BALLISTIC IMPACT TESTING OF BALSA, PVC FOAM, GLASS REINFORCED POLYURETHANE CORE SANDWICH STRUCTURES

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SUMMARY

The impact damage response of sandwich composites with balsa, poly vinyl chloride (PVC) foam and polyurethane E-glass reinforced web core (Tycor®) with E-glass/vinyl ester (VE) facesheets is evaluated by subjecting them to velocities beyond the ballistic limit for multiple impacts. Under high velocity impact loading, laminated composites experience significant damage causing fiber breakage, matrix cracking and delamination. The penetration through the sandwich composite is investigated and it is found that ballistic efficiency of the Tycor® is significantly higher than balsa and and PVC foam core. The ballistic impact study was extended to investigation of balsa wood core with S-glass/epoxy facesheets from an experimental and modeling standpoint. During high velocity impact, composite sandwich laminates undergo progressive damage and hence the sandwich is modeled using a progressive damage model. Experimental ballistic test results agreed well with the corresponding finite element simulations.

Keywords: Sandwich composites, balsa wood, PVC foam core, web core, E-and S-glass facesheet, multi-site impact

INTRODUCTION

Polymer matrix composite (PMC) laminates and sandwich structures have been extensively used in marine, military and aerospace field, due to their lightweight and high strength characteristics [1,2]. These laminates and sandwich structures are frequently subjected to impact loading by primary and secondary threats such as fragments from blast debris, shrapnel and multiple bullet impacts. Despite extensive research and development of laminated and sandwich structures, their response in terms of dynamic failure is less understood.

Under transverse impact of a sandwich composite, the facesheet undergoes significant damage such as fiber breakage, matrix cracking and delamination followed by penetration of the impactor into the core [2]. At higher impact velocities a critical condition is reached when the local contact stress exceeds the local strength, which may be the laminate bending strength, core compression strength or interface delamination strength. This stress leads to partial or complete penetration of the projectile into the sandwich composite structure.

Balsa wood, poly vinyl chloride (PVC) foam core and reinforced polyurethane cores are materials typically used in sandwich composite construction for marine and transportation applications. The objective of the current work is to understand the energy absorption and damage propagation of composite sandwich plates comprising E-glass/vinyl ester (E-glass/VE) and S-glass/epoxy composite laminate facesheets and core made from end-grain balsa wood, PVC foam core and reinforced polyurethane foam core. After providing results for ballistic behavior of sandwich composites made from these respective cores, the paper covers experiments accompanied by simulation studies conducted on balsa wood core sandwich composites.

MATERIALS AND METHODS

Three 4' x 8' (1.21 m x 2.43 m) panels were processed using vacuum assisted resin transfer molding (VARTM). Two layers of E-glass/Derakane 510A-40 brominated vinyl ester composite face sheets of 0.16" (4 mm) thick each sandwiched 2.32" (58.92 mm) thick core material. The panels had 3-D stitched Tycor® foam, Balsa wood, and Poly Vinyl Chloride (PVC) foam cores. Each panel type had a panel schedule is as follows:
[(0/90)/(+45/-45)/(90/0)/(-45/+45)/(0/90)]/Core/[(90/0)/(+45/-45)/(0/90)/(+45/+45)/(90/0)]
20" x 20" (0.508 m x 0.508 m) sample was cut for each of the large panels. These were to be used for the multi site ballistic evaluation. Several 12" x 12" foam sandwich composites were also used to establish the damage zones in the panel using the threat level defined by National Institute of Justice (NIJ) Level III [3]. Ballistic testing was performed on three different composite sandwich panels with dimensions of 20" x 20" x 2.32" thick (0.508 m x 0.508 m x 0.058 m thick).

EXPERIMENTAL

Manually loaded bullets of 9.6 gram (147 grain), 7.62 mm (0.308") nominal diameter and 28.2 mm (1.11") in length were used. The test system had an unvented velocity test barrel mounted in a Universal Receiver [1]. The receiver was attached to a table with sufficient restraint to ensure accurate targeting of repetitively fired rounds. A proof chronograph used three sky-screens with two timers to measure the velocity of projectile. It was used to determine the residual velocity of bullet leaving from the specimen. A two-foot long rail was mounted on a camera tripod that held the three sky-screens precisely [1].

