

Strength Investigations on Laminated Windshield

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ABSTRACT:The application of composites to automobiles has seen tremendous growth over the last two decades and the chief reason for this being the higher specific strength, specific modulus and stiffness that these materials possess when compared to conventional materials used in the manufacture of automobiles. In this paper the laminated windshield of a car has been analysed using finite element method. The windshield is made of two layers of glass with a layer of PolyVinylButryl (PVB) in between them. The linear static analysis of three windshield models has been carried out using appropriate finite elements in ANSYS software. The stresses acting at various locations including the interface have been obtained. The impact analysis of the equivalent isotropic windshield model has been carried out using the software L-S DYNA. Four different cases have been analysed based on the type of material and impact speed.

KEYWORDS:Laminated Windshield, Impact analysis, Finite element method

I. INTRODUCTION

The windshield of an automobile such as car, bus etc., is its front window. Apart from providing a good vision area to the driver, it is designed to provide a good resistance against unauthorized entry into the vehicle. Another important function of the windshield is to protect the passengers from suffering grievous injuries during an accident. But it has been reported that windshield is the most frequent vehicle source for head injuries for the passenger in accident cases of a vehicle [1]. In another report the IHRA pedestrian safety working groups have found out that the windshield is the leading source of head injury for adult pedestrian during a vehicle pedestrian collision [2]. Thus the windshield of a vehicle is a critical component that requires a detailed analysis based on the type of loads acting on it.

In early vehicles flat annealed glass sheets have been used as windshields which possess relatively low strength and involve high risk since it would break into large fragments with sharp edges in case of a collision. This could lead to severe injuries or loss of life to both pedestrian as well as passenger. This can be attributed to the brittleness of glass. Breakage of glass could also happen due to static fatigue, which is a typical property of glass due to progressive growth of cracks initiated by micro defects in the surface under the combined effect of mechanical stresses and environmental humidity. Later developments lead to the introduction of temper hardening process of the glass and this has resulted in an increase in strength and splitting of the glass into a great number of fragments without sharp edges. Curved glass sheets have been developed at a later stage both by simple gravity effect and using press molding without compromising on the optical performance of the glass [3]. The most important goal in the design practice is to study and predict the glass durability in the conditions of standard use.

The most effective development in the design of windshield has been the use of laminated windshield glass. It is globally accepted and is used in almost all passenger cars at present. Laminated windshield glass is made up of two sheets of float glass with a PolyVinylButryl (PVB) interlayer pressed together at a high pressure and temperature. The PVB interlayer is a viscoelastic material. The energy absorbing properties of laminated glass is obtained through a combination of the energy dissipation as a consequence of the fracture behavior of the glass and the viscoelastic deformation of the PVB interlayer. In short time dynamics, the elastic behavior for small deformations of the composite is determined by the glass layers. For large deformations the brittle glass cannot withstand large strains and hence the

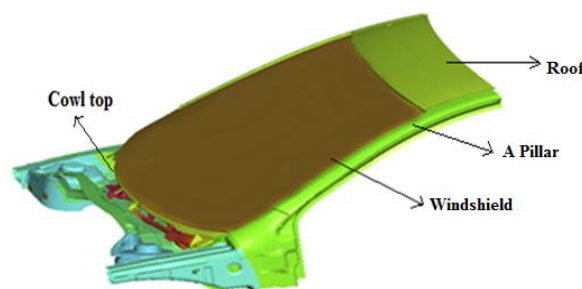
PVB interlayer plays a dominant role. The torsional stiffness of the vehicle body is also increased by the use of bonded laminated windshield glass [4].

The interlayer provides three beneficial properties to laminated windshield. Firstly the interlayer helps to distribute impact forces across a greater area of the glass thus increasing the impact resistance of the windshield. Secondly the PVB layer is so designed as to keep the glass layers together thereby reducing the extent of damage and preserving almost full visibility in practice except through cracked lines in case of breakage of glass. Finally the viscoelastic interlayer undergoes plastic deformation during impact, absorbing energy and reducing penetration by the impactor as well as reducing the energy of the impact that is transmitted to impactor. In order to study the behavior of the glass both static as well as impact analysis are necessary for the determination of stress field and for the prediction of failure pattern. The windshield behavior should be investigated during normal working condition as well as during a sudden impact such as the one occurring during a vehicle pedestrian collision. Finite Element Method which has been globally accepted as a versatile tool for the structural analysis has been employed in the present study for the above purpose.

