



Structural design and testing of pouch cells

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Submitted: 25.11.2020

Accepted: 01.03.2021

Published: 30.06.2021



Abstract: A reliable supply of energy source is required for aerospace applications. Due to their high specific energy density and low self-discharge, Lithium-ion cells are preferred over other energy sources. Pouch cells have much better energy density compared to metallic cell cases. A pouch cell is developed for launch vehicle and automotive applications. Two aluminum-polymer laminates are heat sealed at 180-1900 °C to form the pouch cell. Experimental characterization (lap shear, T-peel and tensile) of bonded laminate/films are carried out. UTS of laminate is obtained from lap shear and tensile tests. Fracture energy (mode-I) is obtained from T-peel tests and used as an input for the cohesive zone model. Mechanics of pouch cell due to internal pressure (abuse condition) is performed by Elasto-plastic finite element structural analysis to arrive at the pressure capacity of cells.

Keywords: Aluminum-polymer laminates, Burst test, Experiment, Finite element analysis, Pouch cell

Cite this paper as: Vamsi, A., Ansari, J.N., Krishnamoorthy S.M., Pany, C., John, B., Samridh, A., Devassia, M.T., Structural design and testing of pouch cells. *Journal of Energy Systems*, 2021,5(2), 80-91, DOI: 10.30521/jes.815160

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Nomenclature	
b	Width of the peel test specimen
CZL	Cohesive zone layer
CZM	Cohesive zone modeling
G	Fracture energy per unit area
P _f	Peel force
U _s	Strain energy of the system
U _{SE}	Surface energy
W	Work potential

1. INTRODUCTION

A battery pack is a system of multiple components and functions. The design involves the application of knowledge and practice in the electrochemical, electrical, mechanical, thermodynamic, and control fields. To achieve higher operating voltages, the positive terminal of one cell is connected to the negative terminal of the next cell in a series combination. Like-polarity terminals of adjacent cells connected to each other in parallel can achieve higher operating power. Cell packaging designs and their combinations in modules and battery packs are offered in a huge variety, for primary and secondary batteries, and for different applications [1-4]. The most critical performance metrics for a Lithium-ion battery pack are energy density, power density, cost, cycle life, and safety. The deviation of the performance metric from the target value is termed as a quality loss. Elimination of the factors responsible for this quality loss is too difficult, expensive, or time consuming. An alternate solution for minimizing this deviation is through robust design methodology [5]. The most popular options available in market are cylindrical and prismatic cells. These types have both goodness and shortcoming. In 1995 [6], Li-polymer surprised the battery world with a radical new design, the pouch cell. Generally, a pouch battery can apply for every application. The pouch cell achieves a 90 to 95 percent packaging efficiency and makes the most efficient use of space, the highest among battery packs, with advantages of flexible size, and safety performance. It reduces weight by eliminating the metal enclosure, however, the cell needs some alternative support in the battery compartment. Further, it reduces cost, as well as optimize packaging efficiency at the battery level. The pouch pack finds applications in consumer, military, automotive applications as well as aerospace application.

Delamination or fracture along an interface between multi-layers material plays a major role in limiting the toughness and the ductility, such as in laminated composite structure and laminated pouch (Aluminum film sandwiched between two polymer layers). This has motivated considerable research on the failure of the interfaces. Interface delamination can be modeled by adopting softening relationships between tractions and the separations, which in turn introduce critical fracture energy, which is the energy, required to break apart the interface surfaces. This is called the cohesive zone material (CZM) model. The interface surfaces of the materials can be modeled by a particular set of interface elements or contact elements, and a CZM model can be used to characterize the constitutive behavior of the interface. The CZM model consists of a constitutive relation between the traction acting on the interface and the corresponding interfacial separation.

In this paper, 1.5Ah pouch cells are developed in-house for launch vehicle and automotive applications. In pouch cells, the electrode stack and electrolyte are enclosed in a laminated pouch. The pouch is made of the Aluminum film sandwiched between two polymer layers: Polypropylene on the inner side and polyamide on the outer side. The total thickness of the film/laminate is approx. 110 μm . The pouch is then heat-sealed at 180-190 $^{\circ}\text{C}$. Laminated pouches are used to contain the active materials and improve the energy density of the cell (as metallic cases are avoided). The maximum effective operating pressure of the pouch cell is 2 bar and in case of cell abuse condition, pressure increases in the cell and causes bursting of cell. This pressure capacity of the cell needs to be estimated prior to usage. Lap shear, t-peel, and tensile tests are studied on bonded Aluminum laminates to obtain the mechanical properties required for structural analysis. Finite element analysis (FEA) and hydro tests are carried out to estimate the capacity of the pouch cell.

