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Microscopic Behaviors of Laminated Glass Plate Due to Foreign Object Impact

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Abstract

A foreign object impact on automotive windshield composed of laminated glass plate can be caused the reduction of the strength of window glass plate. Impact behaviors on laminated glass plate are approached by the formulation of the refined Reddy's Higher-order Shear Deformation Theory (HSDT) with links to Hertzian law and Dharani's PVB interlayer model. This HSDT contains the same dependent unknowns as in Whitney and Pagano's First-order Shear Deformation Theory (FSDT), and accounts for parabolic distribution of the transverse shear strains through the thickness of the plate. And this HSDT needs no shear correction coefficients and predicts the results of simulation more accurately when compared to FSDT. Through this HSDT, we can see micro impact behaviors like in-plane normal stress and transverse shear stress according to thickness of laminated glass more accurately. In-plane stress in monolithic glass plate are prone to more fracture risk than those of laminated glass plate with PVB interlayer, but the thickness of PVB interlayer of laminated glass plate does not present so much effect on impact behaviors. These results can't see a similar trend in those of simulation by using FSDT. That is, we can see so much difference in application of microscopic behaviors for laminated glass plate between HSDT and FSDT, and then we need the approach of HSDT for more accurate predictions of microscopic behaviors through the thickness of laminated glass plate.

Keywords: Foreign Object Impact, Microscopic Behaviors, Higher-order Shear Deformation Theory, Laminated Glass Plate

INTRODUCTION

Laminated glass plate for automotive windshield is composed of two glass plies adhered by a polyvinylbutyral (PVB) interlayer that prevents the glass plies from failure by foreign object impact. But laminated glass (LG) plate unlike the monolithic glass (MG) plate with a brittle material can reduce dangerous flying fragments as many small parts by small mass impact because of a PVB interlayer. The purposes of the PVB interlayer are generally to absorb the impact energy and adhere the two glass plates. Therefore, a PVB interlayer can be provided as a barrier between the two glass plates avoiding penetration and fracture. But in spite of their many advantages, the effective application of LG plate is limited because of the difficulties in their optimization at the preliminary design stage. Therefore, the more refined simulation for LG plate is required for a thorough study of the impact behaviors of laminated glass plate subjected to impact.

Many analytical and numerical papers on isotropic and anisotropic materials due to static and dynamic loading have been studied by Whitney and Pagano's First-order Shear Deformation Theory (FSDT) [1]. And many works about contact law and PVB effect on impact of LG plate for architectural applications have been presented by Hertz [2] and Dharani [3, 4]. Lee and Ahn etc. [5, 6] have been studied the impact behaviors of LG plate system by Whitney and Pagano's First-order Shear Deformation Theory (FSDT). A refined Higher-order Shear Deformation Theory (HSDT) for laminated composite plates is suggested by Reddy [7-10]. This higher-order theory contains the same dependent unknowns as in FSDT, and accounts for parabolic distribution of the transverse shear strains through the thickness of the plate. And also, the HSDT requires no shear correction coefficients and predicts stresses through the thickness of the plate more accurately when compared to FSDT. Recently, Ahn suggested the dynamic prediction of laminated glass plate [11].

In this work, Reddy's Higher-order Shear Deformation Theory (HSDT) in conjunction with Hertzian contact law and Dharani's PVB interlayer model is used to study the overall impact behaviors on the LG plates. The macroscopic impact behaviors such as the histories of deflection, kinetic energy, and the microscopic behaviors such as in-plane normal stress and transverse shear stress through the thickness for various PVB interlayer thicknesses are obtained for the LG plates. The impact behaviors of LG plate are compared and studied with those of the LG plates with the different PVB interlayer thickness and the same total glass thickness subjected to foreign object impact.

IMPACT MODEL

Consider a geometry of glass plate consisting of three laminated layers (total thickness h, outer ply thickness h_0, PVB interlayer thickness h_p, inner ply thickness h_i) due to foreign object impactor (radius R) at the center with initial velocity V_0 as shown in figure 1.

