LS-DYNA® Impact Simulation of Composite Sandwich Structures with Balsa Wood Core

L. J. Deka and U. K. Vaidya*
Department of Material Science & Engineering
The University of Alabama at Birmingham
Birmingham, AL 35294-4461
**Corresponding Author. Tel: 205-975-9199*
E-mail address: uvaidya@uab.edu

Abstract

The impact damage response of balsa core sandwich composite plates with S2-glass/ epoxy reinforced facesheets is evaluated by impacting them with a spherical steel projectile at single impact locations. The impact damage can significantly reduce the structural integrity and load bearing capacity of a composite structure. Under high velocity impact loading, laminated composites experience significant damage causing fiber breakage, matrix cracking and delamination. Energy absorption and delaminations from high velocity impacts with spherical projectile of .30 caliber is discussed. Finite element modeling was used to gain insight into failure modes, energy absorption, and damage prediction. During high velocity impact, composite laminates undergo progressive damage and hence, Material Model 162, a progressive failure model based on Hashin's criteria, has been assigned to predict failure of the laminates. The laminates, the projectiles and the balsa wood core are meshed using brick elements with single integration points. These results were then compared with experimental data obtained from three layer S-2 glass/epoxy facesheets balsa core sandwich structures. An excellent correlation between experimental and numerical results had been established.

Key words: Impact damage, sandwich structures, balsa wood core, numerical modeling

1. 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. 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 [1].

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 is a common core material in composite construction. The cellular microstructure of balsa makes it anisotropic, yet possessing excellent specific strength, stiffness and specific energy dissipation capacity. Wood has been used as a protective material for high velocity impact events for many centuries [3]. There have been only a few systematic studies of the behavior of wood that have investigated high rates of loading from impact events [3–4].

The objective of the current work is to understand the energy absorption and damage propagation of composite sandwich plates comprising S2-glass/epoxy composite laminate facesheets and core made from end-grain balsa wood from both experimental and finite element modeling view point.

2. Model description

The sandwich specimens consisted of S2-glass/epoxy face sheets with balsa wood core and were processed with vacuum assisted resin transfer molding technique. A single stage gas gun was used to impact the sandwich specimens at the center of the exposed area. Energy absorption in each specimen was calculated from the incident and residual velocities. Details of the sandwich panel constructions and average dimensions are provided in Table 1.

Table 1: S2-glass/epoxy balsa core sandwich characteristics

Sandwich specimen	Dimensions (mm x mm)	Number of composite plys in facesheets	Average sandwich thickness (mm)
S2-glass/epoxy unscored balsa	200 x 200	3	27.40

2.1 Mesh generation and contact definition

Hypermesh v 8.0 and finite element model builder (FEMB) were used as pre-processors in the model development. The manufactured composite plate consisted of six plies (three plies each for the top and bottom facesheet) and balsa wood core. The grid geometry of the sandwich plate was designed as three layers of brick elements with one element through thickness per layer and ten elements through the thickness of the core. Each plain weave layer and the balsa core had 16,000 and 27,600 brick elements respectively. The 0.30 caliber steel spherical projectile were modeled with 1300 brick elements. A gradient in mesh density was applied with sufficient detail (0.79 x 0.79 x 0.70 mm^3 with aspect ratio of 1.1) in the impact area and larger elements (6.9 x 1.8 x .7 mm^3 with aspect ratio of 10.74) towards the edges, thereby providing computational efficiency with smooth stress gradient from the impact point to the edge [5].

Hourglassing i.e. mesh distortion is a common numerical instability observed at the impact region [6]. An adequate hourglass energy (HGE) coefficient is required to incorporate as an input parameter to the model, because this coefficient inhibits the hourglass mode of the target and projectile. Type 3 and 4 hourglass control with a HGE coefficient (QM) = 0.01 was used for balsa wood core and composite facesheets respectively. The QM value of 0.01 minimized the HGE excitement at the impact region.

The contact between the projectile and the sandwich composite plate was defined using CONTACT_ERODING _SINGLE_SURFACE which falls under the penalty method [6]. Eroding contact type is recommended when solid elements in the contact definition are subjected to erosion (element deletion) to avoid numerical disturbance due to large element distortion at the impact region [5].

