

Investigation of Adhesive Debonding in Paper Honeycomb Sandwich Panel under Blast Load

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Abstract

Blast mitigation of structures have become a focus of many research works due to the rising threat imposed by explosive based terrorism. Sacrificial sandwich panels are one of such blast mitigation technique, which has proven to be effective in reducing the blast-induced damage on structures. Researchers are studying new materials like honeycomb to mitigate blast load as these materials have high strength to weight ratio, high stiffness and lightweight. The failures in sandwich structures subjected to blast load are core crushing, face-sheet bending and delamination of face-sheet from core. In present investigation, authors studied delamination behaviour of sandwich panel with paper honeycomb core using ABAQUS/Explicit[®]. The face-sheet and back-sheet of the sandwich panels considered here are made of stainless steel and core of paper honeycomb. The adhesive layer of Araldite[®] 2015 is modelled in ABAQUS/Explicit[®] using cohesive zone model (CZM). The authors studied effect of variation of thickness of adhesive layer. The investigation is compared based on internal energy and central point displacement time histories of back-sheet.

Keywords: ABAQUS/Explicit[®], Adhesive Layer, Delamination, Blast Load, Paper Honeycomb

1. Introduction

In recent decades, threat posed by explosive based terrorist attacks has increased exponentially. When explosion happens, it leads to substantial loss of life and property. In addition to that, nature of blast load is non-linear, dynamic and unpredictable. This leads to structure behaving nonlinearly. Therefore, it is necessary to protect structure from blast load and this concern lead to rise in increased investigations in this area. Mitigation of blast load is reducing peak blast pressure acting on the structure. This can be achieved by passive mitigation techniques such as strengthening of structure or using sacrificial cladding. Strengthening of structure against blast load can lead to increase in weight of the structure. However, increasing weight of structure can cause increase in earthquake forces in structure. Sacrificial cladding is a protective panel provided in front of structure that will be damaged before transferring blast pressure to main structure. This reduces blast pressure acting on main structure significantly [1]. The research in the area of sacrificial cladding made of lightweight sandwich panels is increasing day by day. The lightweight sandwich panels have high specific energy absorption, high specific stiffness and high strength to mass ratio [2].

Sandwich panel consists of lightweight material (foams or honeycomb) separated by stiffer outer sheets and this lightweight material is joined to outer sheets by means of adhesive layer like Araldite[®] 2015. The modes of failures observed in sandwich panels are face-sheet bending, core compression, shear failure and debonding of the face-sheet. Some studies are performed to investigate delamination behaviour of sandwich panel where delamination is observed in laminates of face-sheet i.e. sheet exposed to the blast [3–7]. Del-Linz et al. examined delamination behaviour of laminated glass windows subjected to blast loads with experimental and numerical analysis [4]. Wherein, Wei et al. investigated 3-D model of composite panels to study effect of underwater blast and studied delamination between the laminas [7]. Mitra and Baja improved the delamination resistance of sandwich panels using composite shear key provided at face-sheet and back-sheet [8]. Caliskan and Apalak performed experimental analysis and numerical simulation in ABAQUS/Explicit[®] to evaluate the delamination of the face-sheet from foam core in sandwich panels subjected to impact load [9].

Goel and co-authors has studied in details the behaviour of sandwich structures under blast loading [10-12]. Recently

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Tolani et al. [13] studied the relative contributions of the ground shock and air pressure on building responses due to a surface blast SDOF model. They studied four different RC building frames of varying heights under varying blast scenarios. In year 2020, Tolani et al. [14] studied the effect of surface explosion on multi-storied buildings of different heights and concluded that for building with low heights air pressure effect governs the response whereas, for high building ground shock is found to be governing. Hence, in the present investigation, delamination of face and back-sheets from paper honeycomb core is studied using numerical simulation in ABAQUS/Explicit® [15]. Paper honeycomb core is considered in the present study and adhesive layer of Araldite® 2015 is modelled using cohesive zone model (CZM). The effect of thickness of adhesive layer is studied herein and results are compared based on internal (strain) energy and central point displacement of back-sheet.