HSDT with links to Hertzian law and Dharani's PVB interlayer model is conducted for the impact simulation of the MG and LG plates with the same total glass thickness due to small mass impactor. 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 MG and LG plates are 0 (0 interlayer), 0.76 (2 interlayers), 1.52 (4 interlayers) and 2.28mm (6 interlayers) and then, the model is consudered to be impacted at the center by an impactor with radius 6.35mm. Similar HSDT simulating processes are described in Ref. [11] in detail.

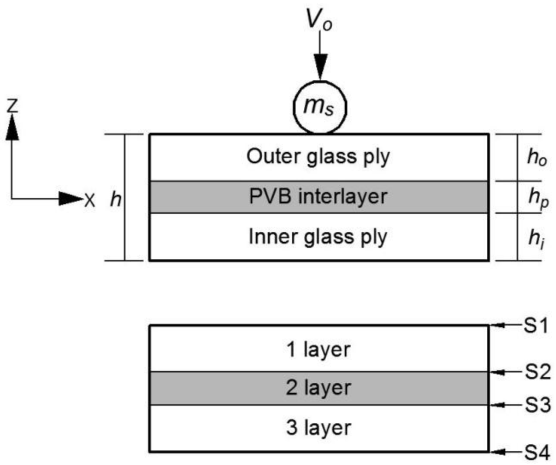


Figure 1: Geometry of a laminated glass plate due to foreign object impactor

RESULTS AND DISCUSSION

Figure 2 depicts deflection shapes of MG and LG for various PVB interlayer thicknesses subjected to small mass impact at 30µs. From figure2, We can see that deflection of MG plate is larger than that of LG plate. figure 3 shows relationship of plate deflection, ball displacement and indentation for various PVB interlayer thicknesses. From figure 3, it can be seen that the thickness of PVB interlayer has small effect on plate deflection, ball displacement and indentation. Therefore, we can see that the deflections in LG plate are a few smaller than that of the MG plate, and the higher the thickness of PVB interlayer in LG plate, the lower the magnitude of deflection becomes because of large flexure stiffness of overall LG plate with large PVB interlayer thickness at given velocity. We can see a typical wave-controlled impact that the plate deflection is localized to the region around the impact point, and the contact force and deflection are never in phase [12, 13].

Figure 4 shows relationship of kinetic energies, rebound energies and absorbed energies for various PVB interlayer thicknesses. Figure 4 shows relationship of kinetic energies, rebound ehergies and absorbed energies for various PVB interlayer thicknesses. From figure 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 like the results by FSDT simulation [5, 6].

Figure 5 shows the in-plane stress histories for MG and LG plate with various thicknesses on S2 (surface on PVB interlayer) and S3 (surface under PVB interlayer) at 15µs by HSDT. We can see that in-plane stress of MG is very larger than that of LG plate as shown in the deflection histories. Figures 6 and 7 depict the in-plane stress histories at various thicknesses on S3 and S4 at 15µs by HSDT.

