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Structural Design and Simulation of the Collision Between a Pedestrian's Head and a Windshield of Vehicle

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ABSTRACT

The vehicle's windshield plays an important role in the safety and comfort of drivers and passengers, so the windshield is solicited to many loads, such as the deformation of the vehicle body, the wind force, the crash between vehicles and vehicles, and a pedestrian. The primary goal of this study is to examine the mechanical and structural design of laminated glass for windshields in the scenario of an adult dummy head impact. The head impactor is represented by a spherical form covered in a rubber hull. The pedestrian head's Finite Element Method (FEM) is created per the requirements of Global Technical Regulations (GTRs). It weighs approximately 4 kg and strikes a windshield at a speed of 11.11 mm/ms. Furthermore, the windshield model is designed with two layers of glass with a layer of Polyvinyl Butyral (PVB). Our study's windshield Finite Element model is modeled with shell elements. The mathematical models of the PVB are described in a systematic manner. The model accurately represents the windshield's behavior, with critical fracture stress occurring in the impacted zone and maximum linear acceleration of the dummy head. The obtained results showed good agreement in energy absorption and maximum stress due to the impact.

1. INTRODUCTION

Pedestrian safety is a paramount concern in urban areas, with head injuries being a leading cause of fatalities in pedestrian-vehicle collisions [1]. This study delves into the essential aspects of accidents where a pedestrian's head collides with a vehicle's windshield, aiming to enhance our comprehension of collision between a Pedestrian's Head and a Windshield of vehicle.

The use of Finite Element Method (FEM) modeling for vehicle windshields involves the application of a numerical technique to reproduce and analyze the structural response of the windshield. This method allows an in-depth understanding of the windshield's reactions to different mechanical and environmental circumstances. Through the use of FEM, it is possible to evaluate elements such as stress distribution, deformation and overall structural performance, providing valuable insight into the durability and safety of the windshield. This approach is crucial for refining the wind-shield design and ensuring its reliability under various operational conditions in the vehicle dynamics.

Through an analysis of collision reports, simulations, and experimental data, this research investigates the impact forces, injury mechanisms, and risk factors associated with these specific incidents. So, pedestrian fatalities account for approximately 22% of all road traffic deaths globally. Specifically, National Highway Traffic Safety Administration (NHTSA) reports indicate that head-on collisions with vehicle windshields contribute to a staggering 60% of all fatal pedestrian accidents nationwide. In our research, we utilized an advanced explicit analysis to gain deeper insights into the dynamics of pedestrian-vehicle collisions. By doing so, we were able to develop safer vehicle designs and innovative safety systems, contributing significantly to the ongoing efforts to improve road safety and reduce the severity of such incidents.

To ensure the safety and comfort of the occupants, the windshield must withstand various loads, such as wind forces, vehicle body deformation, and pedestrian impacts. Therefore, it is essential to examine the windshield's mechanical and structural design under various loading conditions to improve its functionality and reliability. The windshield is an essential component in ensuring the safety of vehicle occupants in the event of a collision. It serves as a barrier between the passengers and the external environment and must withstand various loads during an accident to safeguard its occupants. Additionally, it must resist the deformation of the vehicle body during an impact, which can put significant stress on the glass. If the windshield fails during a collision, the occupants of the car are at risk of severe injury or worse, death.

The Global Technical Regulations (GTRs) mandate the design of pedestrian head forms to improve the safety of vehicle occupants in the event of a collision [2]. Therefore, the windshield must meet these requirements to minimize the risk of head injury during an impact. One important aspect to consider when designing windshields is the impact of an adult dummy head during a collision.

Several researchers have utilized analytical methods to inspect and characterize the impact and crash behavior of laminated glass structures [3, 4]. Xu and Li [5] discussed the crack propagation in laminated glass subjected to a crash using an empirical investigation. They investigated fracture propagation and found that as velocity increases, so do the rates of radial and circular cracking. Several researchers have utilized experimental studies to analyze and outline the impact and crash reactions demonstrated by laminated glass structures [6-11]. These experimental investigations serve the purpose of acquiring a deeper understanding of how laminated glass behaves when subjected to dynamic loading conditions. Wang [12] proposes a numerical method to model the impact between a pedestrian's head and an automobile windshield. The comparison of numerical findings with experimental data reveals a fair level of agreement. Linder et al. [13] tested a mathematical and analytical model of pedestrians to determine whether it could accurately assess the severity of an impact based on real-world data. Six realistic pedestrian collision cases were used to gauge the pedestrian model's dynamic performance.

Peng et al. [14] investigated the mechanical response of windshield laminated glass to the impact of a pedestrian's head. They found that a glass fracture stress of 50 MPa was the best predictor of the linear acceleration level of head form and windshield cracks during a crash. Yang et al. [15] used FEM to analyze Head-windscreen laminated glass collision analysis using LS–DYNA to explore the impact of factors on the impact injury.