2. Finite Element Model

2.1. Geometry and Material of Sandwich Panel

The sandwich panel considered in the present study is assemblage of steel outer sheets (i.e. face-sheet and back-sheet) and paper honeycomb core. This configuration is mentioned here onwards by PHSP. The size of sandwich panel is 400 mm × 400 mm; thickness of outer sheets is 2 mm and core depth of 57 mm (Fig. 1). The adhesive layer thickness is initially considered as 0.2 mm. This sandwich panel is modelled using adhesive Araldite® 2015. The thickness of adhesive layer is changed to 0.25 mm and 0.3 mm for PHSP_2015 configuration to study effect of thickness of adhesive layer on displacement and internal energy (IE) of back-sheet of sandwich panel. Sandwich panel is used as sacrificial wall act as a barrier to limit the blast load acting on structure. The effective barrier would cause minimum damage in structure and this can be indicated by deflection of back-sheet. Hence, back-sheet displacement is focused herein.

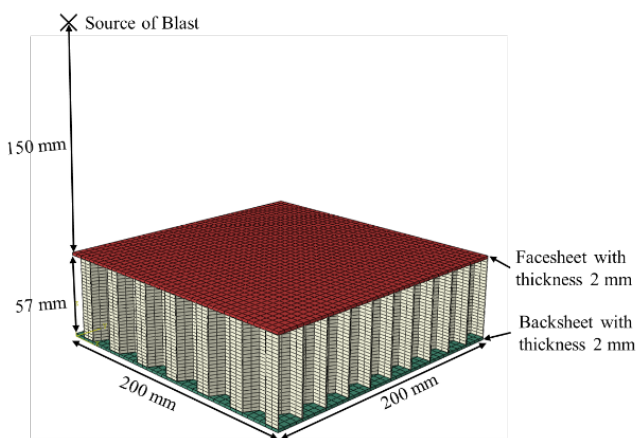


Fig. 1. Representation of Sandwich Panel and Position of Explosive

The face-sheet and back-sheet are made of stainless steel and they are modelled in ABAQUS/Explicit® [15] using Johnson-Cook (J-C) material model. The parameters

of J-C material model are given in Table 1. Paper honeycomb core is modelled using plastic-isotropic model. The properties of paper honeycomb are shown in Fig. 2. Adhesive layer is modelled using cohesive zone model (CZM) and the parameters for CZM are given in Table 2.

Table-1. Johnson-Cook Parameters for Stainless Steel [16]

General Property	
Density (ρ)	7850 kg/m ³
Elastic Properties	
Modulus of elasticity (E)	1.61×10^5 MPa
Poisson's ratio (ν)	0.35
J-C material model	
A	400 MPa
B	1500 MPa
C	0.045
n	0.4
m	1.2
$\dot{\epsilon}_0$	0.001 s ⁻¹
Transition temperature	293°K
Melting temperature	1800°K

Table-2. Parameters for CZM of Araldite® 2015 [9]

Property	
Young's Modulus (E)	1.85 GPa
Shear Modulus (G)	0.56 GPa
Traction in Normal Direction (t_n^0)	21.63 MPa
Traction in Shear Direction (t_s^0)	17.9 MPa
Fracture Energy in Normal Direction (G_n^C)	0.43 N/mm
Fracture Energy in Shear Direction (G_s^C)	4.70 N/mm