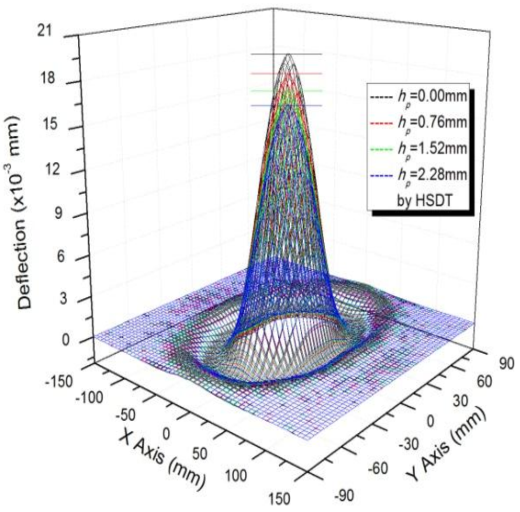


Figure 2: Deflection shapes for various PVB interlayer thicknesses at 30µs

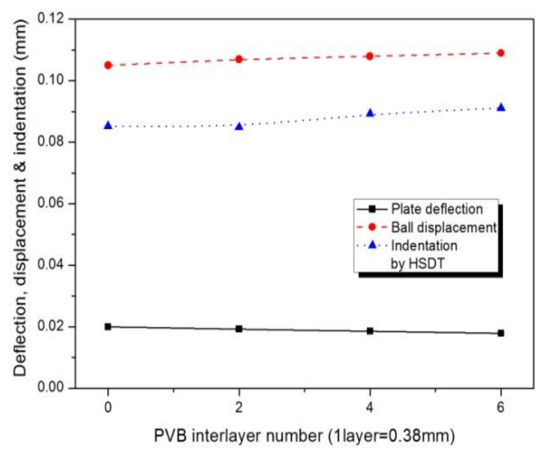


Figure 3: Relationship of deflection, displacement and indentation for thickness of various PVB interlayer

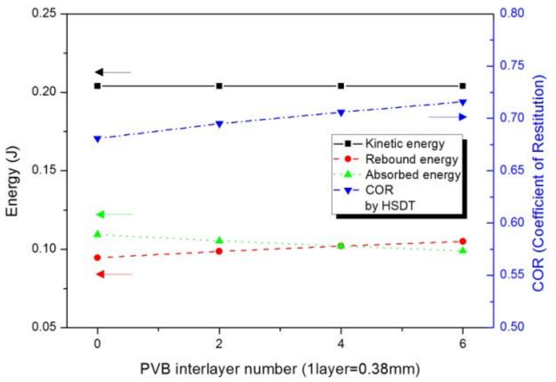
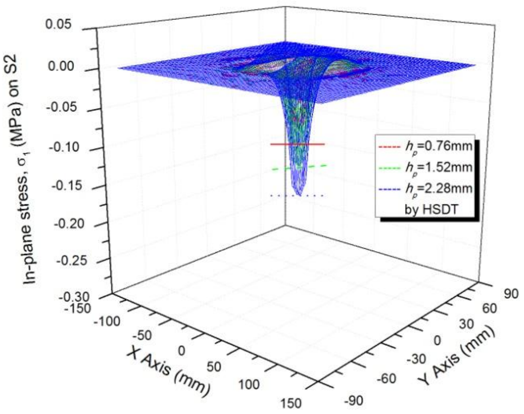
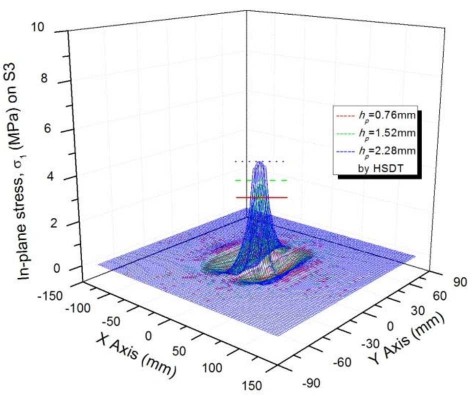


Figure 4: Relationship of kinetic, rebound and absorbed energies for various PVB interlayer thicknesses



on S2



on S3

Figure 5: In-plane stress histories for glass plates with various thickness on surfaces S2 and S3 at 15μs