2.2. Composite progressive failure model and strain softening characteristics

Fiber breakage, crushing, matrix cracking and delamination are the major failure mechanisms in laminated composites subjected to ballistic impact [7]. While a variety of models exist in LS-DYNA for the prediction of failure in composite laminates, recent work [5,7,8] has shown that the progressive failure model, MAT 162 (MAT_COMPOSITE_DMG_MSC) can significantly improve damage prediction and reduce numerical instability in models for high velocity transverse impact in PMCs.

Since the current research work considers plain weave composite materials for the facesheets, the mechanical properties are assumed equal in both in-plane directions. Therefore fiber breakage in the fill and warp direction can be caused by tensile and shear stresses leading to the following failure criteria [6,7]:

$$f_{tensile/shearfill} = \left(\frac{\langle \sigma_1 \rangle}{X_T}\right)^2 + \left(\frac{\tau_{12}^2 + \tau_{31}^2}{S_{XFS}^2}\right) - 1 = 0 \quad if \quad \sigma_1 > 0 \qquad (1)$$

$$f_{tensilewrap} = \left(\frac{\langle \sigma_2 \rangle}{Y_T}\right)^2 + \left(\frac{\tau_{12}^2 + \tau_{23}^2}{S_{yFS}^2}\right) - 1 = 0 \qquad (2)$$

where X_T, Y_T are the axial tensile strengths in the fill and warp directions, respectively and S_{XFS}, S_{YFS} are the fiber shear strength.

During transverse impact, the impact region of the composite laminate is compressed by the projectiles leading to high in-plane compressive stress generation in fill and warp direction expressed by the maximum stress criterion [6,7]:

$$f_{compressionfill} = \left(\frac{\langle \sigma_1' \rangle}{X_C}\right)^2 - 1 = 0, \quad \sigma_1' = -\sigma_1 + \langle -\sigma_3 \rangle \qquad (3)$$

$$f_{compressionwrap} = \left(\frac{\langle \sigma_2' \rangle}{Y_C}\right)^2 - 1 = 0, \quad \sigma_2' = -\sigma_2 + \langle -\sigma_3 \rangle \qquad (4)$$

where X_C, Y_C are the compression strengths in the fill and warp directions, respectively.

The penetration failure mechanism caused by fiber crush under compressive pressure is modeled using the following criterion [6,7]:

$$f_{crush} = \left(\frac{\langle p \rangle}{S_{FC}}\right)^2 - 1, \quad p = -\frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \qquad (5)$$

where S_{FC} is the fiber crush strength.

Matrix mode failure occurs in a plane where the normal and two-shear stress components reach a maximum value. Under loading conditions transverse matrix cracks propagate through the layer thickness and extend along fiber-matrix interface leading to subsequent delaminations. Matrix cracking (6) and interface delamination (7) were predicted by the following criterion [6,7]:

$$f_{matrixcrack} = \left(\frac{\langle\sigma_2\rangle}{Y_T}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 + \left(\frac{\tau_{12}}{S_{12}}\right)^2 - 1 = 0 \qquad (6)$$

$$f_{delamination} = S^2\left\{\left(\frac{\langle\sigma_3\rangle}{Z_T}\right)^2 + \left(\frac{\tau_{23}}{S_{23}}\right)^2 + \left(\frac{\tau_{31}}{S_{31}}\right)^2\right\} - 1 = 0 \qquad (7)$$

where Z_T, S_{23} and S_{12} are the failure strength properties and $\sigma_2, \sigma_3, \tau_{23}$ and τ_{31} are corresponding stress state. A scale factor *S* in eq. (7) is introduced to achieve better correlation of simulated delamination area with experimental values. In this study we incorporated S_d = 1 and S_d = 5 reiteratively for the top and bottom facesheet until adequate correlation of delamination area was obtained with the experiment. The S_d parameter and its effect on delamination and energy absorption is discussed in [5].

Strain softening characteristics of the composite laminate was implemented through continuous damage mechanics (CDM) approach which describes the anisotropic damage in elastic-brittle fiber reinforced composites [9]. The CDM formulation takes into consideration the post failure mechanisms in a composite plate as characterized by a reduction in material stiffness (E_{red}). A set of damage variables, ϖ_i with $i = 1,....6,$ were introduced to indicate the state of anisotropic damage maintaining the orthotropic damage nature of the material through out the damaging process [6,9]