2. MATERIAL CHARACTERISATION

Four sets of lap shear samples and two sets of peel testing (t-peel) samples were tested as per ASTM D 3163 and ASTM D 1876 respectively. The test setup with specimens is shown in Fig. 1. Details of test

specimens are given in Table 1. In lap shear test, four types of specimens are tested: i) heat sealed (lap area = 625 mm², 25mm width, and 25mm length): L01-L05 (specimen ID) ii) heat sealed (lap area = 250 mm², 25mm width, and 10mm length): L06-L10 iii) heat-sealed with tabs (electrodes) in the longitudinal direction (tabs are along with the load): L11-L15 and iv) heat-sealed with tabs in transverse direction: L16-L20.

Results of lap shear tests are given in Table 2. All lap-shear specimens (with and without tab) failed in the laminated sheet indicating robust heat sealing (cohesive fracture in a lap shear test indicates good process control) of pouch cell. From these tests, the tensile strength of the laminated sheet is estimated and values are given in Table 2.

In the t-peel test, two types of specimens are tested, i.e., heat-sealed with and without tabs. The results of t-peel tests are given in Table 3. The following observations are made from tests:

- Presence of tab reduces the peel load of specimens.
- Fracture energy per unit area of the surfaces, G , is estimated from the peel load values as follows. In a peel test, total potential energy of the system is:

$$\Pi = U_S + U_{SE} - W \quad (1)$$

Where, U_S is strain energy of the system (sum of elastic and bending energy), U_{SE} is surface energy

$$U_{SE} = G (\Delta cb) \quad (2)$$

By using Fig. 2, one can write W as,

$$W = Pf\Delta c (1-\cos\theta) \quad (3)$$

If the lamination is considered inextensible, then minimization of potential energy is stated as,

$$\left(\frac{d\Pi}{d(\Delta c)} \right) = 0 \quad (4)$$

Here, Eq. (4) gives,

$$G_b = P_f (1-\cos\theta) \quad \text{i.e.} \quad G = (P_f/b) (1-\cos\theta) \quad (5)$$

Eq. (5) is known as the Rivlin's equation [7]. Whereas, in Kendall's equation [8], U_S term is included. Note that P_f and b are peel force and the width of the peel test specimen, respectively. T peel test is performed at $\theta = 90^\circ$. Fracture energy per unit area (G) values are found out from tests presented in Fig. 1. Average value is found to be of $G = 2.33$ N/mm.