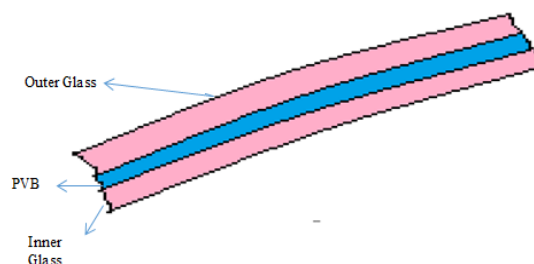
Studies on three models of the windshield are proposed for the finite element analysis, such as an equivalent isotropic model where the composite windshield is considered as a cylindrical shell panel with an integrated structure and a layered model where a finite element with layered structural analysis capabilities has been utilized and finally a solid model where three layers of solid element are used along the thickness direction.

II. DESCRIPTION OF THE STRUCTURE

The windshield of a car has been shown in Fig 1. It is supported at two sides by the A pillars and on the top and bottom by the roof and cowl top respectively. Structurally the windshield can be idealised as a doubly curved shell panel.



(a)



(b)

Fig. 1.a) Windshield Structure b) Assembly of the Laminated Windshield

III. LOADS ACTING ON THE STRUCTURE

During normal service condition the vehicle is subjected to aerodynamic forces such as the Drag, Lift and Side forces. Side force has significance in the event of heavy cross winds. The windshield is mainly subjected to aerodynamic drag force which acts against the forward motion of the vehicle. The drag force is divided into five constituents and the pressure drag which is closely associated with the external shape of the vehicle is the most significant among these. It depends on the velocity, area and the drag coefficient.

Therefore the total drag force is given by (1) where the contemporary automobiles achieve a drag coefficient of about 0.30 to 0.35.

$$F_D = \frac{1}{2} \rho V^2 a C_D \quad (1)$$

This pressure drag is considered to be acting on the vehicle at a particular velocity and the raking of the windshield plays a significant role in reducing the drag coefficient thereby reducing the drag force [5].

The drag pressure is given by,

$$P_D = \frac{1}{2} \rho V^2 C_D \quad (2)$$

The impact analysis of windshield is very important for the automobile industry so as to determine the strength of the structure. The load cases for the weight, velocity and end conditions for the pedestrian head impacts are given by [1] which have been commonly used in the analytical investigations of windshield structure.

IV. DIMENSIONS OF THE WINDSHIELD AND PHYSICAL AND MECHANICAL PROPERTIES OF THE CONSTITUENTS

The geometry of the actual doubly curved shell panel is shown in Fig 2.

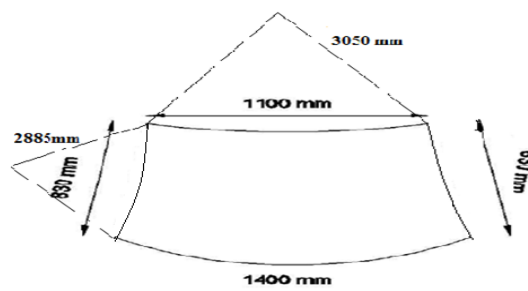


Fig. 2 Actual Shell Panel

The major geometric approximation that has been incorporated regarding the curvature of the windshield is along the transverse direction where the windshield is supported by the A pillars. This has been idealised as a straight meridian of a cylindrical shell with curvature along the longitudinal direction. Therefore the windshield can be idealised as a segment of a cylinder of diameter 5000mm and chord length 1400mm and height 830mm. The thickness of the outer glass, PVB and inner glass are 2.1mm, 0.76mm, and 1.6 mm respectively.

The physical and mechanical properties of glass, PVB and the equivalent shell structure are given in Table 1. The properties of the equivalent shell structure have been calculated by assuming the composite windshield as an integrated model. It can be assumed that full bonding occurs between the glass and PVB interlayer. Therefore the equivalent elastic modulus and Poisson's ratio can be calculated using the equations given below [4, 6].

$$E_{EQ} = \frac{2 t_G E_G + t_{PVB} E_{PVB}}{2 t_G + t_{PVB}} \quad (3)$$

$$\vartheta_{EQ} = \frac{2 t_G \vartheta_G + t_{PVB} \vartheta_{PVB}}{2 t_G + t_{PVB}} \quad (4)$$

Equivalent thickness can be obtained using the following bending stiffness equivalence

$$(EI)_{Model} = \frac{(2E_G + E_{PVB})t_E^3}{12}$$

$$= 2 E_G \left[\frac{t_G^3}{12} + t_G \left(\frac{t_G + t_{PVB}}{2} \right)^2 \right] + E_{PVB} \frac{t_{PVB}^3}{12} \quad (5)$$

From which,

$$t_E = \sqrt[3]{t_G^3 + 3t_G(t_G + t_{PVB})^2 + \frac{E_{PVB}}{3E_G} t_{PVB}^3} \quad (6)$$

and the new equivalent density is,

$$\rho_E = \frac{(\rho_G t_G + \frac{1}{2} \rho_{PVB} t_{PVB})}{t_E} \quad (7)$$

Table 1 Physical and Mechanical Properties of Glass and PVB and Equivalent Shell Structure

Properties	Glass	PVB	Equivalent Shell Structure
Density (ρ)	2500 kg/m ³	1100 kg/m ³	1493 kg/m ³
Elastic Modulus (E)	74 GPa	2.6 GPa	67 GPa
Poisson's Ratio (ϑ)	0.23	0.435	0.248

The thickness of the equivalent shell structure is 6.45 mm and has been obtained by solving equation (7) by considering the layer thickness of the cylindrical shell panel where t_E is the sum of the thickness of the outer and inner glass.