$$E_{red} = (1 - \varpi_i)E_i \qquad (8)$$

$$\varpi_i = 1 - e^{\frac{1}{m_i}\left(1 - r_i^{m_i}\right)}$$

where ϖ_i = damage variable, m_i = strain softening parameter and r_j = damage threshold. The damage variable ϖ_i varies from 0 to 1.0 as r_j varies from 1 to ∞, respectively. There are four strain softening input parameters (m_1-fiber damage in *x* direction, m_2-fiber damage in *y* direction, m_3-fiber crush and punch shear damage and m_4-delamination damage) required for MAT 162. Xiao et al. [8] proposed certain values (fiber damage, m_1/m_2 =2, fiber crush and shear damage, m_3=0.50, delamination, m_4= 0.2) for the above mentioned strain softening parameters for S2-glass/SC-15 epoxy composites using quasi-static punch shear technique. In the previous study [5] the authors calibrated the m_1/m_2 parameters (m_1/m_2 = 0.6) and established a good matching between experimental and simulation events. In the current study we conducted all the simulations with same strain softening parameters calibrated in [5] and established a good correlation between experiment and numerical results.

Table 2: Material properties of a plain weave S2-glass/epoxy laminates [5,8]	
Density, ρ, kg mm^{-3}	1.85E-06
Tensile modulus, EA, EB, EC, GPa	27.1, 27.1, 12.0
Poisson's ratio, v21,v31, v32	0.11, 0.18, 0.18
Shear modulus, GAB, GBC, GCA, GPa	2.9, 2.14, 2.14
Inplane tensile strength, SAT, SBT, GPa	0.604
Out of plane tensile strength, SCT, GPa	0.058
Compressive strength, SAC, SBC, GPa	0.291
Fiber crush, SFC, GPa	0.85
Fiber shear, SFC, GPa	0.30
Matrix mode shear strength, SAB, SBC SCA, GPa	0.075, 0.058, 0.058
Residual compressive scale factor, SFFC	0.30
Friction angle, PHIC	10
Damage parameter, AM1, AM2, AM3, AM4	0.6, 0.6, 0.5,0.2
Strain rate parameter, C1	0.10
Delamination, S_DELM	1, 5
Eroding strain, E_LIMIT	1.20

Table 3: Material properties for the tool steel spherical projectile [5,7]	
Density, ρ, kg mm^{-3}	7.86.E-06
Young's modulus, E, GPa	210
Poisson's ratio	0.28
Yield strength, GPa	1.08

Table 4: Material properties of end-grain balsa wood core [11–13]	
Density, ρ, kg mm^{-3}	1.55E-07
Moisture content, %	1.20E+01
Stiffness :	
Parallel normal modulus, EL, GPa	5.30
Perpendicular normal modulus, ET, GPa	0.20
Parallel shear modulus, GLT, GPa	0.166
Parpendicular shear modulus, GLR, GPa	0.085
Parallel major poisson's ratio	0.25
Strength :	
Parallel tensile strength, XT, GPa	0.0135
Perpendicular tensile strength, YT, GPa	0.0004
Parallel compressive strength, XC, GPa	0.0127
Perpendicular compressive strength, YC, GPa	0.0023
Parallel shear strength, SXY, GPa	0.003
Parpendicular shear strength, SYZ, GPa	0.004

2.3. Wood material model

Wood is a porous, fibrous, complex anisotropic material. It exhibits different properties with time, temperature, moisture content and loading rate [10,11]. Under static conditions or low strain rate, wood can be treated as a linear elastic material. With increasing loading rate the cell walls start to buckle locally and the behavior of wood becomes non-linear [10]. For analytical purposes, wood can be assumed to be an orthotropic material because it possesses different properties in three directions; the longitudinal, tangential, and radial directions [10].

Very few studies have dealt with non-linearity of wood from a modeling standpoint [10–12]. Murray et al. [11] developed a wood model to simulate the deformation and failure of wooden guard rail posts impacted by vehicles. This material model is currently implemented in LS-DYNA as MAT 143 [6].

For most practical purposes, balsa wood can be categorized as transversely isotropic with an isotropic plane being perpendicular to the axis of the tree [11,12]. Material model 143 is based on transverse isotropy. In material model MAT 143, separate damage parameters are incorporated to account for parallel and perpendicular grains. With progression of damage, the stiffness of the wood reduces along these directions. The visible structure of wood suggests that the planes perpendicular to the longitudinal (z), radial (r) and tangential (θ) directions, respectively, as shown in Figure 1 are considered as planes of elastic symmetry (orthotropic). In our current study we evaluated wood damage and energy dissipation associated with each failure mode using material models MAT 143 and MAT 2. The material properties used for the simulation of the laminate and the balsa wood core are summarized in Table 2 [5,8] and Table 3 [11–13], and for the projectile(s) in Table 4 [5,7] respectively.