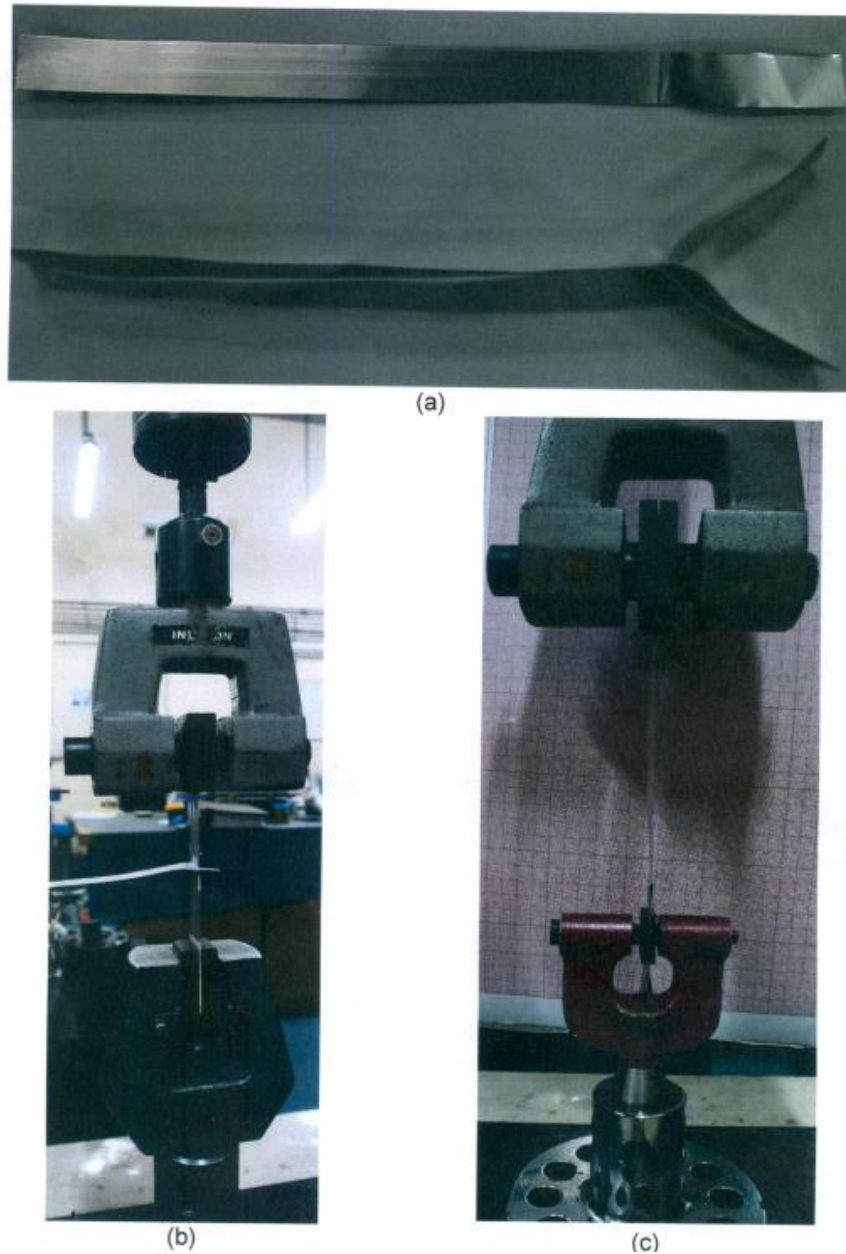


Figure 1. (a) T-peel specimen, (b) T-peel test setup and (c) Lap shear test setup

Table 1. Details of test specimens.

Type of test	Specimen ID	Number of specimens	Bond detail	Lap area (width x length)	Specimen size
Lap shear test	L01-L05	5	Heat sealed	25 x 25	25mm width x 150mm length
	L06-L10	5	Heat sealed	25 x 10	
	L11-L15	5	Heat sealed with tab in longitudinal direction of load	25 x 25	
	L16-L20	5	Heat sealed with tab in transverse direction of load	25 x 25	
Peel test (T peel)	P01-P05	5	Heat sealed	--	25mm width x
	P06-P10	5	Heat sealed with tab	--	340mm length

Table 1. Results of lap shear test.

Lap area size (wid. x leng. x thk.) (mm)	Condition	Spec. ID	Max. load (N)	Location of failure	Tensile strength (MPa)
25 x 25 x 0.125	Heat sealed	L01	174	Laminated sheet	55.68
		L02	181	away from bond	57.92
		L03	196	Laminated sheet	62.72
		L04	197	near to bond	63.04
		L06	195	Laminated sheet near to bond	62.40
25 x 10 x 0.125	Heat sealed	L07	179	Laminated sheet away from bond	57.28
		L08	203		64.96
		L09	191	Laminated sheet near to bond	61.12
		L10	184		58.88
		L11	195		62.40
25 x 25 x 0.125	Heat sealed with tab in longitudinal direction of load	L12	190		60.80
		L13	188	Laminated sheet near to bond	60.16
		L14	197		63.04
		L15	186		59.52
		L16	183	Laminated sheet	58.56
25 x 25 x 0.125	Heat sealed with tab in transverse direction of load	L17	180	away from bond	57.60
		L18	173	Laminated sheet near to bond	55.36
		L19	183	Laminated sheet	58.56
		L20	189	away from bond	60.48

Table 2. Results of t-peel test.

Condition	Spec. ID	Average peel load (N)	Remarks	G (Fracture energy per unit area) (N/mm)
Heat sealed	P01	65.0	Nil	2.60
	P02	51.6		2.06
	P03	-	Laminated strip failed	-
	P04	50.0		2.00
	P06	49.2	Nil	2.89
Heat sealed with tab	P07	36.7		2.16
	P08	-	Laminated strip failed	-
	P09	35.6		2.09
	P10	42.5	Nil	2.50

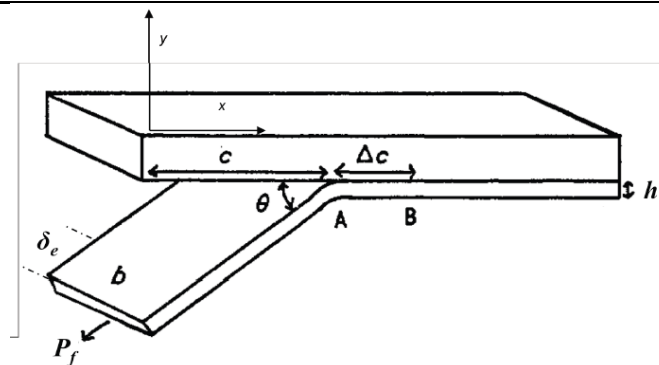


Figure 2. Schematic of peel test for an extensible tape [9].