Two Infrared Ballistic Screens were used to detect projectile passage through a reference plane providing the striking velocity of bullet at the specimen. They used an infrared light source mounted at the top of the screen and a series of photo-detectors mounted in the base. Automatic gain control was included to compensate for effects such as dust in the light path. The screen provided a nominal +12 volt pulse of approximately two-millisecond duration from a panel mounted BNC connector. The output was approximated by 50 ohms to +12V in the high state and by 10K ohms to ground in the low state. The rise time was approximately 0.1 microseconds.

The specimen was held using a square steel bracket in a fixed-fixed boundary condition positioned at approximately 30’ (9.144 m) from the firing barrel. The proof chronograph was placed at the back of the fixture. The two Infrared Ballistic Screens in front of the specimen were 4’ (1.21 m) apart. The velocity data were displayed on a built-in printer connected to the screens.

Five specific shot locations were marked on each specimen panel. Three of them were located in close proximity to get the relative ballistic interaction among them for consecutive shots. For Tycor® sandwich panel two target marks were located on the intersection of the web of the core and other three marks were at locations between the web to evaluate the responses based on location.

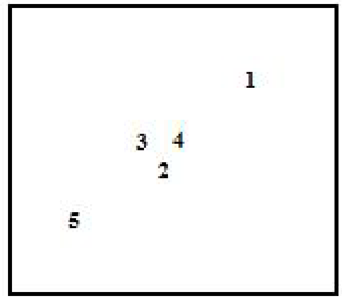
RESULTS AND DISCUSSION

Tables 1, 2 and 3 summarize the ballistic response for the balsa wood, PVC foam core and the Tycor® web core sandwich panels. The test velocities exceeded the ballistic limit in each case and full penetration through the sandwich panels was observed. The difference in kinetic energy before and after penetration is a measure of the energy absorbed by the sandwich panel. Figures 1 to 9 illustrate modes of ballistic failure of the panels.

Table 1. E-glass / Balsa vinyl ester sandwich			Shot locations (Front view)
Shot ID	Striking Velocity ft/s (m/s)	Residual Velocity ft/s (m/s)	
1	2919 (890)	2871 (875)	
2	-	2897 (883)	
3	2911 (887)	2890 (881)	
4	2888 (880)	2843 (867)	
5	2951 (899)	-	
6	2885 (879)	-	

The strike velocity was approximately 2900 m/s for all the panels tested. The exit velocities were measured to be between 2400 – 2800 m/s indicating that the tests represented conditions exceeding ballistic limit. Due to the debris generated in the core, a large number of small particles exit the back face, and residual velocity was not possible to record in several cases. However Figures 3, 6 and 9 provides a comparative performance based on the damage zone on the exit side of the panel.

The PVC foam core had very minimal damage on the exit face implying that the least amount of energy has been absorbed. The balsa core provides a higher degree of interaction between the core and the face sheets. The back face damage is larger compared to the PVC core panel. The Tycor® foam core provides the highest degree of engagement of the core for a projectile that strikes the intersection (x-y intersection) of the z-direction web core members, i.e. fiber stiffeners. The size of the damage zone size reduces if the projectile strikes one (either x or y) or between the web in the area covered by unreinforced polyurethane. If the projectile strikes between the stiffeners, i.e. in the unreinforced polyurethane foam area, the damage on the back face is very similar to the PVC foam core.

Table 2. E-glass /PVC vinyl ester sandwich			Shot locations (Front view)
Shot ID	Striking Velocity ft/s (m/s)	Residual Velocity ft/s (m/s)	
1	2935 (895)	2927 (892)	
2	2950 (899)	2865 (873)	
3	2961 (903)	-	
4	2970 (905)	-	
5	2978 (908)	-	

