in Table 1. The maximum principal stress and central deflection of laminated glass were greater than those of the monolithic glass. This is because the PBV interlayer had almost negligible stiffness when compared to that of the glass ply.

**Parametric study:**

When considering the effect of a parameter on the maximum principal tensile stress only this parameter was varied while keeping all other parameters same as the baseline configuration. The initial impact velocity varied from 3.34 m/s to 20 m/s. The proper law fit showed that the maximum principal stress is almost proportional to V.
The effects of impact side glass ply thickness on the maximum principal tensile stress. As expected, the thicker impact side ply meant lower maximum principal tensile stress. Increasing the non-impact side glass poly thickness beyond 2 mm decreased the maximum principal tensile stresses at crucial points.
The effects of thickness ratio of impact side ply to non-impact side ply on the maximum principal tensile stress. The total thickness of the plate is the same as the baseline value (h=4.76 mm). The maximum stress corresponds to hi/ho=0.6. For thin laminate with h=4.76 mm and hp=0.76mm, the worst combination would be hi=1.5mm and ho=2.5 mm. After the peak value,

the stress is reduced significantly with increasing thickness ratio. It indicated that reducing the non-impact side ply thickness and increasing the thickness to the impact side ply while keeping the total glass thickness as a constant is a good way to increase the impact resistance of the glazing system without increasing the total glass thickness.

The effect of PVB thickness on the maximum principal tensile stress was also studied. The results indicate that PVB thickness has no significant effect on the maximum principal tensile stress. There is no additional benefit by using PVB interlayer in the laminated automotive glazing.

In the baseline case, the panel area is 600 X 400 mm. In order to study the effect of panel area on the dynamic response, another glass panel with area 700 X 500 mm is now compared with the baseline case. Incerase in the plate area results in lower maximum principal stress This means that the larger plate would suffer less damage than a smaller plate with all other parameters held constant. When subjected to the same impact load, since the larger plate is more flexible, the central deflection is larger than that of the smaller panel. The stresses in the larder plate are therefore lower.

Three different laminate configurations with same panel area are used to study the effect of laminate aspect ratio a/b on the dynamic response. The laminate aspect ratio has negligible effect on the dynamic response.

**Table 1. Baseline headform, material, impact and panel parameters.**

| | Parameter and Properties |
|---|---|
| Skull | (Aluminum)E=70GPa, $\rho$ = 2700kg/m$^3$, v=0.29 |
| Skin | Go=6 GPa, G$\omega$ =1 GPa, K = 540GPa, $\rho$ =1100kg/m$^3$,<br>$\beta$ = 3800s$^{-1}$ |
| Glass | E=72 GPa, $\rho$ = 2500 kg/m3, v= 0.25 |
| PVB | Go=0.33GPa, G$\omega$=0.69X10$^{-3}$ GPa, K=20GPa, $\rho$=1100Kg/m$^3$,<br>$\beta$=12.6 s$^{-1}$ |
| Configuration | Panel dimensions (a X b): 600 mm X 400 mm<br>Laminated panel: h = 4.76 mm, ho=h1=2mm, hp=0.76 mm<br>Monolithic panel: h =4.76 mm<br>Head form: R=72.3 mm, head mass = 4.5 kg, skin thickness hs = 3mm<br>Initial impact velocity Vo=6.67 m/s |

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