Tensile tests are performed on five specimens from S1 to S5 (as in Figure 1) and material curve of S1 (strength is low) is input for FE analysis. Tensile strength from lap shear tests and tensile tests are close to each other.

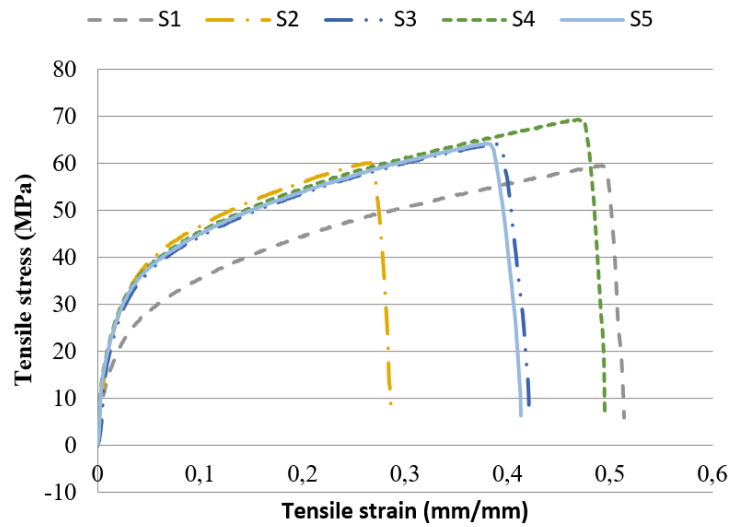


Figure 1. Tensile test data

3. COHESIVE ZONE LAW (CZL) FOR FEA

Theory of elasticity predicts stress singularity at the edge of crack tip. The global energy balance equations of Rivlin and Kendall do not dwell into the local behavior of the bonded interface. That is, they cannot estimate the forces and displacements at the interface. One method is to use a CZL, a constitutive law in the form of a traction-separation law, to model the mechanics of process zone (ahead of the crack tip).

From the peel test, G is obtained. This is quantitatively the area under the traction-separation curve. The CZL used for FEA is shown in Figure 2.

$$(1/2) \sigma_o \delta_f = G \tag{6a}$$

$$\sigma_o \delta_f = 2G = 4.66 \tag{6b}$$

Values of σ_o and δ_f are unknown. Procedure to extract CZL is described by Christopher [10]. For FEA, δ_f is assumed as 0.4, then $\sigma_o = (4.66/\delta_f) = 11.65$ MPa. [$\delta_o = 0.1$]