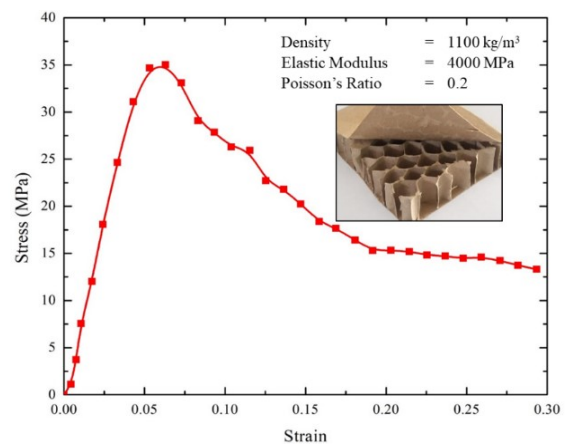


Fig. 2. Stress-Strain Behaviour and Properties of Paper Honeycomb Core

2.2. Finite Element Modelling in ABAQUS/Explicit®

The face-sheet, honeycomb core and back-sheet are modelled using eight-noded linear brick element with reduced integration (i.e. C3D8R element). The face-sheet and back-sheet are divided into 5×5 element size. The honeycomb is discretized into 25 elements along the depth. The meshing of adhesive layer and honeycomb is coincided in planer direction. The adhesive layer is discretized into only one element along the depth direction. The adhesive layers are created with eight-noded 3D cohesive elements (COH3D8) with maximum degradation 0.95. The finite element model of sandwich panel is presented in Fig. 3. Sandwich panel is fixed at all four edges and explosive charge is placed 150 mm from face-sheet along the centre of sandwich panel. Due to symmetry, one-fourth of sandwich panel is modelled in ABAQUS/Explicit® [15]. General contact with coefficient of friction 0.2 and “hard” contact are used to simulate self-contact behaviour between various elements of sandwich panel.

The nodes of cohesive elements are tied to face-sheets and honeycomb core. The elastic-traction relation for cohesive elements is given by Eq. (1), where, elasticity matrix is E , stress vector is t , ϵ is strain vector. The strain vector can be converted into separation (δ) vector by multiplying by thickness of cohesive element. The CZM relates stresses in cohesive elements to relative displacement by using elasticity law upto damage initiation and then degrading cohesive material upto failure (damage evolution).

$$\begin{Bmatrix} t_n \\ t_s \\ t_t \end{Bmatrix} = \begin{bmatrix} E_{nn} & E_{ns} & E_{nt} \\ E_{ns} & E_{ss} & E_{st} \\ E_{nt} & E_{st} & E_{tt} \end{bmatrix} \begin{Bmatrix} \epsilon_n \\ \epsilon_s \\ \epsilon_t \end{Bmatrix} \quad (1)$$

The graphical representation of traction separation is shown in Fig. 4. In the present simulation, quadratic-linear separation law is used and this law is given by Eq. (2) where, peak stresses are t_n^o along normal direction and t_s^o, t_t^o along shear directions. The area under traction separation curve gives fracture energy (G_n^C in normal direction and G_s^C in shear direction). Linear power law used for damage evolution in present study given by Eq. (3). The CZM parameters used in present study are reported in Table 2.

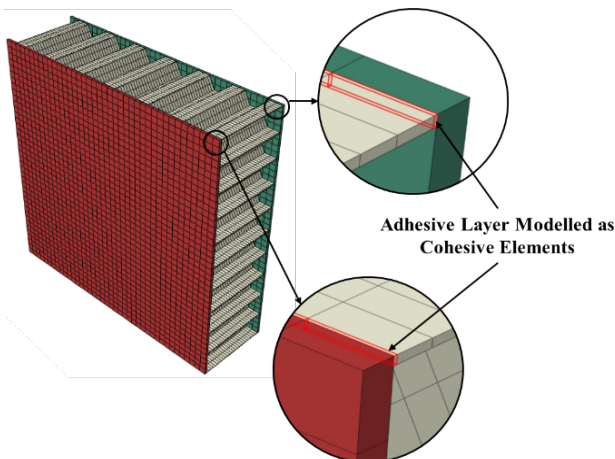


Fig. 3 Finite Element Model of Sandwich Panel

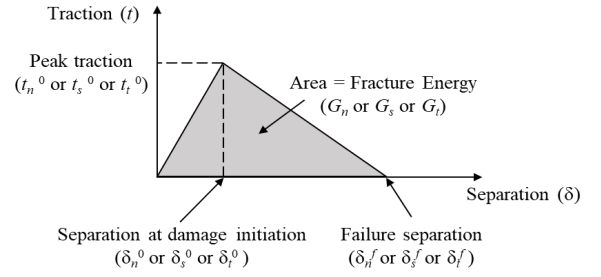


Fig. 4. Linear Traction Separation Law

The sandwich panel is subjected to blast load using CONWEP configuration available in ABAQUS/Explicit® [15]. The charge of 1 kg is placed at 150 mm standoff distance from face-sheet of sandwich panel.