Jiang [16] used pure mechanical structure design to reinforce vehicle safety. Prasongngen et al. [17] employed the element deletion method to analyze the crack behavior, and they concluded that the triangular shape mesh with 1 mm offers a good result of laminated glass. The simulation gives a good compromise with the experimental results.

Rooij et al. [18] employed multibody modeling of various pedestrian anthropometries and vehicle models to simulate various driving scenarios. They used advanced pedestrian injury criteria to assess vehicle damage and pedestrian injuries. Timmel et al. [19] created laminated glass using an explicit finite element solver. They used two models to achieve a developed bending response following a fracture: the physical model, in which the glass is viewed as elastic/brittle, and the smeared model, in which they implemented two shell elements of equal thickness with elastoplastic material properties. The concept's validity was tested through experiments involving a spherical impactor.

Asik and Tezcan [20] developed a mathematical model that provides information on laminated glass beams' static and dynamic behaviors. One of the primary points of contact for pedestrian head injuries is the windshield of moving vehicles, with which pedestrians frequently come into contact [21]. Liu et al. [22] described the energy absorption of PVB laminated windshields during human head impacts. They used the Split Hopkinson Pressure Bar (SHPB) method to understand the material's dynamic behavior, and finite element simulation to analyze energy absorption, velocity, and position impacts. Chen et al. [23] developed the cohesive zone modeling framework in response to the glassply cracking behaviors of a laminated glass beam exposed to low-velocity impact. Kosiski and Osiski [24] proposed a modified design of a laminated windscreen in case of a vehicle-pedestrian accident. Behr et al. demonstrated in their study [25] that the behavior of the layered beam at room temperature was influenced by the thickness of the PVB and the effects of shear.

The primary focus of this study is twofold: first, to investigate the mechanical behavior of laminated glass in windshields during a pedestrian head impact, and second, to evaluate the role of laminated glass in enhancing passenger safety. The study validates the importance of windshield in a vehicle by analyzing the estimated injury criteria in each simulated scenario involving a mannequin head.

2. THEORY AND METHODOLOGY

2.1 Methodology

In order to effectively represent the physical design, it is crucial to have a thorough understanding of the problem being solved during the modeling process. The objective of this research is to create a precise, comprehensive, and reliable Finite Element Model (FEM) of the windshield. The simulation of a pedestrian's head and windshield collision would typically entail following the steps outlined in Figure 1.

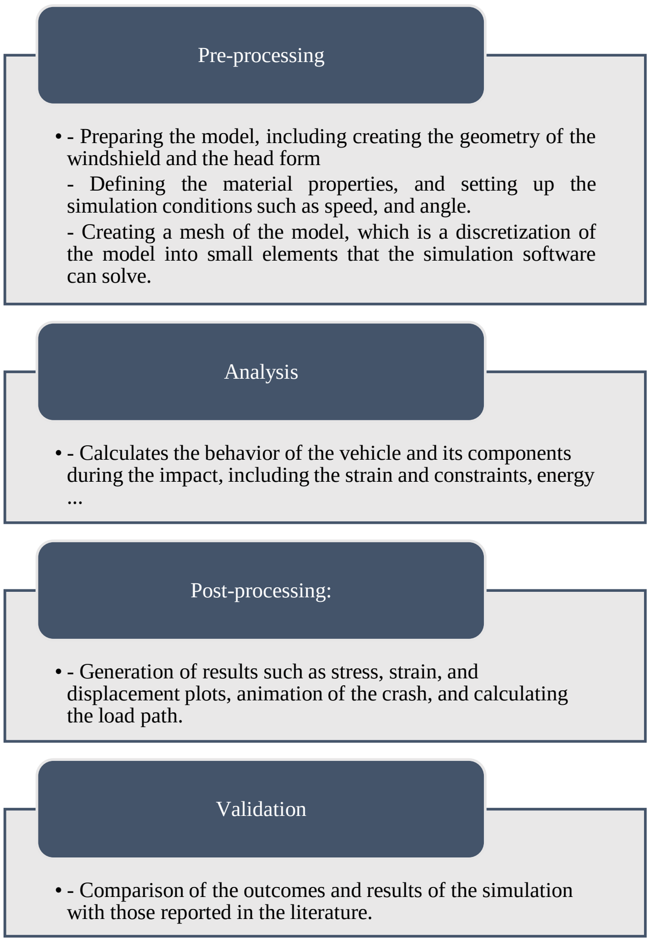

Figure 1. Modeling logic of the problem

2.2 Modeling and design of the windshield crash

2.2.1 Design

Polyvinyl Butyral (PVB) is a material that is extensively used in the production of laminated glass, notably in automotive windshields. During the lamination process, a transparent interlayer of PVB is inserted between two layers of glass. This results in a highly durable and robust laminate that can withstand heavy impacts without breaking, thus making it an ideal material for safety purposes.