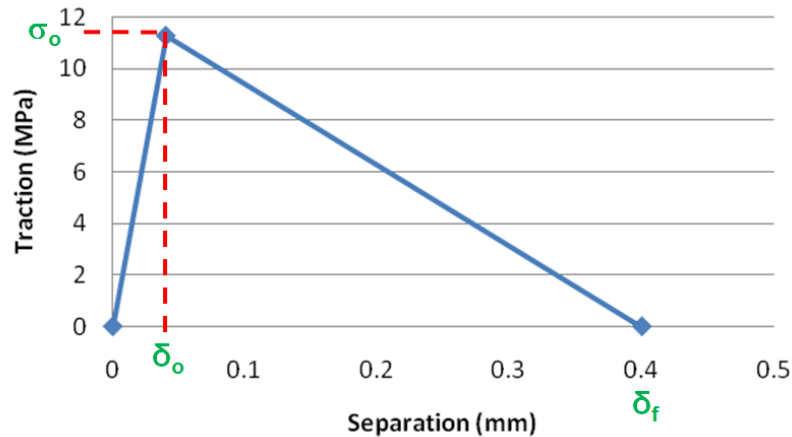


Figure 2. Cohesive zone law for FEA

4. FEA AND RESULTS

Finite element model of the laminated pouch is shown in Fig. 5. The quarter model (36.25 x 45.5) has been considered because of the symmetric loading conditions. The boundary conditions and internal pressure of 2 bar are shown in Fig. 5. The boundary conditions are for an assembled cell condition. As the stiffness of the stack of the adjacent cells is high, the normal degree of freedom is constrained. Combined geometric & material (material stress - strain curve is shown in Fig. 6) nonlinear analysis has been performed. Symmetric boundary conditions are applied on the symmetric plane and closed - end condition is simulated on the free edge on the vertical surface. The cohesive zone materials (CZM) is used with interface elements and contact elements allow exponential CZM for simulating interface delamination and fracture phenomena, which is explained in previous section. The parameters C_1, C_2 and C_3 are supplied for Ansys simulation, which correspond to σ_0 , δ_f and δ_0 .

The maximum deformation of 1.61 mm (Fig. 7) is observed in the pouch cup. Max. von - Mises stress at 2 bar is 50.47 MPa and plastic strain is 0.44 and is shown in Fig. 8 and Fig. 9 respectively. These stresses and strains are very local and are due to the sharp corner at the edges of the pouch. A fillet radius will reduce these peaks and stresses and strains show a high gradient from this corner and reduce drastically. From the tensile test data, ultimate strength is 60 to 70 MPa and the ultimate strain is 0.4 to 0.5. Hence, the pouch cell is safe at 2 bar.

The axial deformation at the interface of the pouch to cover is shown in Fig. 10. The separation at 1st node is 0.0637, which is greater than 0.04 mm, while at 2nd node separation is less than 0.04 mm. Thus, debonding at the interface has started at 2 bar pressure and a further increase in pressure may cause further debond. Ting Miao et al., [11] predicted the delamination behavior of arterial wall through four types of CZMs. They could predict the tearing propagation behavior in the medial layer of the arterial tissue. Similar approach has been followed by Bonifaz [12] to simulate the crack tip opening displacement (CTOD). Zhang et al. [13] utilised the concept of CZM to investigate dynamic failure process in homogeneous and functionally graded materials (FGMs).

Failure is expected to take place when the stress in the cell through the thickness is equal or more than the ultimate tensile strength of the material. ANSYS has the provision for checking the global plastic deformation i.e. where non-convergence in solution occurred [14]. It shows the pressure level for complete plastic flow through the cylinder wall (i.e. bursting pressure). The pressure capacity of the pouch cell is estimated to be 6.4 bar. The deformation, plastic strain and effective stress in the cell are shown in Fig. 11, Fig. 12, and Fig. 13, respectively. A considerable increase in the plastic strain is observed when the pressure has increased from 2 bar to 6.4 bar (which is evident from the material curve

of Fig. 6). At the interface, debonding of 2 mm is expected to occur, but 8 mm bond length is still intact as observed from the deformation values at the interface. However, burst tests are needed to validate the analysis results.

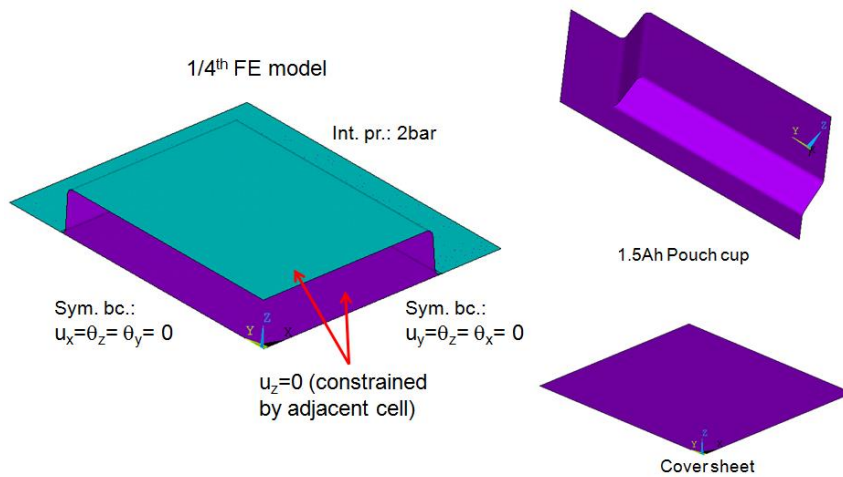


Figure 3. Finite element model (Quarter model laminate).