$$\left(\frac{t_n}{t_n^o}\right)^2 + \left(\frac{t_s}{t_s^o}\right)^2 + \left(\frac{t_t}{t_t^o}\right)^2 = 1 \quad (2)$$

$$\frac{G_n}{G_n^C} + \frac{G_s}{G_s^C} + \frac{G_t}{G_t^C} = 1 \quad (3)$$

2.3. Validation of FE Model

For validating present numerical scheme, double cantilever beam (DCB) with a cross section of 10.16 mm $\times$ 25.4 mm and length 228.6 mm separated by adhesive layer is used. The beam is fixed at one end and separation displacement of 4.1 mm is applied at another end. This DCB is modelled in ABAQUS/Standard® [15].

The adhesive layer is modelled as two-dimensional cohesive elements with four-nodes i.e. COH2D4. The adhesive layer meshes are matched with top and bottom beams. The adhesive layer is modelled with elastic-traction behaviour with $E_{nn} = E_{ss} = E_{tt} = 55.16 \times 10^7$ MPa. The damage initiation is defined using quadratic stress $t_n^o = t_s^o = t_t^o = 5.516$ MPa and damage evolution is defined with Benzeggagh-Kenane (B-K) law having $G_n^C = G_s^C = 0.140$ N/mm and power $\eta = 1.75$.

The top and bottom beam is modelled as four-noded bilinear plane strain CPE4 element. The bottom and top beams are discretized into mesh 90×4 . The material properties applied to beam are Young's modulus, $E = 55.16$ GPa and Poisson's ratio, $\nu = 0.3$.

The results reported by Simulia [15] and present simulation results are presented in Fig. 5. The Fig. 4 shows linear traction law which is followed by cohesive zone model. The cohesive elements follow elastic law upto displacement of 2.05 mm. As the displacement increases first, the force is also increased linearly upto displacement of 2.05 mm. At the peak point damage initiation starts as traction stress reaches to peak traction. The adhesive layers start degrading i.e. damage evolution initiated. Hence, reaction force is reduced as more displacement is applied at cantilever end. The maximum deviation of peak forces is observed to be 0.85% from Fig. 5, which is within acceptable limit.

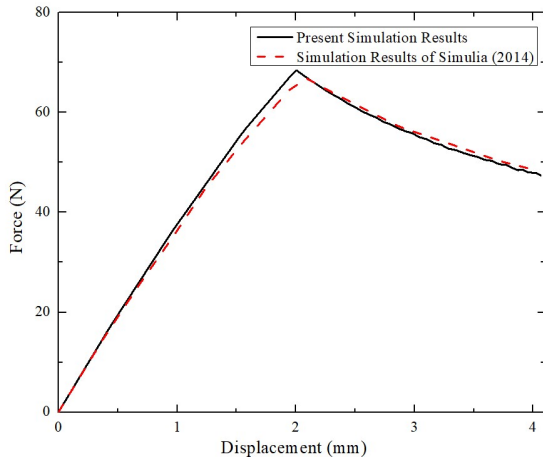


Fig. 5. Comparison of DCB Results for Present Simulation Results and Simulia [15] for Validation of Numerical Scheme

3. Results and Discussions

Fig. 6 shows deformation shape contours at various time steps (t). When sandwich panel is subjected to blast load, the panels are imparted with kinetic energy. The face-sheet of sandwich panel deforms and bends as seen from Fig. 6 at $t = 0.4$ ms. When centre of face-sheet achieves maximum displacement, the back-sheet resists this motion and thus face-sheet rebounds. Due to this rebound motion, the face-sheet delaminates from paper honeycomb core of sandwich panel and continues to delaminate as established from Fig. 6 from $t = 0.70$ ms to $t = 3.25$ ms. The face-sheet of sandwich panel transfers load to honeycomb core and core of sandwich panel commences to crush.