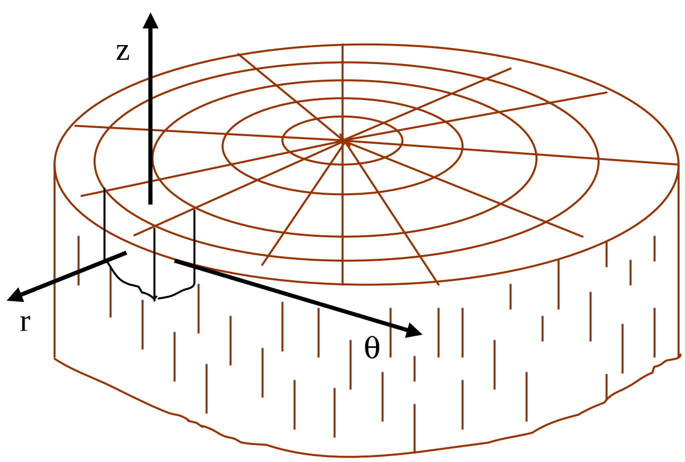

Figure 1: The three principal directions in wood

3. Results and Discussion

Energy absorption and new surface creation due to delamination were estimated from the impact experiments. Energy absorption of the composite facesheets and the balsa wood core provides an indication of ballistic efficiency. Delamination at ply interfaces as well as facesheet to core interfaces was considered.

3.1 Single projectile impact

As a first step, single point impact tests were performed on 3-layer composite facesheets (2 mm thickness) and balsa wood core (25 mm thickness) separately to establish the prediction accuracy of the numerical simulation. Detailed information on the composite facesheet can be found in Ref [5]. Impact testing of the balsa wood core was conducted on 200 mm^2 cross section balsa wood specimens and the results are tabulated in Table 5.

Table 5 : Unscored balsa wood core, single projectile results above the ballistic limit

Specimen	Projectile	Incident velocity (m s^{-1})	Residual velocity (m s^{-1})	Impact energy (J)	Residual energy (J)	Average energy absorption (J)	Predicted average energy absorption (J)	
							MAT 143	MAT 2
1	0.30 caliber	224.02	208.00	51.19	44.13			
2	0.30 caliber	265.70	254.54	72.01	66.09	6.55	10.60	5.87
3	0.30 caliber	295.65	284.37	89.16	82.48			

3.1.1 Single projectile impact: Sandwich composite

High velocity impact by a single projectile to a sandwich composite plate was evaluated. 0.30 caliber steel spherical projectiles were used to impact the sandwich composite at velocities of 220–307 m s^{-1}. The impacted specimens were sectioned to study the damage modes. Table 6 and 7 summarize the experimental results and corresponding numerical predictions respectively.

Table 6: 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 (cm^2)	
							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

