Response of Monolithic and Laminated Glass under Impact Loading

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Abstract-- The response of monolithic and laminated glasses, without damage, subjected to wave controlled impact, is studied by the use of the coded finite element program. The performance of the monolithic and laminated glass beams subjected to the transverse impact loading is thoroughly examined. To model and simulate impact response of both the monolithic and laminated glasses, a simple finite element approach based on the Sun’s higher-order beam finite element and Dharani’s PVB interlayer model is proposed. The verification of the numerical model is conducted by using the equivalent mass model and wave propagation theory for the monolithic and laminated glass beams. The present finite element results show a good agreement with two open literature results and it is recommended for future impact predictions. The response results such as the time histories for contact force, deflection, strain and energy during impact event regarding the impact velocity changes are obtained and compared with each other between the monolithic and laminated glass.

Index Term-- monolithic glass (MG), laminated glass (LG), PVB interlayer, impact response, impact energy

1. INTRODUCTION

The monolithic glass (MG) like annealed glass is the most commonly available a single lite of glass. Large shards with sharp edges will be produced when the glass breaks. When penetration and collapse of the glass structure may occur, the failure stress of the MG is also relatively low. Laminated glass (LG) has been developed for resisting blast and impact loading. LG consists of two or more layers of glass plies adhered by a interlayer made of polyvinyl butyral (PVB). The main purposes of the PVB interlayer are to provide absorption to the impact energy and adhesion to the two glass plies. When LG is subjected to an impact that caused by a sufficient heavy and fast impactor, it will break. However, unlike MG that fails in a brittle manner, LG can reduce the number of dangerous flying fragments as many fragments will be adhered by the PVB layer. Hence, the risk of injuries of people can be significantly reduced. At the same time, the PVB interlayer can act as a barrier avoiding penetration. Another advantage of LG over MG is that it is possible to reduce the weight of the glass of the same total thickness. In spite of their advantages, however, the efficient application of LG is limited, because of the difficulties in their strength calculations at the stage of their design. Foreign object like a small stone thrown into the windshields shall give an impact to automotive glass. For optimal design of the MG and LG that minimizes body injury and property damage during a vehicle accident is required a thorough understanding of the impact behaviors of automotive glass subjected to dynamic impact.

The dynamic responses of isotropic materials and composite laminates subjected to transient dynamic loading have been studied in terms of analytical, numerical and experimental works¹⁻³. When the beam is applied to impact loading, the elastic waves generated in the beam are short wavelength vibration modes. Sun and Huang¹ developed a higher order beam finite element with six degrees of freedom for the dynamic response of elastic isotropic beams subjected to impulsive loadings. This higher order beam finite element showed to be more efficient than the conventional element with four degrees of freedom. A series of paper on impact of LG for automotive and architectural has been published by Dharani and his coworkers⁴⁻¹¹. In several earlier studies⁴⁻⁵ on laminated architectural glazing, the PVB interlayer has been traditionally modeled as linear-viscoelastic. The most recent works⁸⁻¹¹ on LG have shown that PVB can be modeled as linear elastic.

Therefore, in the present study, a simple approach based on Sun’s higher-order beam finite element and Dharani’s PVB interlayer model is proposed and simulated a coded FEM program for low-velocity impact analysis of the MG and LG beams. The verification of a numerical approach is conducted by using the equivalent mass model⁹ and wave propagation theory¹³,¹⁴, respectively. Additionally, the response results such as the time histories for contact force, deflection of target, displacement of impactor, strain and energy during impact event due to the impact velocity changes are obtained and compared with each other between the MG and LG.

2. FINITE ELEMENT MODELING

Consider the MG and LG beams consisting of a single layer and multiple layers of total thickness h subjected to transverse impact by a steel ball of radius R with initial impact velocity V₀, as shown in Figure 1. The thickness of the outer and inner plies and the PVB interlayer in LG beam are h₀, h₁ and h₂, respectively.

The purpose of this study is to investigate impact induced responses through the MG and LG beams. We assume a low velocity impact such that the glass ply does not fracture. Therefore, a higher-order beam theory with six degrees of freedom is used to analyze the MG and LG beams for contact force, deflection, strain and energy.

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The element displacement function is taken as

\[ v = a_1 + a_2 x + a_3 x^2 + a_4 x^3 + a_5 x^4 + a_6 x^5 \]  

where \( v \) is the transverse displacement and \( a_i \) are constant coefficients.

The three degrees of freedom at each node are the transverse displacement \( v_i \), the rotation \( \theta_i \) and the curvature \( k_i \). The coefficients \( a_i \) in Equation (1) can be replaced by the six generalized nodal displacements at the two end nodes and, as a result, the displacement function can be alternatively expressed in terms of the nodal displacements.

