Dynamic Responses of Laminated Glass Plate Subjected to Small Mass Impact

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***Abstract*— Low velocity impact on laminated glass plate like automotive window glass caused by foreign object can be generated internal damage that reduces the strength of the structure significantly. Dynamic responses on automotive glass window like the monolithic and laminated glass are studied by the use of the developed plate finite element simulation. To predict the dynamic response of laminated glass plates, an effective approach based on the Whitney and Pagano's First-order Shear Deformation Theory (FSDT), Dharani's PVB interlayer model and Hertz's contact law is suggested. Consequently, dynamic responses in MG plate system is more sensitive than those of LG plate system of the same glass thickness and prone to more failure risk. And we can see that the variation of PVB thickness of LG plate system does not affect so much on impact responses.**

***Index Term*— Laminated glass plate, Dynamic responses, Monolithic Glass (MG), Laminated glass (LG), Low velocity impact**

1. INTRODUCTION

Laminated glass (LG) plates are widely used as automotive and architectural glasses. LG consists of two or more layers of glass plies adhered by a polyvinyl butyral (PVB) interlayer. Glass plies are separated by a PVB interlayer that prevents the glass plies from shattering on impact and then, greatly reducing the possibility of injury. But unlike the monolithic glass (MG) plate that fails in a brittle manner, LG plate can reduce the number of dangerous flying fragments as many fragments will be adhered by a PVB interlayer. The main purposes of the PVB interlayer are to provide absorption of impact energy and adhesion to the two glass plies. Therefore, the PVB interlayer can be acted as a barrier avoiding penetration and fracture. However, despite of their advantages, the efficient application of LG plate is limited, because of the difficulties in their strength analyses at the initial stage of their design.

For optimal design for LG plate is required a thorough understanding of the impact behaviors of automotive glass under impact. The dynamic responses of isotropic materials and composite laminates subjected to transient dynamic loading have been studied in terms of analytical and numerical works by Whitney and Pagano's First-order Shear Deformation Theory (FSDT) [1, 2]. A lot of papers on impact of LG plate for automotive and architectural applications have been studied by Dharani and his coworkers [3, 4].

In this research, Whitney and Pagano's First-order Shear Deformation Theory (FSDT) in conjunction with Dharani's PVB model and the Hertzian contact law is used to predict the overall dynamic responses on the MG and LG plates. The glass plies and PVB interlayer are assumed as linear elastic. The dynamic responses such as the histories of contact force, deflection and stresses etc. during impact are obtained to study PVB interlayer effect for the MG and LG plates. From these results, the dynamic responses of LG plate are compared with that of the MG of the same total glass thickness, and PVB interlayer effect on dynamic response of LG plate subjected to low velocity impact is studied.

2. FINITE ELEMENT SIMULATION

Assume a LG plate consisting of three layers of total thickness h under small mass impact by an impactor of radius R with initial impact velocity V_0 as shown in Fig. 1.

To study dynamic response between glass plate and impactor, the element displacement function by Whitney and Pagano is applied. The Young's modulus E_p and the Poisson's ratio ν_p for the PVB by Dharani's PVB interlayer model are given in terms of short term shear modulus $G = G_0$ and bulk modulus K as

$$E_p = 9KG_0/(3K + G_0) \quad (1)$$
$$\nu_p = (3K - 2G_0)/(6K + 2G_0)$$

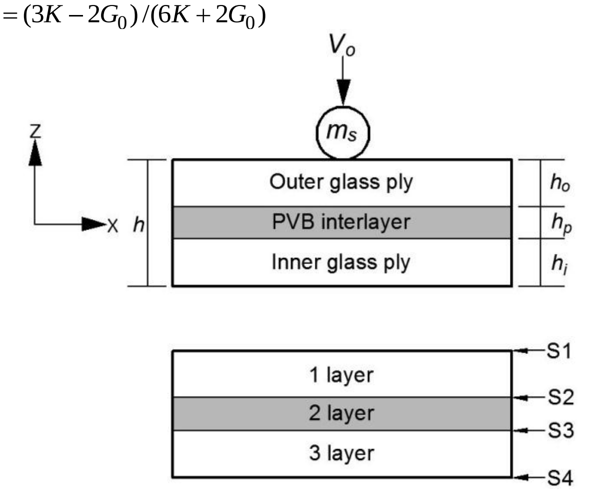

Fig. 1. Concept of a laminated glass plate under low velocity impact

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FSDT in conjunction with Hertzian contact law that both loading and unloading process is conducted for the study of the dynamic response of the MG and LG plates with the same total glass thickness due to low velocity impact. The thicknesses of the MG and LG plates considered are 12mm and 12.76, 13.52, 14.28mm, respectively. In other words, the thicknesses of PVB interlayer of LG plates are 0.76 (2 interlayers), 1.52 (4 interlayers) and 2.28mm (6 interlayers) and then, the model is assumed to be impacted at the center by an impactor with radius 6.35mm.