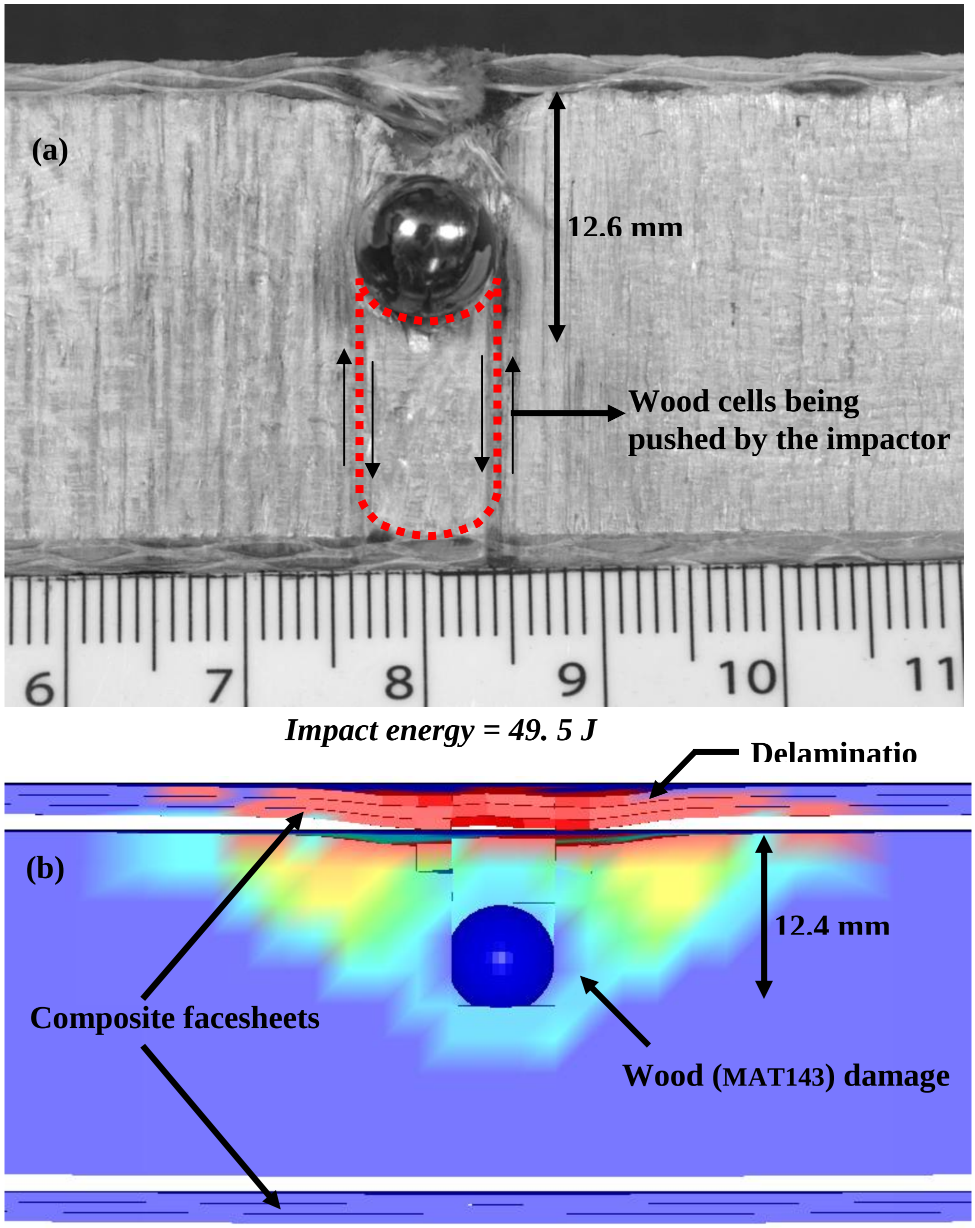

Figure 2: (a) Low resolution stereograph of polished section S2-glass/epoxy balsa core sandwich panel subjected to impact energy of 49.5 J (b) simulation showing wood damage and delamination

The damage section of a representative sandwich plate subjected to impact energies between 49.5 and 66.99 J under .30 cal. single projectile impact is shown in Figures 2 and 3. These energy levels are below the ballistic limit of the specimen for the .30 cal. impact.

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 2a) 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 6). 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 2a.