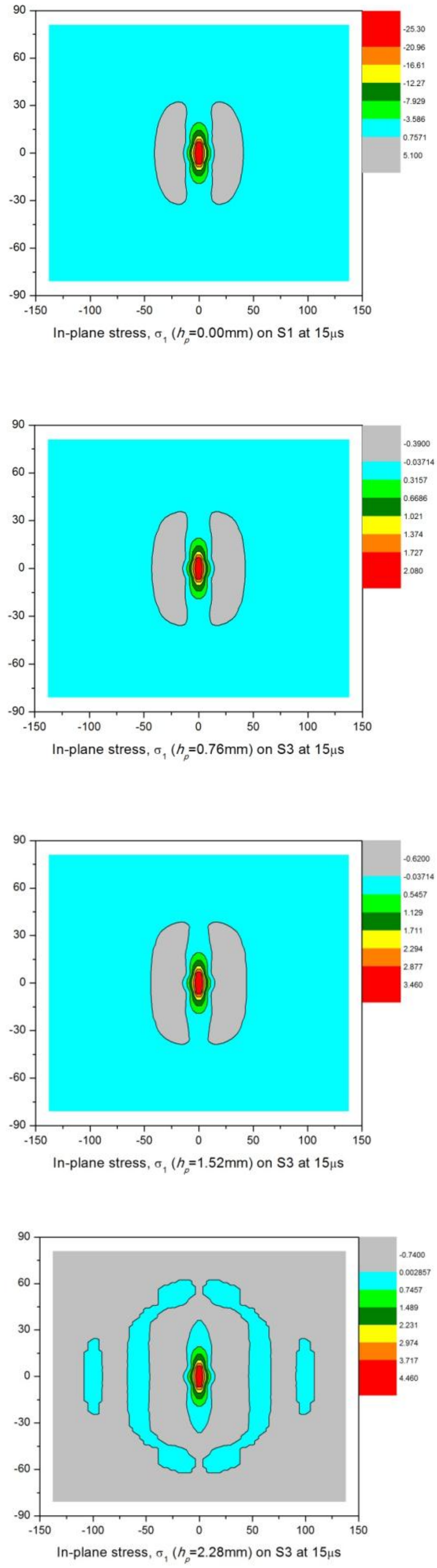


Figure 6: In-plane stress histories through the layer of (a) homogeneous (h_i= h_o= 6mm) and (b) layered system (h_i= h_o= 6mm and h_p=0.76, 1.52, 2.28mm) on S3.

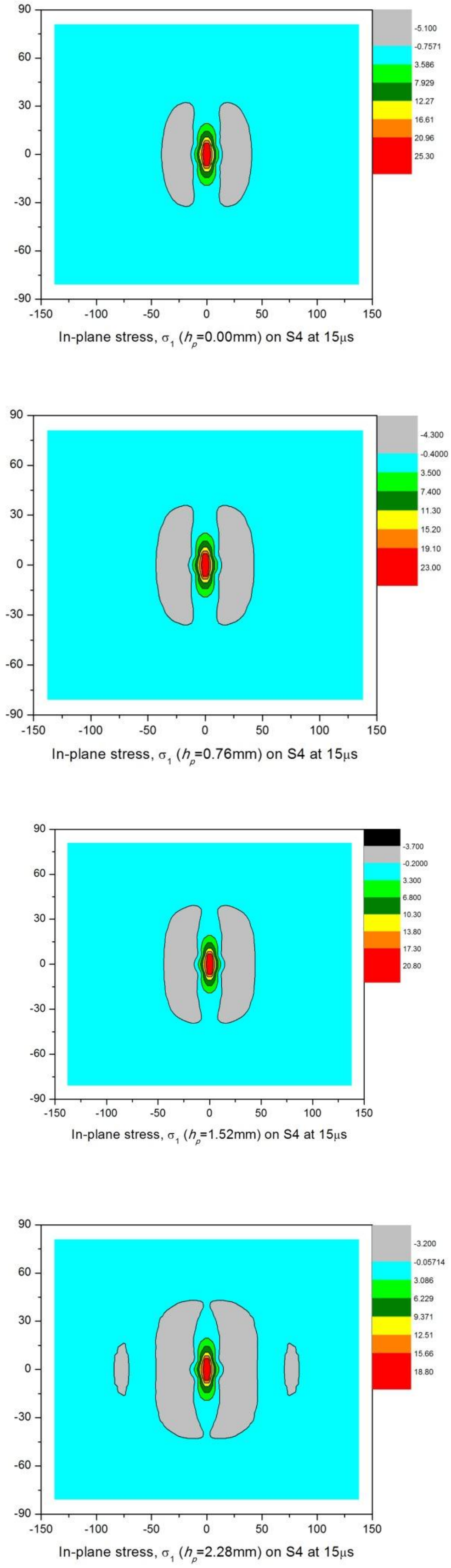
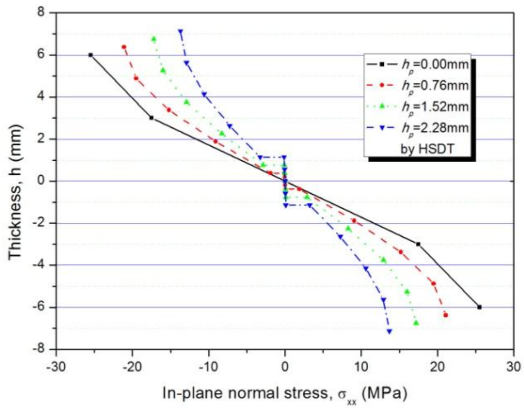
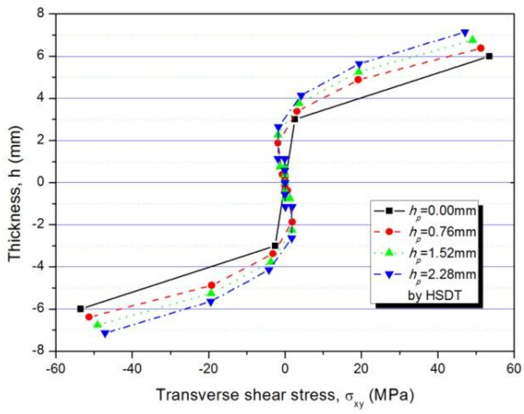