Similar dynamic finite element simulating processes were described in detail in Ref. [5, 6].

3. Results and Discussion

Fig. 2 shows deflection histories for various PVB interlayer thicknesses at 30μs at same total glass thickness under impact loading. We can see that the deflections in LG plate are larger than that of the MG plate, and the higher the thickness of PVB interlayer in LG plate, the higher the magnitude of deflection becomes because of low flexure stiffness of PVB interlayer at given velocity. And also, we can see that the maximum contact force does not occur at the maximum deflection. It shows a typical wave-controlled impact that the beam deflection is localized to the region around the impact point, and the contact force and deflection are never in phase.

Fig. 3 shows relationship of plate deflection, ball displacement and indentation for various PVB interlayer thicknesses. From Fig. 3, it can be seen that the thickness of PVB interlayer has significant effect on plate deflection but does not affect so much on ball displacement and indentation.

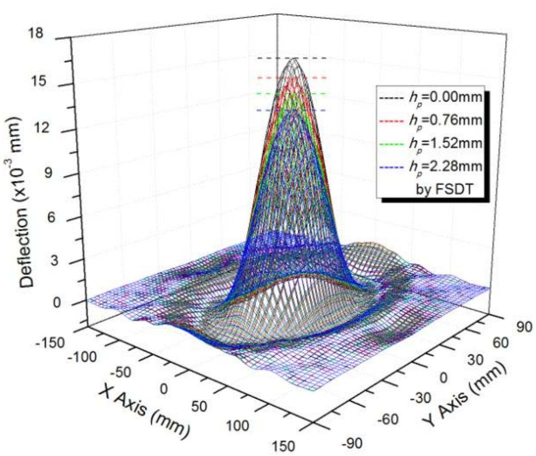

Fig. 2. Deflection histories for various PVB interlayer thicknesses at 30μs

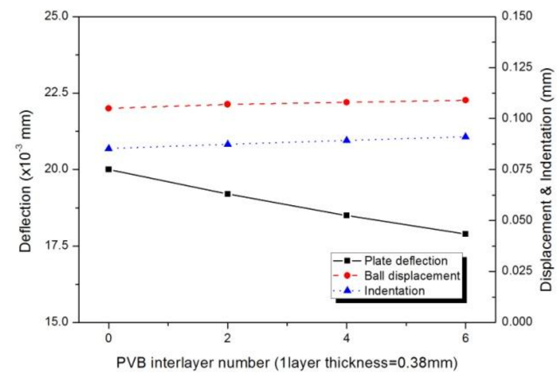

Fig. 3. Relationship of deflection, displacement and indentation for thickness of various PVB interlayer

From Fig. 4, it can be seen that PVB interlayer number is no significant effect on absorbed and rebound energies of MG and LG plates except COR.

Fig.5 depicts the deflection histories for MG and LG plate with various thicknesses at impact point at 30μs. We can see that deflection of MG plate is larger than that of LG plate. Fig. 6 shows the in-plane stress histories for MG and LG plate with various thicknesses on S4 (opposite side of impact point) at 15μs. We can see that in-plane stress of MG is larger than that of LG plate as shown in the deflection histories.

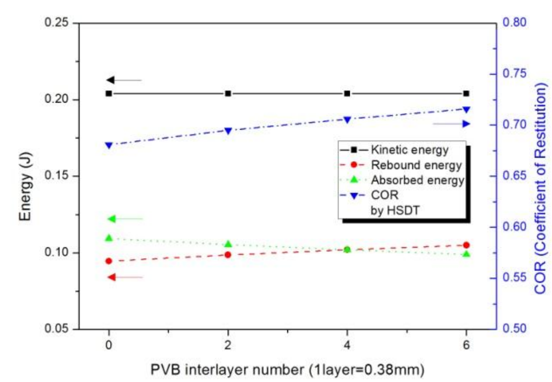

Fig. 4. Relationship of kinetic, rebound and absorbed energies for various PVB interlayer thicknesses

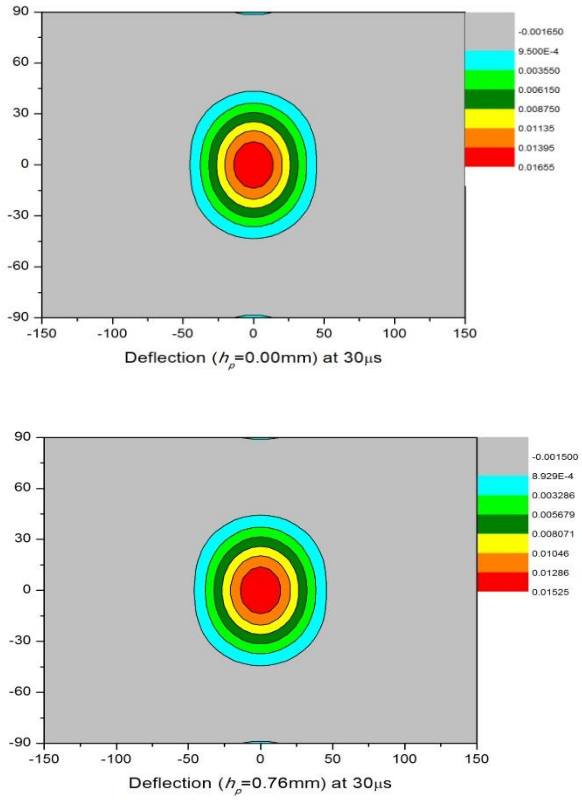

Fig. 5. The deflection histories for MG and LG plate with various thicknesses at impact point at 30μs