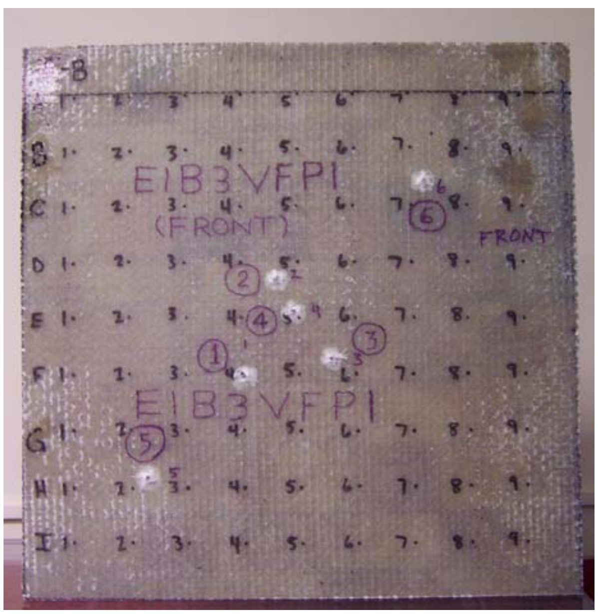


Figure 1: E-glass / Balsa vinyl ester sandwich – Front view

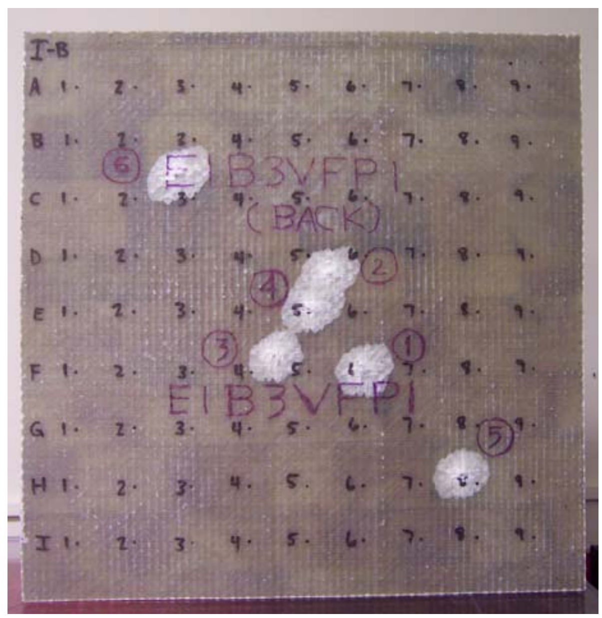


Figure 2: E-glass / Balsa vinyl ester sandwich – Back view


Figure 3: E-glass / Balsa vinyl ester sandwich – Side view (projectile exit)

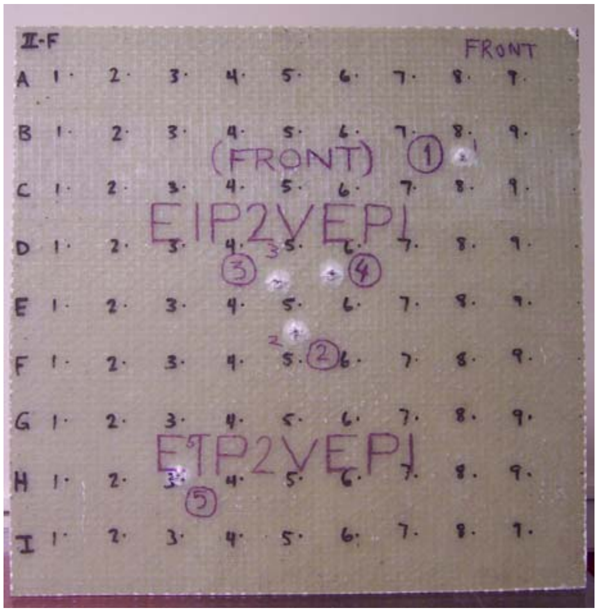


Figure 4: E-glass / PVC vinyl ester sandwich – Front view

Figure 5: E-glass / PVC vinyl ester sandwich – Back view

Figure 6: E-glass / PVC vinyl ester sandwich – Side view (projectile exit)

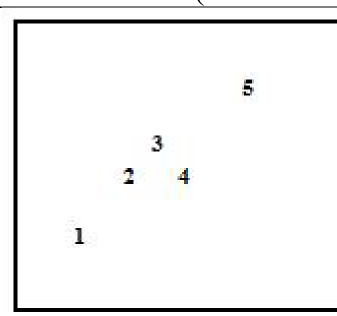
Table 3. E-glass /Tycor vinyl ester sandwich			Shot locations (Front view)
Shot ID	Striking Velocity ft/s (m/s)	Residual Velocity ft/s (m/s)	
1	2925 (892)	2443 (745)	
2	2898 (883)	-	
3	2969 (905)	-	
4	3007 (917)	-	
5	2948 (899)	-	