Glass is widely used in many engineering applications (vehicles, aircraft, buildings and electronic etc.). The simple applications of this material have the shape of a glass beam panels. In case of impact of a hard projectile, impact responses are expected to occur in the impact zone where direct contact of the projectile and the glass takes place. Thus, it is very important to estimate accurately the contact force and its history.

The relaxation modulus \( G(t) \) for a linear viscoelastic material is generally given in the form

\[ G(t) = G_\infty + (G_0 - G_\infty) e^{-\beta t} \]  

where \( G_\infty \) is the long time shear modulus, \( G_0 \) is the short time shear modulus and \( \beta \) is the decay factor.

Since the impact duration is in the range of milliseconds, the stress relaxation modulus \( G(t) \) of PVB changes very little during impact. In this short time, PVB behaves like a solid glassy material. The linear elastic treatment of the PVB not only facilitates a closed form solution but also results in a significant reduction in computational time. In the time durations for low velocity impact problems, the difference in stresses obtained by treating the PVB as linear viscoelastic and linear elastic is less than 2%[9]. The most recent works[8-11] have shown that PVB can be modeled as linear elastic by using the short term shear modulus for a transient response. The Young’s modulus \( E_p \) and the Poisson’s ratio \( v_p \) for the PVB are given in terms of short term shear modulus \( G = G_0 \) and bulk modulus \( K \) as

\[ E_p = \frac{9 K G_0}{(3 K + G_0)} \]  

\[ v_p = \frac{3 K - 2 G_0}{(6 K + 2 G_0)} \]

In this study, therefore, the PVB will be modeled as a linear elastic material. The governing equation of this structures dynamic behavior is given by the Hamilton’s principle in the following form

\[ [M] \dot{\{u\}} + [K] \{u\} = \{F\} \]

where \([M]\) and \([K]\) are the mass and stiffness matrix of the beams, respectively. \{\dot{u}\} and \{u\} are the displacement and acceleration vector, respectively. \{F\} is the equivalent of external load, which includes the impact force.

In order to get numerical solution on the impact responses of the MG and LG beams, we adopt another equations of the Hertzian contact law applied the rule of mixtures[9]. Newton’s second law for the dynamic equation of the impactor and Newmark’s integration scheme for solving the dynamic equations of the target and the impactor for each time step including Equation (4). Similar simulating process were described in detail in Ref. [14].

3. NUMERICAL INVESTIGATION

A higher-order beam finite element is conducted for the study of the dynamic response of the MG and LG beams of identical thickness due to low-velocity impact.

It is applied to the contact law that both loading and unloading process are treated as elastic because the glass is a brittle material. The dimension of the MG and LG beams considered in this study is 5.76x300x1500mm. The beams are assumed to be impacted at the center by a steel ball impactor with diameter 12.7mm. The models are simply supported on both side edges. The material properties of target and impactor for simulation are shown in Table I.

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<th>Table I</th>
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<td>Material properties of target and impactor for simulation.</td>
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<td>Materials</td>
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<td><strong>Target</strong></td>
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<td>Glass (MG &amp; LG)</td>
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<td>PVB (LG)</td>
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4. RESULTS AND DISCUSSION

In order to verify the coded finite element program for this study, the present finite element analysis (FEA) is compared with the equivalent mass model (EMM) that the maximum contact and the contact duration can be estimated easily. But Sun and Huang[1] showed that the EMM can
predict approximately the maximum contact force but not the contact duration due to the long tail portion. Fig. 2 shows a comparison of contact force histories obtained from this FEA and the EMM for the MG and LG at velocity 10 m/s and 20 m/s. From Figure 2, in this FEA, the maximum contact forces for both the MG and LG occur at around 20 μs and 15 μs after the initial impact at velocity 10 m/s and 20 m/s, but in the EMM at around 15 μs and 12.5 μs, respectively. The two results of the FEA and the EMM in the maximum contact force at two velocities are agreed well to each other except that small tail portion at the contact force histories happens at the FEA. The maximum contact forces in the MG are a little (2-3%) larger than those of LG at velocity 10 m/s and 20 m/s.

![Fig. 2. Comparison of the contact force histories by the present result (FEA) and equivalent mass model (EMM) at (a) V=10m/s, (b) V=20m/s.](image)

Next, for verification of this coded program, the present numerical results are compared with the wave propagation theory. Figure 3 shows the dynamic strain histories at the points (0, 75, 150 mm apart from the center) on the surface S4 which is opposite to the impacted surface in the MG and LG beams at velocity 10 m/s. From Figure 3(a), the strains in the MG are less than those of LG during the impact event because the PVB interlayer has less stiffness than the glass ply. In Figure 3(b), the first dynamic strain responses of LG beam at 75 mm and 150 mm apart from the impact point occur at around 22.5 μs and 45 μs after the initial impact, respectively. From these results of the dynamic strain responses, the transverse wave velocity becomes 3333 m/s.