V. LINEAR STATIC ANALYSIS OF VARIOUS MODELS OF WINDSHIELD

Equivalent Shell Model

The finite element analysis of the equivalent idealised cylindrical shell panel has been carried out using ANSYS software version 12.1 and SHELL 181 element has been used to analyse the structure. The finite element model is made up of 625 elements and 676 nodes. The structure has been assumed to be simply supported on the A pillars as well on the roof and cowl top. The raked cylindrical shell panel is analysed for the drag coefficient of 0.30 and velocity 12.5 m/s (45 km/h). The resulting drag force of 34.17 N has been uniformly distributed on the structure.

Layered Model

Eight noded SHELL281 elements are used to make the layered model which consists of 625 nodes 1976 elements.

Solid Model

The finite element model of the outer glass, inner glass and PVB core of the windshield are modeled using '20 noded structural solid 186 element'. There are 5814 elements and 30078 nodes on the structural model.

VI. IMPACT ANALYSIS OF THE WINDSHIELD

The impact analysis of the windshield has been carried out using the software LS DYNA. The impact of the head of a pedestrian on the outer surface of the windshield has been considered in the analysis presented here. The equivalent idealised windshield structure developed using equations 5 to 7 has been considered for the analysis and the human

head has been idealised as a sphere. The analysis has been carried out for various material model of the sphere and various impact velocities.

Table 2 Various Load Cases Considered for the Analysis of the Windshield

Cases	Material Model		Impact Velocity
	Windshield	Sphere	
Case A	Elastic	Rigid	27.77 m/s (100 km/h)
Case B	Elastic	Rigid	22.22m/s (80km/h)
Case C	Elastic	Elastic	27.77 m/s (100km/h)
Case D	Elastic	Elastic	22.22 m/s (80km/h)

The elastic modulus, Poisson’s ratio and density of human skull are 6.5 GPa, 0.22 and 1412 kg/m³ respectively [7]. The input parameters of the equivalent shell panel have been taken from Table 1.

The finite element modeling of the structure has been carried out in LS PrePost. The equivalent idealised windshield and the sphere have been modeled using four noded shell elements. The aspect ratio of each element of the windshield is 1: 1.34. There are 500 elements on the model of the windshield. The finite element model for the impact analysis of the wind shield is shown in Fig 3.

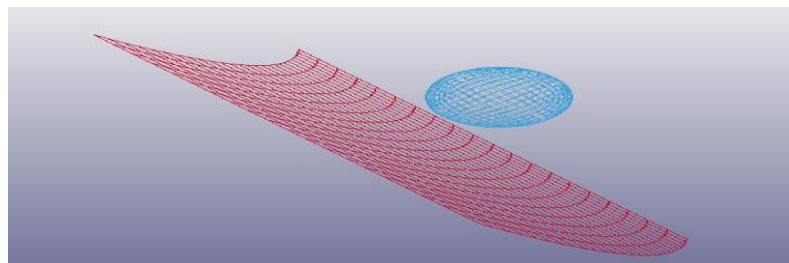


Fig. 3 Finite Element Model for Impact Analysis of Windshield

VII. RESULTS AND DISCUSSIONS

Equivalent Shell Model

The maximum displacement normal to the windshield structure is 0.00102mm. The stresses obtained from the linear static analysis are presented in Table 3. The values have been compared at regions away from the support.

Table 3 Comparison of the Stresses acting on the Equivalent Shell Panel

Location	Hoop Stress (N/mm ²)		Longitudinal Stress (N/mm ²)	
	Classical	FEM	Classical	FEM
Near the midpoint	0.011	0.011	0.0057	0.0058

Layered Model

The Results of the linear static analysis on the layered windshield are presented below. The maximum displacement of the structure is 0.0016 mm. The average value of the hoop and meridional stresses acting at various locations at the middle region of each layer of the laminated windshield are given in Table 4.