Figure 7. E-glass/Tycor vinyl ester sandwich – Front view

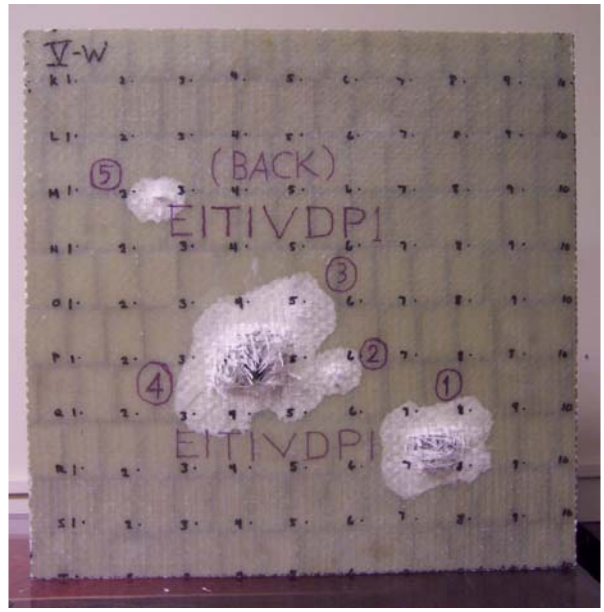


Figure 8. E-glass/Tycor vinyl ester sandwich – Back view

Figure 9. E-glass / Tycor vinyl ester sandwich – Side view (projectile exit)

Energy absorption

The kinetic energy (KE) in joules is the absorbed by the target panel which is calculated using the following relation [1]:

$$KE = ½ \times m \times (V_S^2 - V_R^2) \qquad (1)$$

where, m = projectile mass (kg), V_S = striking velocity (m/s) and V_R = residual velocity (m/s)

Figure 10 illustrates energy absorption capacity or ballistic efficiency of the three types of sandwich panels. It shows Tycor® sandwich panel absorbs the highest kinetic energy (1150 J) for the strike condition at the web intersection, as compared to PVC foam and balsa core sandwich panels which absorbed about the same energy ~100-200 J, significantly lower than the Tycor® sandwich.

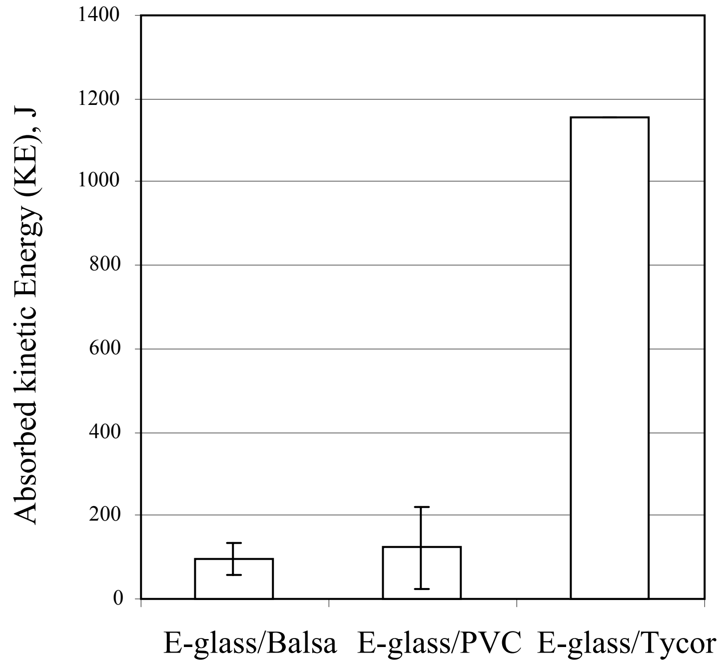


Figure 10. Energy absorption capacity of sandwich composites.

E-glass/Balsa Wood Core Sandwich Composite

In a different set of experiments, balsa wood core/S-glass epoxy sandwich composites were evaluated for their ballistic impact response. For these investigations, the strike velocity used was closer to the ballistic limit so as to evaluate progressive damage. 0.30 caliber steel spherical projectiles were used to impact the sandwich composite at velocities of 220–307 m/s. The impacted specimens were sectioned to study the damage modes. The experiments were compared to finite element analysis, LS-DYNA based modeling.