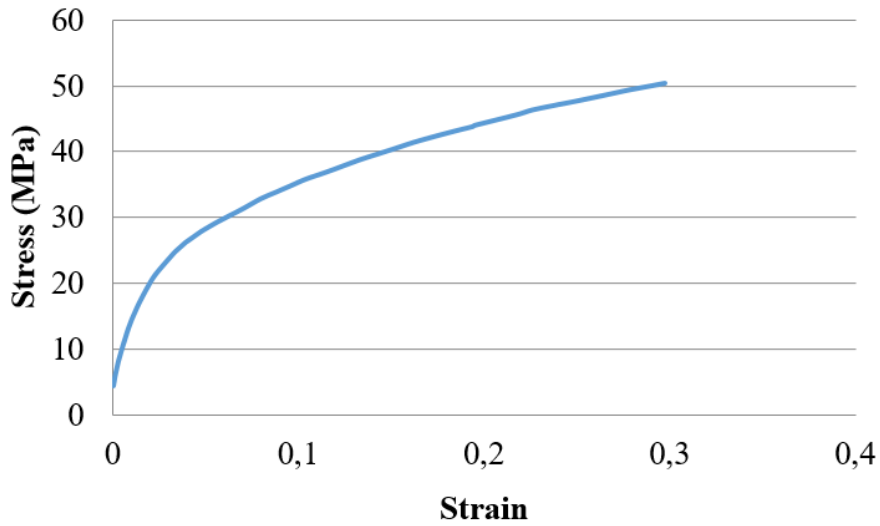


Figure 6. Material stress-strain curve of laminate

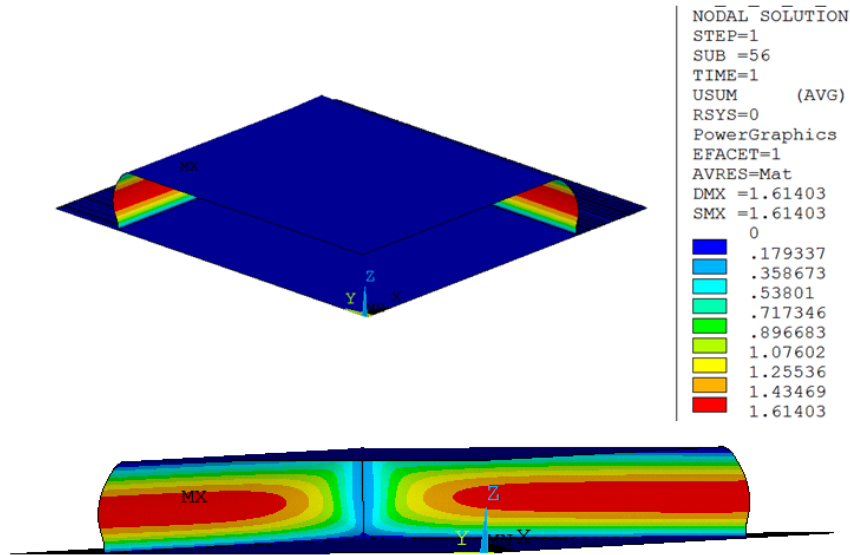


Figure 7. Deformed configuration at 2 bar internal pressure

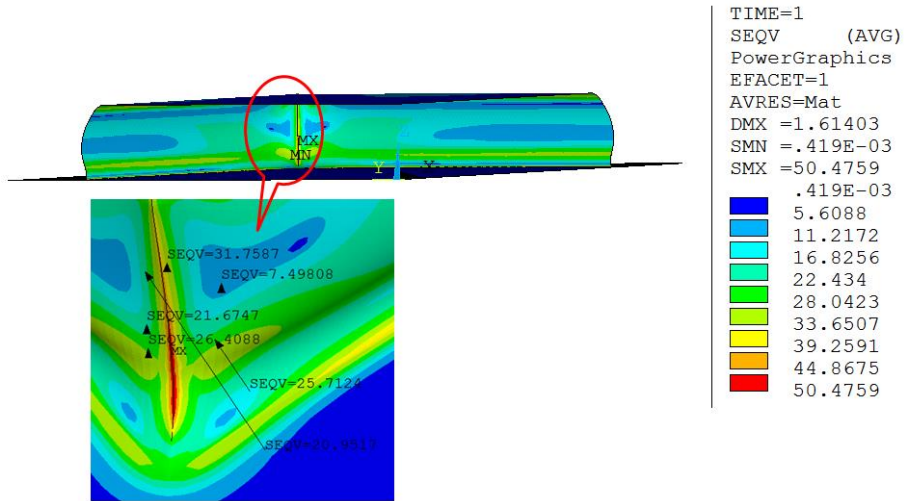