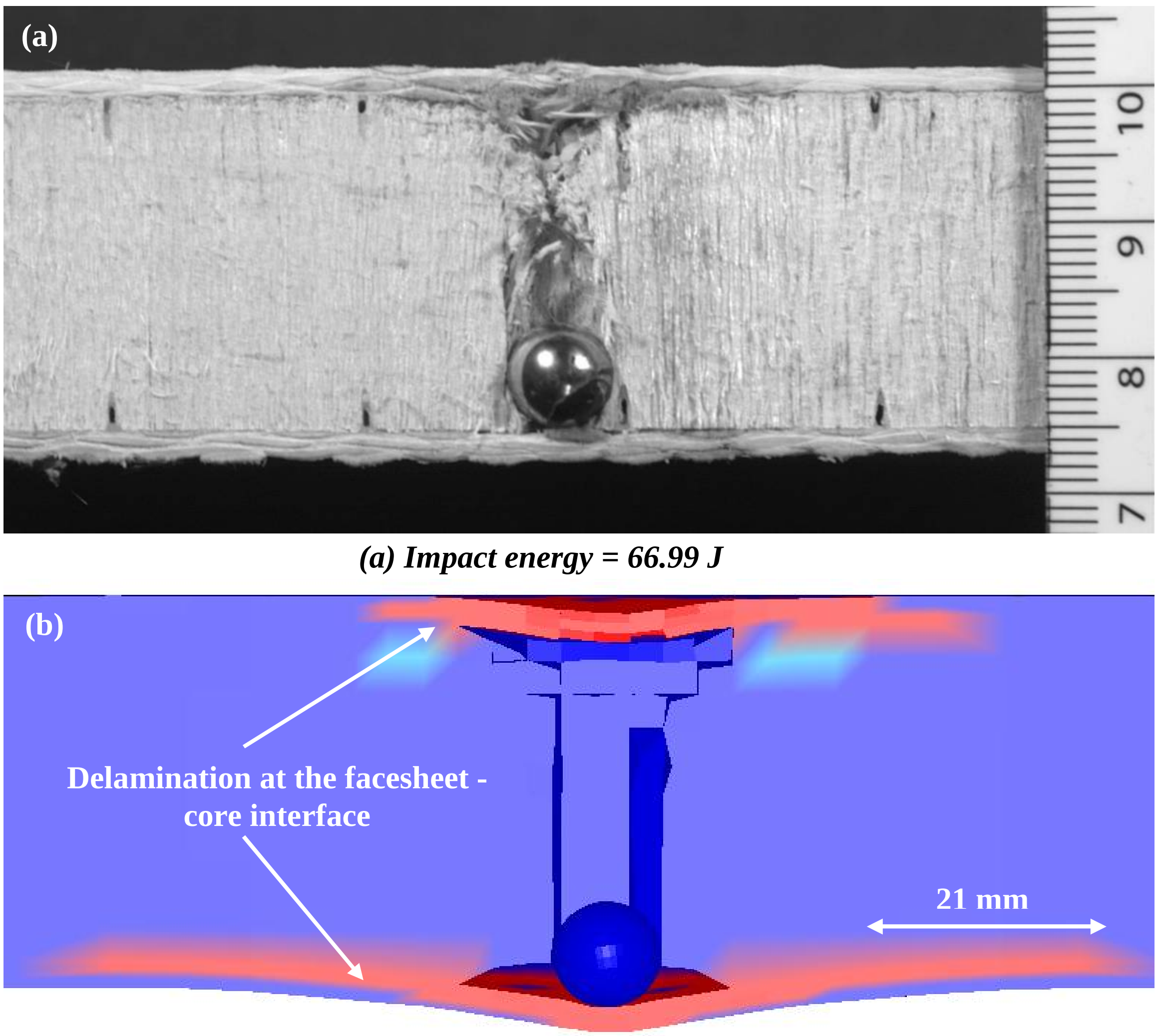

Figure 3. 0.30 caliber projectile impact at 66.99 J (a) Experimental damage (b) Simulation showing delamination (red area) at the top and the bottom facesheet

The simulated damage of the sandwich composite plate subjected to a 49.5 J impact event is illustrated in Figure 2b. 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 3a. 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 (Table 6) 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 is summarized in Table 7.

Table 7: Numerical predictions of single projectile impact of S-2 glass/epoxy balsa core sandwich plate

Specimen	Incident velocity ($m\ s^{-1}$)	Residual velocity ($m\ s^{-1}$)	Energy absorption (J): Front facesheet (J)	Energy absorption (J): Back facesheet (J)	Energy absorption (J): Wood core (J)	Energy absorption (J): Total energy absorption (J)	New surface creation (cm^2): Front facesheet (cm^2)	New surface creation (cm^2): Back facesheet (cm^2)
1	220.37	0.00	32.58	0.00	16.92	49.50	14.20	0.00‡
3	256.34	0.00	33.59	11.90	21.50	66.99	15.60	43.50‡

Figure 3b 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, Table 6 and 7. Numerical prediction of energy dissipation and damage evolution i.e. new surface creation at the impacted and non-impacted faces of the sandwich composite are discussed in Table 7 for the specimens numbered 1 and 3. The results illustrate the energy lost during penetration through each constituent i. e. top facesheet, balsa core and bottom facesheet of the sandwich plate.

4. Summary

The response of S2-glass/epoxy balsa core sandwich structures under high velocity impact has been focused with the aid of experiments and finite element 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. Impact on the balsa wood core was simulated using MAT 2 and MAT 143. Although both material models showed good correlation of the impact damage of balsa wood with experiments, MAT 143 was found to be performed better and showed consistency (within 92% of the corresponding experimental results) in case of both balsa wood impact and sandwich impact events. 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. FEA prediction for kinetic energy absorption and delamination was found to be reasonably well agreement, 98% and 95%, respectively, with corresponding experimental data provided the S_d factor has to be assigned to 1 and 5 for top and bottom facesheets respectively. An important contribution of this work is to analyze/predict high velocity impact response and an overall damage assessment of a composite sandwich panel from an experiment and numerical viewpoint.

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