Pedestrian head injuries are a major concern in vehicle-to-pedestrian accidents, often leading to long-term disabilities or even death [26-29]. The windshield of a vehicle is a significant contact point in such accidents, making it a crucial factor in head injury prevention. However, modeling windshields for pedestrian safety is currently a challenging task due to the non-linear fracture that glass presents in the event of an accident. Laminated windshields with Polyvinyl Butyral (PVB) are typically used in vehicles [30, 31]. One highly effective tool for optimizing the design of laminated safety glass and ensuring compliance with regulations is the combination of the Maxwell model and finite element analysis (FEA). This model can accurately predict the stress-strain behavior of PVB, which is crucial in determining how the glass will behave under various loading conditions that may occur during a crash. Accurate predictions of PVB behavior can be made over a wide range of loading conditions by fitting the model parameters to experimental data. Therefore, the Maxwell model illustrated in Figure 2 and FEA can be used to design laminated safety glass that can withstand the impact of a collision and reduce the severity of injuries caused by shattered glass.

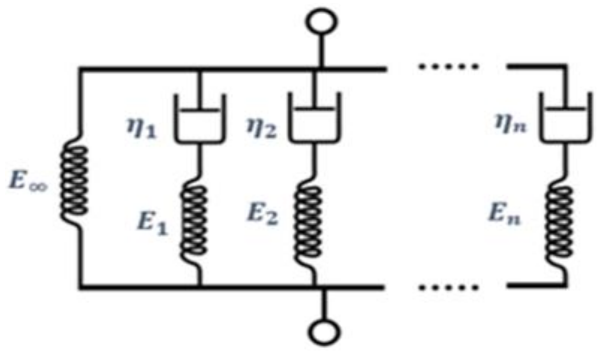

Figure 2. Generalized Maxwell viscoelastic material model [32]

The equation for the Maxwell stress in a PVB interlayer laminated windshield glass is as follows:

$$\sigma(t) = \int_0^t 2G(t-\tau)\frac{\partial\varepsilon_k}{\partial\tau}\partial\tau + I\int_0^t K(t-\tau)\frac{\partial\varepsilon_v}{\partial\tau}\partial\tau \quad (1)$$

where, $\boldsymbol{\varepsilon_k}$ and $\boldsymbol{\varepsilon_v}$ are the deviatoric and volumetric strain, and $\boldsymbol{G(t-\tau)}$ and $\boldsymbol{K(t-\tau)}$ are shear and bulk relaxation functions.

From the rheological model, the shear and bulk modulus of the linear viscoelastic material [33-37] can be expressed as:

$$G(t) = G_0(1 - \sum_{i=1}^{n} g_i(1 - e^{-\frac{t}{\tau_i^G}})) \\ K(t) = K_0(1 - \sum_{i=1}^{n} k_i(1 - e^{-\frac{t}{\tau_i^k}})) \quad (2)$$

where, $G_0 = \frac{E}{2(1+\vartheta)}$ initial shear modulus (t=0), and $K_0 = \frac{E}{3(1-2\vartheta)}$ initial bulk modulus (t=0), and k_i, g_i are the bulk and shear modulus and corresponding times, τ_i represent the relaxation time, and ϑ the Poisson coefficient.

The diagram in Figure 3 shows the complicated structure of windshields. This design is crucial for the safety of passengers while driving. The adhesive that bonds the glass layers together, even when the windshield is broken, is made of Polyvinyl-butyral (PVB), which is a vital component. PVB's strength is essential because it prevents the glass from shattering into large and potentially harmful pieces, thus reducing the risk of injuries to the vehicle occupants. Although the composite's elastic behavior is determined for small deformations, the intermediate PVB layer plays a vital role in large deformations due to the fragile nature of the glass, which cannot withstand significant deformation. The intermediate layer provides additional strength and flexibility to the windshield, allowing it to absorb substantial amounts of energy during a collision or impact. The structural design of windshields is a complex interplay between various materials and components, all aimed at ensuring passenger safety and reducing the risk of injuries.