Progressive damage and delamination of composite facesheet have been modeled using LS-DYNA with the material model MAT 162 which incorporates continuum damage mechanics of anisotropic materials [4]. Impact on the balsa wood core was simulated using material model MAT 143 [5].

Table 4 summarizes the experimental results and corresponding numerical predictions respectively. The damage section of a representative sandwich plate subjected to impact energies between 49.5 and 66.99 J for .30 cal. projectile is shown in Figures 11 and 12. These energy levels are below the ballistic limit of the specimen for the .30 cal. impact. Specimens 4 and 5 in Table 4 are above the ballistic limit.

Table 4: S-2 glass/epoxy balsa core sandwich plate, single projectile impact results								
Specimen	Projectile	Incident velocity (m s-1)	Residual velocity (m s-1)	Impact energy (J)	Residual energy (J)	Energy absorption (J)	New surface creation (cm2)	
							Front skin	Back skin
1	0.30 caliber	220.37	0	49.5	0	49.5‡	13.45	15.22
2	0.30 caliber	254.8	0	66.18	0	66.18‡	16	39.64
3	0.30 caliber	256.34	0	66.99	0	66.99‡	17.64	38.53
4	0.30 caliber	266.1	0	72.23	0	72.23‡	12.5	35.4
5	0.30 caliber	307.24	113.69	96.28	13.18	83.1†	14.6	78.65

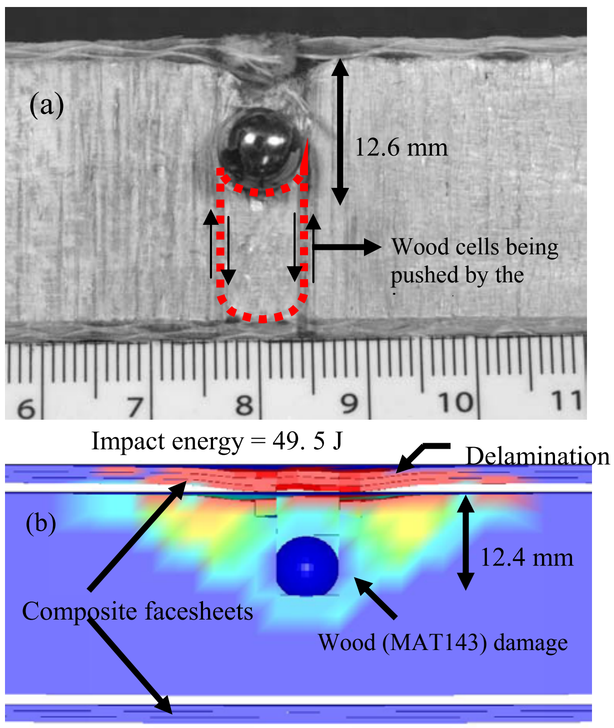


Figure 11. (a) Failure mode of S2-glass/epoxy balsa core sandwich panel subjected to impact energy of 49.5 J (b) simulation showing wood damage and delamination

A closer examination of the sandwich composite plate subjected to a 49.5 J impact shows that the top composite facesheet undergoes complete perforation indicating fiber fracture and delamination at the facesheet-core interface. The balsa core exhibited localized crushing directly below the point of impact (Figure 11a) up to a distance of 12.6 mm through the core thickness. The .30 cal. projectile is trapped within the balsa core by pushing the cells around the projectile. Kinetic energy is dissipated in deforming the wood cells. Small amounts of delamination (≅ 15.22 cm^2) were observed at the distal side of the specimen (Table 4). The delamination can be attributed to the energy imparted by the wood cells that are pushed down by the projectile towards the bottom facesheet shown in Figure 11a.