The transverse wave velocities of the MG with a single layer and LG with multiple layers by wave propagation theory are 3394 m/s and 3295 m/s, respectively. This transverse wave velocity of LG is calculated using the equivalent properties $G_e$ and $\rho_e^{[7,9]}$. From this comparison, the present coded program can be verified relatively by good coincidences between the two wave velocities.

From Figures 2 and 3, it can be seen that the present finite element program gives relatively reasonable simulated results in comparison with the open literature results.

![Fig. 3. The dynamic strain histories at (a) impact point, (b) 75 mm and 150 mm apart on surface S4 at V=10 m/s.](image)

The small differences among these results need to be reviewed later again with other researcher's paper if it can be found. The deflection histories of the MG and LG beams of the same total thickness subjected to impact loading are shown in Figure 4. The central deflection of the LG during impact event is about two times larger than that of the MG due to low flexure stiffness of PVB interlayer at each velocity.

Figure 5 shows contact force-deflection curves on the MG and LG regarding two different impact velocity levels 10 and 20 m/s. It shows that impact velocity level has strongly effect on the contact force and maximum deflection of the specimen. The maximum contact forces of the MG and LG show almost the same magnitude at identical velocity because the contact surface is the same glass panel but the maximum deflection does not occur at the maximum contact force.

It shows a typical wave-controlled impact that the contact force and beam deflection are never in phase $^{[15]}$. The numerical results for impactor velocity and energy histories according to initial impact velocity for the MG and LG are given in Figure 6. The velocity and energy at the time zero are the initial velocity and energy of impactor at which the
impactor hits the target. Velocity curves of Figure 6(a) decrease and take negative values and remain constant by time. These negative values represent rebound velocity of

![Figure 4](image1.png)

**Fig. 4.** The beam deflection histories.

![Figure 5](image2.png)

**Fig. 5.** Relationships of contact force and beam deflection.

the impactor. Minimum kinetic energy in Figure 6(b) occurs when velocity is zero.

At these curves, the lowest tip of the curve shows minimum kinetic energy and the end of curve that remain constant shows the rebound energy. And, also, the energy difference between initial energy and rebound energy becomes absorbed energy by target.

Figure 7 depicts relationships of contact force and ball displacement at velocity changes. The rigid impactor hitting the deformable target involves loading and unloading processes. The loading process is represented by curve O-A, whereas the unloading process is represented by curve A-O.

The energy of the impactor is the product of contact force by displacement, thus, the area under these closed curves represents the loading and unloading energy phase, respectively. If energy loss is negligible, the area under the loading curve O-A represents the initial energy \((E_i)\), which is the same as the kinetic energy at the start of impact. The area under the unloading curve A-O represents the rebound energy \((E_r)\) to the impactor. The absorbed energy \((E_a)\) absorbed during the impact is \(E_i\) minus \(E_r\) and is shown in the loop area of the contact force-displacement curve O-A-O.

In this study, the absorbed energy is attributed wholly to crushing of the target because the impactor is not damaged.

![Figure 6](image3.png)

**Fig. 6.** The (a) velocity and (b) energy histories.

![Figure 7](image4.png)

**Fig. 7.** Relationships of contact force and ball displacement.

![Figure 8](image5.png)

**Fig. 8.** Relationships of energy and impact velocity.
Figures 8 and 9 show relationships for summarizing the impact responses of Figures 6 and 7 through the numerical simulations at velocity 5, 10, 15 and 20 m/s. From Figure 8, three energies of the MG and LG increase proportional to the impact velocity.

In special, in the same initial impact energy, rebound energy of the MG is higher than that of LG during impact event but absorbed energy of the MG is lower than that of LG. In Figure 9, the absorbed ratios of velocity and energy regarding initial impact velocity represent $V_i/V_b$ and $E_i/E_b$, respectively. Two absorbed ratios of LG like the maximum deflection are two times larger than those of the MG, respectively, but two absorbed ratios of the MG and LG are approximately constant regarding initial impact velocity. Results show that PVB interlayer of LG has stronger effects on the impact resistance than the glass of the MG.

5. CONCLUSION

In the present study, a simple finite element approach for solving the impact responses of the MG and LG under impact loading is proposed and the corresponding finite element program is coded. Numerical results using the program are compared with those of equivalent mass model and wave propagation theory, and are verified by a good agreement among these results. The impact responses and the impact energies of the MG and LG under various impact velocities are additionally analyzed and compared with each other.

Through the present numerical results, it can be seen that the PVB interlayer do not affect so much on the contact force history, however, there is significant effect in the deflection and strain of the beam. When they have the same initial impact energy, the rebound energy in the MG and the absorbed energy in LG are larger than those of LG and the MG, respectively. Also, the absorbed ratios of velocity and energy of LG are larger than those of the MG but two absorbed ratios regarding impact velocity become constant.

This means that the MG beam may eventually be damaged because of lower absorbed ratios during impact. And, also, results indicate that LG is more impact resistant than the MG.

ACKNOWLEDGEMENT

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