Figure 8. Von-mises stress (MPa) in the pouch cup at 2 bar

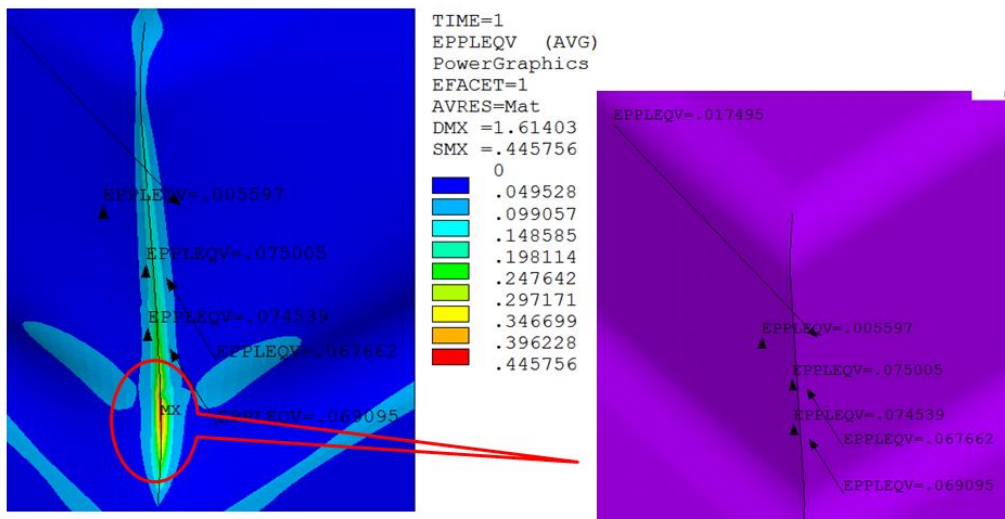


Figure 9. Plastic strain in the pouch cup at 2 bar

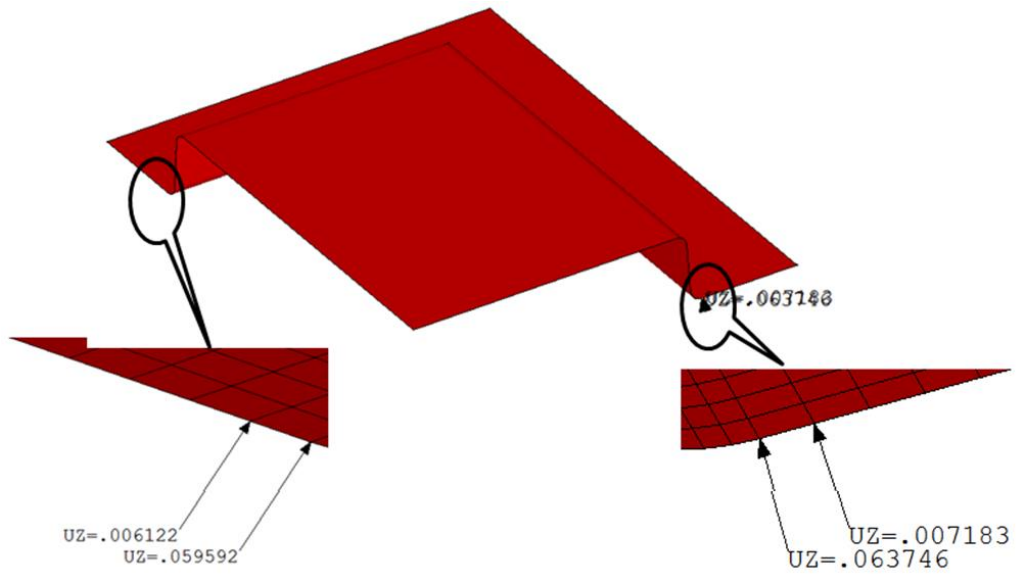


Figure 10. Axial deformation (indicating delamination in cohesive elements) at 2 bar