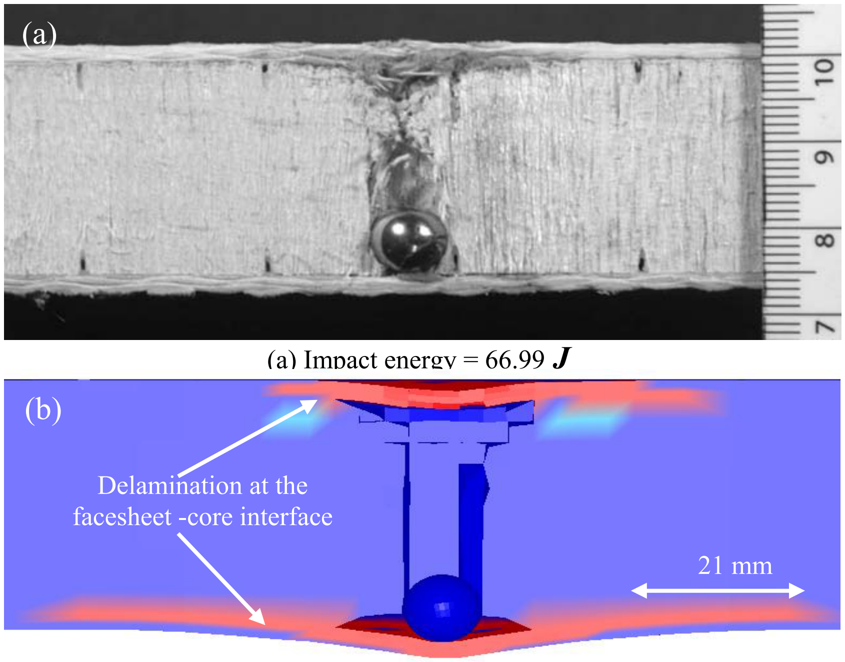


Figure 12. 0.30 caliber projectile impact at 66.99 J (a) Experimental damage (b) Simulation showing delamination (red area) at the top and the bottom facesheet

The simulated damage of the sandwich composite plate subjected to a 49.5 J impact event is illustrated in Figure 11b. Numerical prediction of energy absorption was 49.5 J which was in close correspondence to the experimental result.

The front facesheet delamination (≅14.2 cm^2) was adequately predicted in the simulation, while the bottom facesheet delamination (15.2 cm^2) was not adequately predicted. This can be explained as follows. As the impact energy increased, the projectile struck the bottom composite facesheet, which then exhibited small amounts of splitting at the core to facesheet interface as shown in Figure 12a. The strike face shows fiber breakage, fiber-matrix debonding, interlaminar and facesheet to core interface delamination. No fiber breakage was observed at the bottom facesheet. A closer examination of the balsa core specimen revealed complete crushing of the wood core with indications of significant shear deformation. The projectile was arrested by the bottom composite facesheet resulting in complete energy absorption by the sandwich plate. The average delamination (or new surface creation) at the front facesheet was 15.7 cm^2 for the impact energy range of 49.5 – 66.99 J, while the bottom facesheet delamination was 39.1 cm^2 at impact energy of 66.6 J. The predicted energy absorption and delamination area for impact energy 49.5 J and 66.99 J .

Figure 11b shows 64% higher delamination growth (red area) for the bottom facesheet compared to the top facesheet of the sandwich plate at 66.99 J impact energy. The 0.30

caliber projectile penetrated through the balsa wood until it made contact with the bottom facesheet, and rebounded from the bottom facesheet with a velocity of 39 m s^{-1}, specimen 1. The delamination prediction in an overall sense falls within 95% of corresponding experiment results.

CONCLUSIONS

Multi-site high velocity projectile impact testing was conducted on sandwich panels with E-glass/vinyl ester skins and different core materials. Residual velocity of the projectile was highly influenced by the energy absorbability of core material. The visual analysis of post impact views of composite panels concludes that projectiles passed through the panel thickness, tearing and delaminating the E-glass/vinyl ester skin as well as penetrating core materials. The delamination and puncture of the skin due to penetration occupied more area at the back face with respect to the front face due to high deceleration rate. Energy absorbed by the Tycor® core when impacted at the web intersection was 575% higher than that for balsa and PVC cores. The damage in balsa and PVC core was minimal, indicating lower energy absorption capacity. These unreinforced cores offer less shear resistance at high velocities, while energy absorption enhances with core reinforcement.

Progressive damage and delamination of composite facesheet have been modeled. The sandwich composite exhibited a number of failure and energy absorbing mechanisms such as fiber breakage, fiber-matrix delamination, facesheet-core delamination, fiber splitting/debonding along the primary yarns and localized collapse of the balsa wood cells. Delamination at the bottom face was found to be 64% higher than the top face delamination for .30 caliber impact results on S-glass/epoxy balsa core sandwich composites.

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