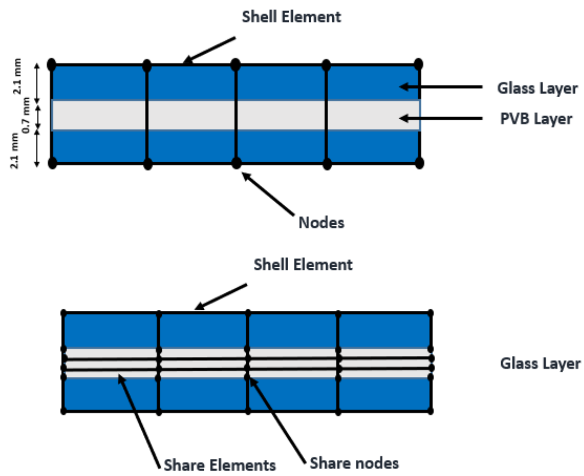

Figure 3. Structure design of the windshield

Based on Timmel et al. [19], to determine the corresponding thickness, you can use the following bending stiffness equivalency.

$$EI_{model} = \frac{(2E_{Gl}+E_{PVB})t_{Eq}^3}{12} = 2E_{Gl}\left[\frac{t_{Gl}^3}{12} + t_{Gl}\left(\frac{t_{Gl}+t_{PVB}}{2}\right)^2\right] + E_{PVB}\frac{t_{PVB}^3}{12} \quad (3)$$

From which:

$$t_{Eq} = \sqrt[3]{t_{Gl}^3 + 3t_{Gl}(t_{Gl}+t_{PVB})^2 + \frac{E_{PVB}}{3t_{Gl}}t_{PVB}^3} \quad (4)$$

And new equivalent density is:

$$\rho_{Eq} = \frac{\rho_{Gl}t_{Gl} + \frac{1}{2}\rho_{PVB}t_{PVB}}{t_{Eq}} \quad (5)$$

where, E_{Gl} and E_{PVB} are Young's modulus of glass and PVB respectively ρ_{Gl}, and ρ_{PVB} are the density of glass and PVB respectively; t_{Gl} and t_{PVB} is the thickness of glass and PVB respectively, and the total thickness is:

$$t_{total} = t_{Gl} + t_{PVB} \quad (6)$$

This paper presents a multibody approach to develop models of the vehicle and the head impactor. Figure 5 shows that the head impactor is a spherical form that weighs about 4 kg and has an initial speed 11.11 mm/ms. it impacts the windshield of the vehicle. Although the head model is extremely simplified with just one sphere, it helps to understand the key components used in a crash analysis.

The study uses a multibody model of the windshield, which is shown in Figure 4, the model comprises a layer of Polyvinyl Butyral (PVB) that is laminated between two glass sheets as shown to Figure 4.

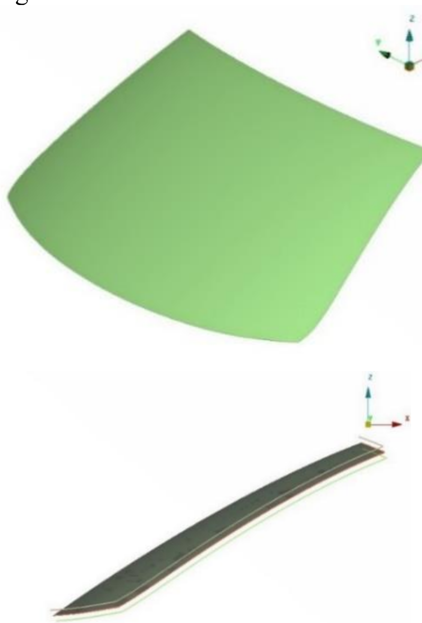

Figure 4. 3D model of windshield

The multibody representative of a head impactor with a mass of 4 Kg, and 165 mm in diameter employed in this investigation, as illustrated in Figure 5, is:

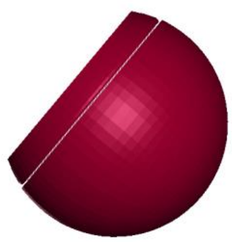

Figure 5. A 3D model of head impactor

2.2.2 Finite Element Model (FEM)

Windshield model. Several critical parameters need to be defined to create a finite element model of a windshield. First, the geometry and material properties of the windshield must be specified. This involves detailing the dimensions, curvature, and material properties of the different layers, such as thickness, density, and elastic modulus. Second, the loading conditions to which the model will be subjected also need to be defined. For instance, the model could undergo a range of different loading scenarios, such as impact loads, wind loads, or temperature changes.

Several articles have discussed various ways to design laminated glass for windshields [19, 38-40], with many of them using shell elements to model their windscreen. In this method, the layered structure of the laminated windshield is represented by three shell components and common nodes at their borders. The external sides of the two shell components show the glass layers, while the inside shell element symbolizes the PVB interlayer.

The windshield model displayed in Figure 6 is supported by the A-pillars on two sides, the roof, and the cowl top on the top and bottom, respectively. The windshield structure is designed to provide an aerodynamic profile and absorb the impact of small stones or other objects that may hit the vehicle. The curved shape of the windshield also provides additional strength and rigidity, which is crucial for passenger safety. The windshield has been modeled using quadrilateral and triangular elements with a mesh size of about 5 mm, allowing a more detailed analysis of its behavior under different loading conditions. Overall, finite element modeling is a powerful tool that enables engineers to design safer and more efficient windshields for modern vehicles.