Figure 7: In-plane stress histories through the layer of (a) homogeneous (h_i= h_o= 6mm) and (b) layered system (h_i= h_o= 6mm and h_p=0.76, 1.52, 2.28mm) on S4.

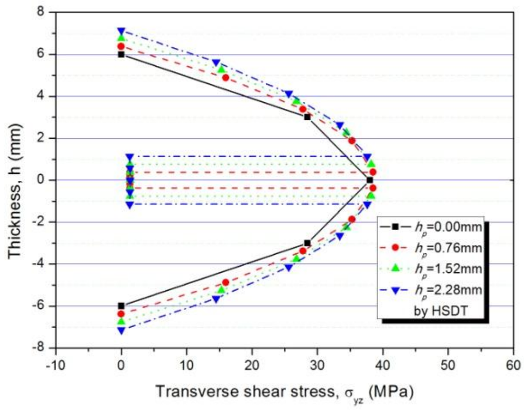
Figure 8 depicts the variations of in-plane stress $\boldsymbol{\sigma_{xx}}$, transverse shear stress $\boldsymbol{\sigma_{xy}}$ through the each layer of various glass plates. In figure 8, when the thickness of PVB interlayer in LG plate increases, in-plane stress on impacted surface S1 decreases, whereas stress on surface (S2 or S3) over or under PVB interlayer is approximately zero in nonlinear curve independent of PVB interlayer thickness unlike that of MG plate perfectly. And also, in-plane stress, transverse shear stress on the bottom surface S4 of plate is reversed in nonlinear line 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 impact stresses due to foreign object impactor. We can see that this nonlinear shape by refined HSDT analysis is very different from linear shape of FSDT simulation. Therefore we can predict dynamic behaviors more accurately through this HSDT than FSDT analysis.



(a)



(b)



(c)

Figure 8: Variations of (a) in-plane stress σ_{xx} (b) transverse shear stress σ_{xy} through the each layer of various glass plate systems

CONCLUSION

A refined finite element simulation in conjunction with Reddy's Higher-order Shear Deformation Theory (HSDT), Hertzian law and Dharani's PVB interlayer model for the impact responses of glass plates due to foreign object impact is studied. Through this HSDT, we can see micro impact behaviors like in-plane normal stress and transverse shear stress according to thickness of laminated glass more accurately when compared to FSDT. And this HSDT accounts for parabolic distribution of the transverse shear strains through the thickness of the plate and needs no shear correction coefficients**.** In-plane normal stress in MG plate (h_p=0.00mm) shows the linear shape but in LG plates the nonlinear curves. From this trend, we can predict that MG plate is prone to more fracture risk than LG plate with PVB interlayer, but the thickness of PVB interlayer of LG plate does not present so much effect on impact behaviors. These results can't see a similar trend in those of simulation by using FSDT. That is, we can see so much difference in application of microscopic behaviors for LG plate between HSDT and FSDT, and then we need the approach of HSDT for more accurate predictions of microscopic behaviors through the thickness of laminated glass plate.

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