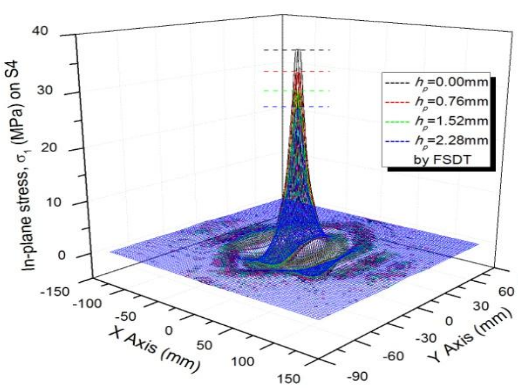

Fig. 6. The in-plane stress histories for MG and LG plate with various thickness on S4 at 15μs

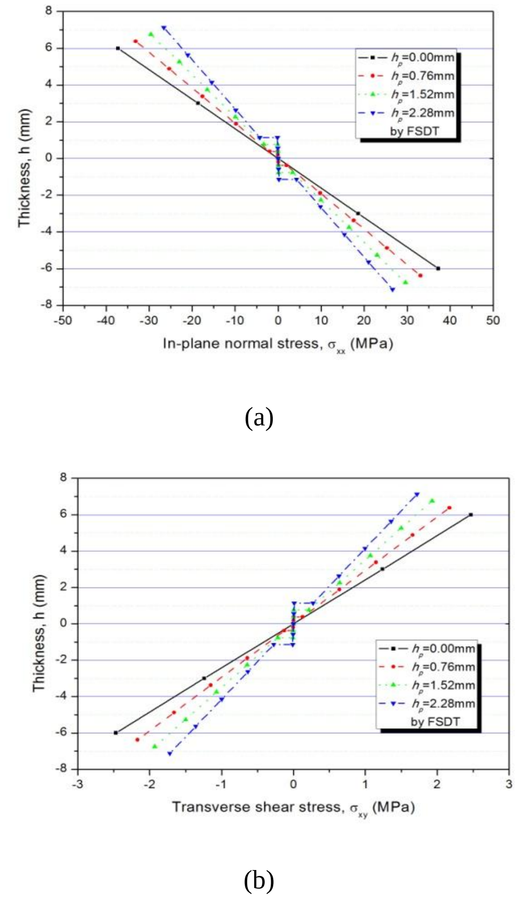

Fig. 7. Variations of (a) in-plane stress σ_{xx} (b) transverse shear stress σ_{xy} th rough the each layer of MG and LG plate systems

Fig. 7 shows the variations of in-plane stress, transverse shear stress through the each layer of MG and LG plates. In Fig. 7, when the thickness of PVB interlayer in LG plate increases, in-plane stress on impacted surface S1 decreases, whereas stress on surface (S2 or S3) over or under PVB interlayer is approximately zero independent of PVB interlayer thickness unlike that of MG plate perfectly. In addition, two stresses on the bottom surface S4 of plate is reversed those on the surface S1 of four plates. Therefore, it can be seen that PVB interlayer thickness in LG plate except MG plate does not affect so much on dynamic stresses occurred by low velocity impact

4. CONCLUSION

In this research, an effective finite element approach in conjunction with Whitney and Pagano's First-order Shear Deformation Theory (FSDT), Hertz's contact law and Dharani's film model for the dynamic responses of MG and LG plates under low velocity impact is suggested. The dynamic responses such as contact force, deformation, displacement and stress etc. of MG and LG plates are analyzed and compared with each other. From these numerical results, it can be concluded that Hertzian contact law and Dharani's film model applied is very effective on prediction of dynamic responses of MG and LG plates. We can see that the deflections in LG plate are larger than that of the MG plate, and the higher the thickness of PVB interlayer in LG plate, the higher the magnitude of deflection becomes because of low flexure stiffness of PVB interlayer at given velocity. Dynamic responses in MG plate are more sensitive than those of LG plate of the same glass thickness and prone to more failure risk. And we can see that the variation of PVB thickness of LG plate does not affect so much on dynamic responses. That is, it means that the PVB interlayer between two glasses under low velocity impact is essential for protection the inner glass from damage of foreign object. These results may be used as a guideline in making some initial design considering low velocity impact for plate composed of multilayer with different material properties and PVB interlayer in the future.

ACKNOWLEDGEMENT

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