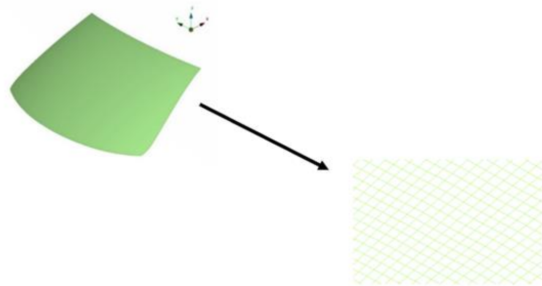

Figure 6. FEM model of laminated windshield

Pedestrian head form. Our investigation shows a finite element model of the adult head form impactor. This model illustrated in Figure 7 is designed to simulate the impact of an adult head in an accident and uses a viscoelastic solid continuum element to represent both the steel core and vinyl skin components. The model is reliable and adheres to the World Technical Regulations (WTRs) requirements for pedestrian head form impactors [41].

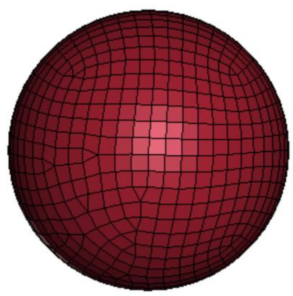

Figure 7. FEM model of pedestrian

The HIC factor, standing for Head Injury Criterion / Coefficient, is used by engineers to determine the level of damage to the head region [42].

$$HIC = max\left\{\left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_1} \gamma(t)dt\right]^{2.5} (t_2 - t_1)\right\} \tag{7}$$

where, $\boldsymbol{t_1}$ and $\boldsymbol{t_2}$ are the initial and final time periods chosen to maximize HIC, and $\boldsymbol{\gamma}$ is the acceleration over the period of time from $\boldsymbol{t_1}$ to $\boldsymbol{t_2}$.

Figure 8 shows the resultant acceleration of the head forms while during crash. HIC value is calculated regarding Eq. (2). The HIC value stands at 68.6. This is below the established safe threshold of 650 according to the Euro NCAP Protocol. The reason for this is that the windshield effectively absorbs the impact energy, undergoing deformation in the process.

The peak HIC value on Figure 8 signifies the moment of highest potential head injury during impact. Effective attenuation of HIC values post-peak suggests that safety features, like windshields or restraint systems, are successfully mitigating head injury potential.

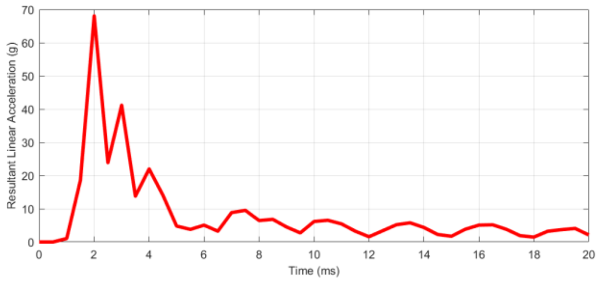

Figure 8. HIC value

Understanding HIC values in head-form and windshield testing involves awareness of injury thresholds, striving for lower values, assessing compliance with standards, and considering simulated impact conditions. Adherence to safety regulations is crucial for the overall effectiveness of vehicle safety systems.

2.2.3 Model settings

When building a laminated glass construction, such as an automobile windshield, it is essential to consider the mechanical characteristics of the materials used. Both glass and PVB have unique qualities that can affect the structure's performance. Young's modulus, which measures a material's stiffness, is a crucial factor to remember. A material with a higher Young's modulus is stiffer and less deformable, while a lower modulus means more flexibility. The overall stiffness and strength of the laminated glass structure can be influenced by the stiffness of the glass layers and the PVB interlayer.

Table 1. Physical and mechanical properties of glass and PVB [43]

Physical and Mechanical Properties	Glass	PVB
Density	2500 $Kg.m^{-3}$	950 $Kg.m^{-3}$
Hardness	5-6 on the Mohs scale	2-3 on the Mohs scale
Thermal Conductivity	1 W/mK	0.2 W/mK
Poisson's ratio	0.2	0.4
Young Modulus	70000 MPa	50 MPa
Yield stress	50 MPa	20 MPa
Compressive strength	600 MPa	200 MPa
Flexural strength	90 MPa	20 MPa
Strain at failure	1%	5%

Another vital attribute to consider is the shear modulus, which measures a material's resistance to deformation under shear stress. This characteristic can impact the laminated glass structure's ability to absorb energy during an impact or collision. The thermal expansion coefficient is also critical in designing laminated glass structures. Glass and PVB can expand and contract at different rates when exposed to temperature changes, leading to stress buildup and potentially cause structural failure. Other properties, such as density, Poisson's ratio, and tensile strength, can also impact the performance of laminated glass structures.