Table 4 Average Value of Stresses Acting at various Locations at the Middle Region of Each Layer
(Negative sign indicates compressive stress)

Location	Hoop Stress (N/mm ²)			Meridional Stress (N/mm ²)		
	Outer Glass	PVB	Inner Glass	Outer Glass	PVB	Inner Glass
Average Value of Stress at the Centre	-0.018	-0.00079	-0.019	-0.0031	-0.00030	-0.0040
Average Value of Stress at the Sides	-0.017	-0.00073	-0.018	-0.0028	-0.00028	-0.0027
Average Value of Stress at the Top and Bottom	0.0026	0.000075	0.0027	-0.0030	0.000039	-0.0030

The shear stress acting along the middle plane of the outer glass, PVB and inner glass layers are 0.000463 N/mm², 0.000046 N/mm², and 0.000611 N/mm² respectively. These values are relevant to quantify the brittle failure of the material.

Solid Model

The maximum displacement of the structure is 0.00194mm. The average value of the stresses acting at different locations of the outer glass – PVB and inner glass – PVB interface are given in Table 5.

Table 5 Average value of Stresses Acting at Different Locations of the Interface

Interface	Hoop Stress (N/mm ²)			Meridional Stress (N/mm ²)		
	Average Value of Stress at the Centre	Average Value of Stress at the Sides	Average Value of Stress at the Top and Bottom	Average Value of Stress at the Centre	Average Value of Stress at the Sides	Average Value of Stress at the Top and Bottom
Outer Glass-PVB	-0.0120	-0.0106	0.00044	-0.0014	-0.002	0.0004
Inner glass-PVB	-0.0125	-0.012	0.00055	-0.00141	-0.0019	-0.0011

The significant shear stress values at the Outer glass- PVB interface and Inner glass- PVB interface are found to be 0.00113 N/mm² and 0.001128 N/mm² respectively.

The bond between glass and PVB is broken when the bond strength of the resin is exceeded by the interlaminar shear stress. The stress values presented here correspond to the drag force due to air. It may be noted that in the real situation lift and side forces as well as force from the frame will also be present apart from air drag. So the real stresses in the actual in service condition will be considerable and the realistic estimation of the interlaminar shear stress is relevant in selecting the appropriate resin.

The utility of these two models viz layered and solid model can be judged based on the computational effort and efficiency. The element used for the layered model is eight noded shell element having six degrees of freedom at each

node. This element can predict the relevant stress values at each layer and hence this model is appropriate for the prediction of interlaminar stresses. The element used for the solid model is a twenty noded structural solid element having three degrees of freedom at each node. Even though the computational effort for the solid model is more compared to the layered model, it is capable of predicting the stress values at the interface of the glass and PVB.

Impact Analysis

The impact analysis of the equivalent windshield structure has been carried out in LS DYNA and the post processing of the results have been carried out in LS PREPOST. The values of the maximum displacement along the loading direction and the value of stress components for each cases at the point of contact of the sphere on the windshield are given in Table 6.

Table 6 Normal Displacement and Stress Components at the Point of Contact of the Sphere on the Windshield

	Case A	Case B	Case C	Case D
U _z (mm)	2.822	0.288	1.376	0.6
σ_x (MPa)	49	43	84	60
σ_y (MPa)	35	24	62	42
σ_z (MPa)	0.010	0.011	0.027	-0.33
σ_{xy} (MPa)	-0.10	-0.54	-0.814	-0.37
σ_{yz} (MPa)	-0.96	--0.54	-1.041	-0.24
σ_{xz} (MPa)	-0.13	-0.26	-2.1	--0.39
von Mises stress (MPa)	42	40	76	53
Maximum Principle Stress (MPa)	52	44	84	60

VIII. CONCLUSION

- Static analysis of the windshield has been performed using three finite element models such as equivalent isotropic, layered and solid model. The stresses acting at the middle portion of each layer and the stresses acting on the outer glass-PVB and inner glass-PVB core have been obtained. The scope of various finite element models for the windshield has been established.
- The impact analysis of the equivalent isotropic windshield model has been done using the software L-S DYNA. Four different cases have been analysed based on the type of material and the impact speed.
- The normal displacement along the loading direction, the stress components acting in each direction as well as the von Mises stress and the maximum principle stress have been obtained from the impact analysis.

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Nomenclature

C_D	- Drag Coefficient
E_G	- Young's Modulus of Glass
E_{PVB}	- Young's Modulus of PVB
E_{EQ}	- Young's Modulus of Equivalent shell
F_D	- Drag Force
P_D	- Pressure Drag
R	- Radius of the Shell
V	- Velocity of the car, m/s
a	- Area of Cross Section, mm ²
t_E	- Thickness of Equivalent Shell Model
t_G	- Total Thickness of Glass, mm
ν_{EQ}	- Poisson's Ratio of Equivalent Shell
	Structure
ν_G	- Poisson's Ratio of Glass
ν_{PVB}	- Poisson's Ratio of PVB
ρ_E	- Density of Equivalent Shell Model
ρ_G	- Density of Glass
ρ_{PVB}	- Density of PVB
σ_θ	- Hoop Stress
σ_x	- Meridional Stress