After the core crushing, load is transferred to back-sheet of sandwich panel and back-sheet starts to deform. This can be observed from $t = 0.7$ ms as back-sheet of sandwich panel begins to deform. At $t = 1.25$ ms, the centre of back-sheet attains maximum displacement. Once the back-sheet attains maximum displacement, the back-sheet rebounds and attains stabilised displacement. This leads to delamination of back-sheet from core of sandwich panel as it is evident from Fig. 6 from $t = 0.7$ ms to $t = 3.25$ ms. The percentage of delamination of back-sheet from core of sandwich panel was noted 19.3% for 0.3 mm adhesive layer, 24.3% for 0.25 mm adhesive layer and 27.2% for 0.2 mm adhesive layer.

Each part of sandwich panel resists the imparted kinetic energy with internal energy (IE) of structure. Herein, internal energy i.e. strain energy of back-sheet and deflection of back-sheet is examined. Fig. 7 shows comparison of centre point deflection of back-sheet. The back-sheet undergoes deflection as soon as core is crushed and it continues this motion. However, after a point, back-sheet resists this motion and hence rebound in displacement curve can be seen in Fig. 7. The back-sheet undergoes delamination of about 39% of total area. The stiffness of adhesive layer is inversely proportional to thickness of adhesive layer. The deflection of back-sheet is reduced by 7% and 3.75% for configurations with thickness of adhesive layer as 0.3 mm and 0.25 mm, respectively. Hence, it can be observed that as thickness of adhesive layer is increased, the deflection of back-sheet is also increased.

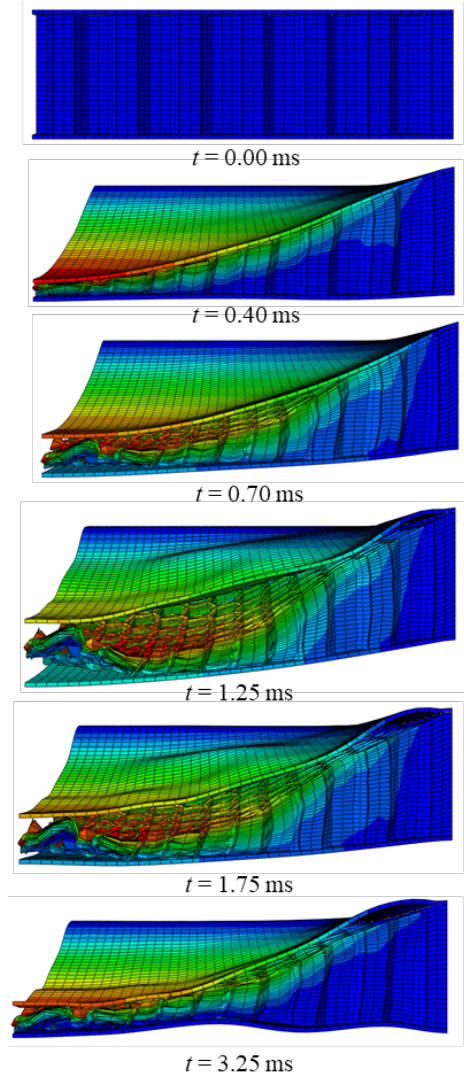


Fig. 6. Deformation and Delamination of PHSP at various time instant

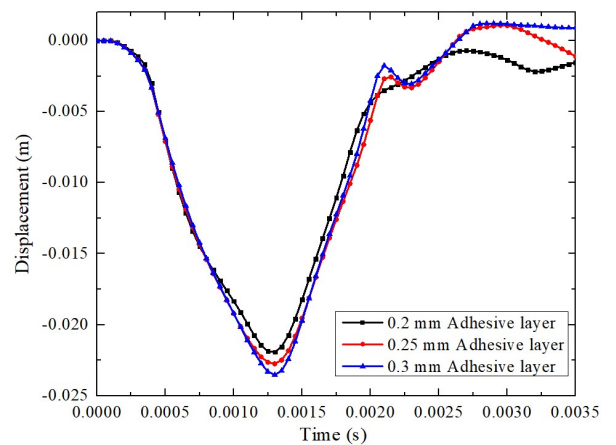


Fig. 7. Centre Point Displacement Time-History of Back-sheet for Varying Thickness of Adhesive Layer