Table 1 presents the mechanical properties of the glass and PVB [43] used in investigating the behavior of a windshield during a collision.

2.2.4 Boundary conditions and loadings

The boundary conditions and loadings for windshields are critical considerations in the design and analysis process to ensure that they meet safety, performance, and durability requirements under various operating conditions.

In Figure 9, the boundary conditions for laminated glass are outlined. In the Finite Element Method (FEM) analysis of the windshield, all edges are set as fixed. In the Finite Element (FE) model of the windshield structure, the components connected to the frame are also fixed, with a total of 49176 elements in the model.

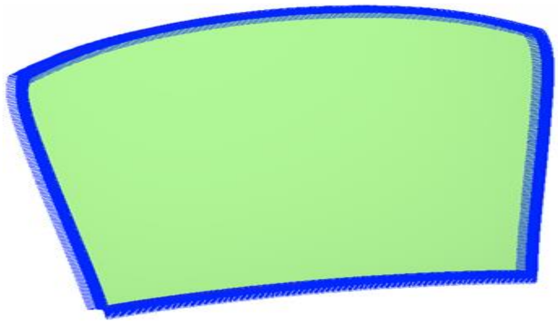

Figure 9. Windscreen 3D model with boundary conditions

When conducting crash tests for vehicles, testing organizations consider various impact scenarios, including different angles and locations. This helps in assessing how well a vehicle protects occupants in diverse collision situations. Figure 10 illustrates a common head windshield impact scenario in which a sphere representing a head with a velocity of 11.11 mm/ms is shown.

As per Euro NCAP standards, the initial velocity is taken as 11.11 mm/ms at an angle 50°.

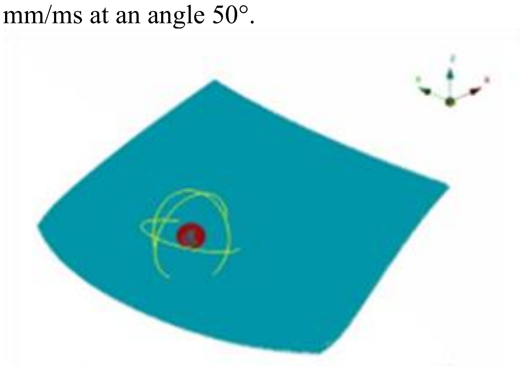

Figure 10. Model of the windshield under loading

3. RESULTS AND DISCUSSION

Several simulations were carried out using Meta Post to evaluate the impact resistance of windshields made of laminated glass. Analyzing the effect of a pedestrian's head striking the windshield was one of these simulations.

Figure 11 displays the results of the impact study, which prove that the windshield was able to withstand the collision and prevent any significant harm to the pedestrian. Furthermore, Figure 11 provides a detailed visual representation of the forces and strains that were present during the collision between the pedestrian's head and the windshield.

To analyze the windshield's performance, we are used, ANSA, Radioss, and METapost perform and calculate Von Mises stress in explicit analysis. These constraints are essential in measuring the maximum stress that the laminated glass structure can withstand before it fails. By providing valuable insights into the durability and strength of the windshield, these constraints are crucial in determining the safety and reliability of the glass structure.

In this study, a comprehensive analysis was conducted to investigate the mechanical properties of laminated glass subjected to different loading conditions. The material's stress-strain response was fully simulated by performing numerical simulations at various time intervals ranging from 0 to 0.8 seconds.