Internal energy of back-sheet i.e. strain energy is energy stored in back-sheet due to its deformation. As a result, more deformation will cause more internal energy. Similar observation is noted from Fig. 8, as thickness adhesive layer is increased, the internal energy of back-sheet

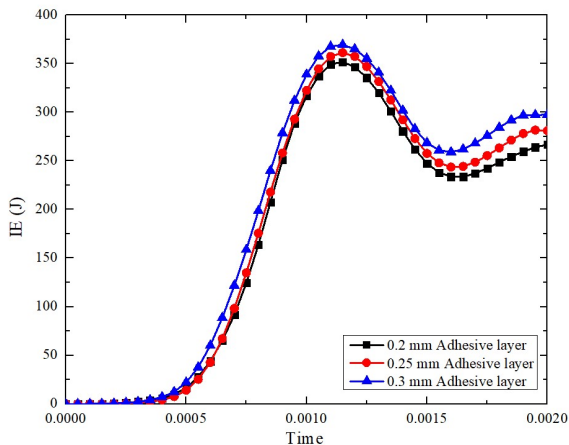


Fig. 8. Internal Energy Time-History of Back-sheet for Varying Thickness of Adhesive Layer

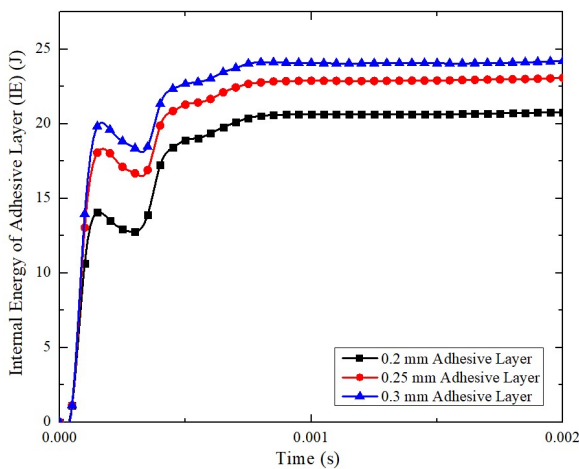


Fig. 9. Comparison of Internal Energy of Adhesive Layer

is reduced. As stiffness of adhesive layer is more for lesser thickness, more internal energy is required to resist the imparted kinetic energy. Therefore, lower thickness of adhesive layer shows lowest internal energy.

The internal energy time-histories of adhesive layers are compared in Fig. 9. It can be noted from Fig. 9 that as more deformation is observed in case of 0.3 mm adhesive layer, the internal energy of 0.3 mm thick adhesive layer is more. Compared to maximum (stabilised) internal energy of 0.2 mm thick adhesive layer, maximum internal energy of 0.25 mm thick adhesive layer is 11.75% more and for 0.3 mm thick adhesive layer is 17.7% more.

4. Conclusions

Numerical simulation on delamination behaviour of sandwich panel with honeycomb core subjected to blast load was studied here. The adhesive layer of Araldite® 2015 is modelled in ABAQUS/Explicit® using cohesive zone model. The delamination behaviour of paper honeycomb core from face-sheet and back-sheet of sandwich panel is observed. It was observed that the face-sheet of sandwich panel is delaminated completely except at the edges of sandwich panel face-sheet. The back-sheet delamination is lesser than face-sheet delamination and extent of delamination varies with thickness of adhesive layer. The variation of thickness

was studied and comparison was done based on centre point displacement of back-sheet. It was noted that stiffness of adhesive layer is inversely proportional to thickness. Hence, as thickness is increased, the back-sheet displacement also increases.

Strain energy is energy stored in body due to deformation. Since deformation is more in sandwich panel with 0.3 mm thick adhesive layer configuration, internal energy i.e. strain energy is more in it.

Disclosures

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