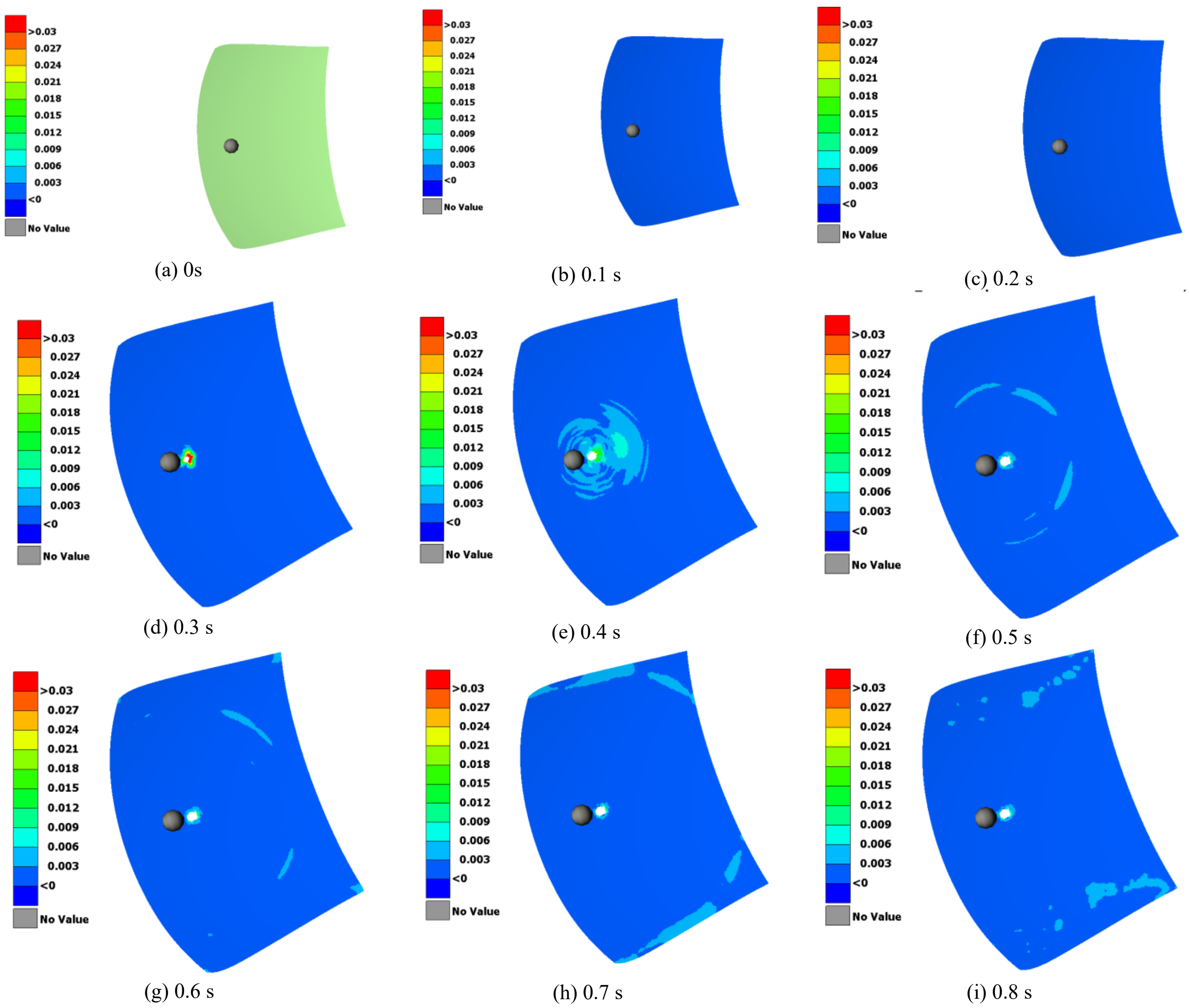

Figure 11. Simulation and results of von mises stress

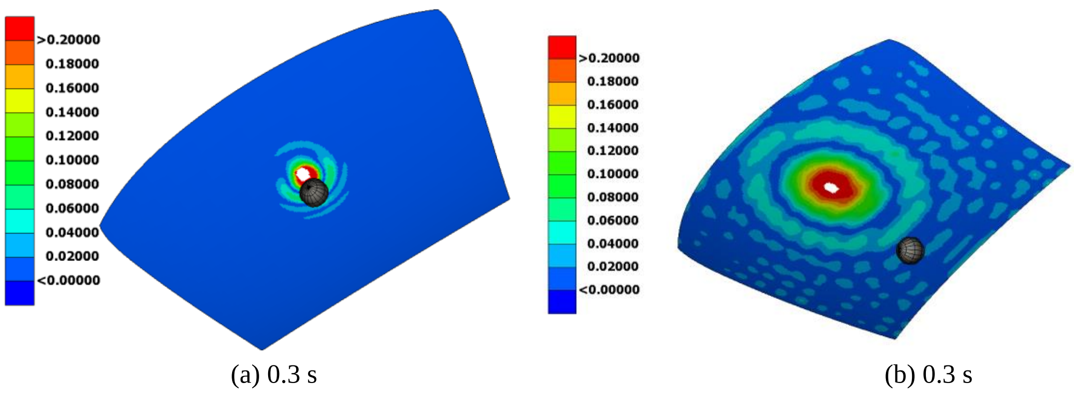

Figure 12. Simulation and results of von mises strain

The results of the study indicate that the laminated glass windshield experiences stress levels below the elastic limit during the time intervals of 0 s and 0.1 s as showed in Figure 11(a), and 11(b). This suggests that the material can sustain significant deformation without undergoing permanent deformation or fracture.

The maximum peak of Von-Mises stress was observed at 118 MPa in the impact area during the time intervals of 0.2 s and 0.3 s, as depicted in Figures 11(c) and 11(d). Additionally, the maximum peak of Von-Mises stress during the time interval of 1 s was 79 MPa.

Furthermore, the maximum peak of Von-Mises stress during the time intervals of 0.4 s to 0.8 s was found to be 15.3, 18, 15.8, 17, and 21 MPa, respectively. These results suggest that the laminated glass windshield can withstand a considerable amount of loading without undergoing failure.

Furthermore, the Figure 12 shows the maximum peak of Von Mises strain during the time intervals of 0.3 s and 0.4 s was found to be 0.165 and 0.198, respectively.

Overall, the results of this study offer insightful information about the mechanical behavior of laminated glass under various loading scenarios, which can guide the development of windshields that are safer and more resilient in the future. It is crucial to keep in mind, though, that in conditions of severe loading, the material's over-constrained components could fracture. This is clear from the contours' representation of the plastic limitations, which draw attention to the parts of the material that have undergone plastic deformation.

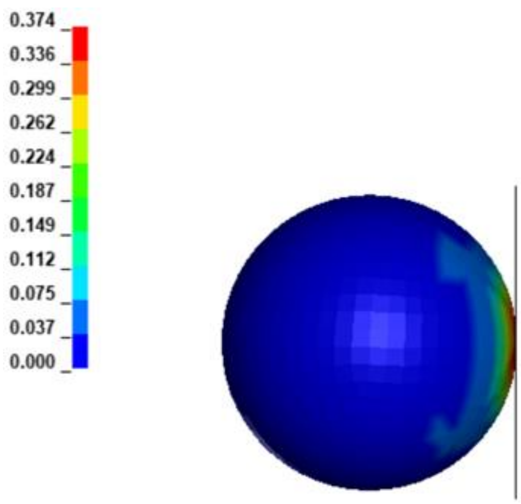

Figure 13. Von-Mises stress of head of pedestrian

Figure 13 illustrates the simulation outcomes regarding the interaction between the head impactor and the windshield. To validate our model, we are used the Von Mises stress which is a critical parameter to assess the potential for yielding or deformation in the material of the headform.

The stress registered at the impact location, resulting in permanent deformation, was 0.374 Mpa. The Von Mises stress can help evaluate the structural integrity of the headform under different impact conditions.

The results demonstrate a significant correlation between our tests and the results obtained by Cai et al. [44], particularly regarding deformation and Von Mises constraints.

It's important to note that the von Mises criterion provides valuable insights into the behavior of materials under complex loading conditions. However, a comprehensive pedestrian-vehicle collision analysis also considers other factors such as the pedestrian's kinematics, vehicle speed, impact angle, and injury criteria to assess the overall safety of the collision scenario and develop effective safety measures.

4. CONCLUSION

The main objective of this article was to study the mechanical response of laminated glass used in windshields during head impacts. To achieve this, we conducted several simulations using different combinations of glass and Polyvinyl Butyral (PVB) with different connections and assumptions. The windshield model proposed consisted of two layers of glass with a layer of PVB sandwiched between them. We developed a Finite Element model (FEM) of the windshield using shell elements to simulate the laminated structure of the windshield. Our results demonstrated that the model accurately represented the windshield's real behavior. The impacted zone, which was cracked using the maximum value of the linear acceleration of the dummy head, provided critical fracture stress. The highest Von-Mises stress peak, reaching 118×10^{-3} MPa, was recorded within the impact area between time intervals 0.2 s and 0.3 s, as illustrated in Figures 10(c) and 10(d). This finding emphasizes the importance of adhering to the design of the windshield in the automotive industry to maintain safety and security programs related to pedestrian head impacts.

In conclusion, this study provides valuable insights into the mechanical response of laminated glass for windshields during head impacts. The results highlight the significance of proper windshield design and construction to ensure the safety of drivers, passengers, and pedestrians. Future research can build on these findings to develop even more accurate models of windshield behavior during impacts, ultimately leading to even safer vehicles on the road.

4.1 Limitations

Although this study has made significant contributions to our understanding of laminated glass for windshields, it has several limitations. Firstly, the study only focuses on the impact of a spherical object coated with a rubber hull, which may not accurately represent real-world situations. Secondly, the study only considers the response of the windshield to impacts made by adult dummy heads, and does not account for other types of impacts, such as those caused by children or animals. Lastly, the study does not take into consideration the effect of environmental factors, such as temperature and humidity, on the mechanical response of the windshield.

4.2 Future research recommendations

To address the limitations mentioned above, it is recommended that future research should encompass a wider range of impact scenarios, including those that involve children and animals. Furthermore, investigations on the effects of environmental factors on the mechanical response of windshields are crucial to ensure their reliability in different environments. It is also recommended to consider the impact of debris and other objects that may hit the windshield during a vehicle collision. Finally, it's essential to explore advanced materials and technologies, such as smart glass and self-repairing materials, to improve the safety and performance of windshields.

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