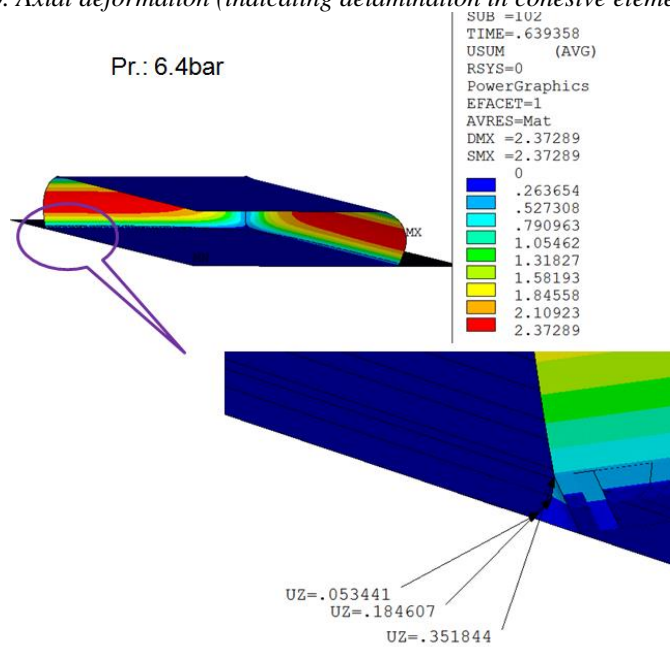


Figure 4. Deformed configuration (U_{sum}) at 6.4 bar internal pressure

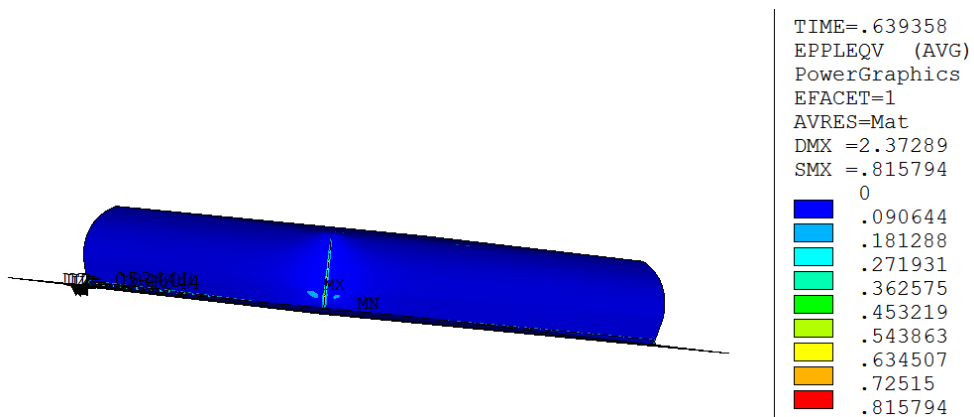


Figure 5. Plastic strain in the pouch cup at 6.4 bar internal pressure

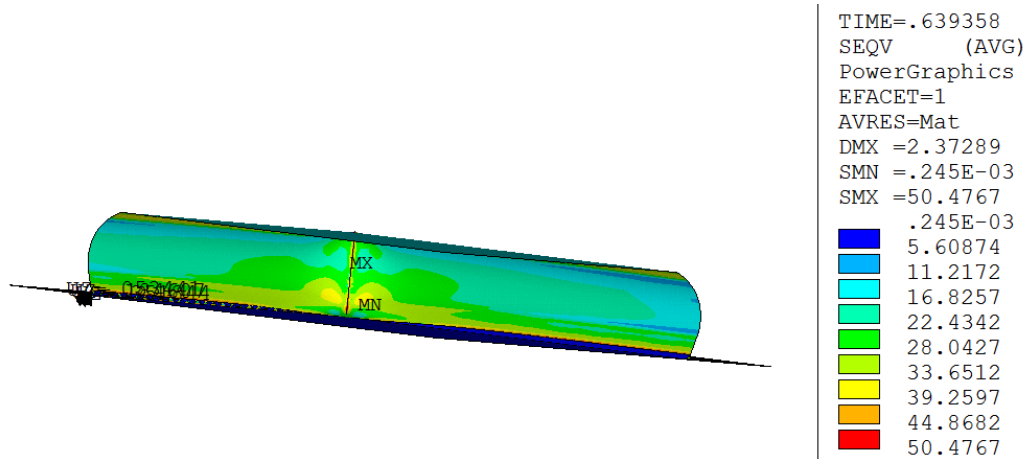


Figure 6. Von-mises stress (MPa) in the pouch cup at 6.4 bar internal pressure

5. BURST TEST OF POUCH CELL

The faces of cell cases are restrained in the normal direction as shown in Fig. 14. The cell is internally pressurized with water and 3 number's of cell case is burst tested and the mode of failure observed is delamination at the sealed edge. The failure pressure of the three cell cases are 12.8, 13.8, and 13.9 bar.

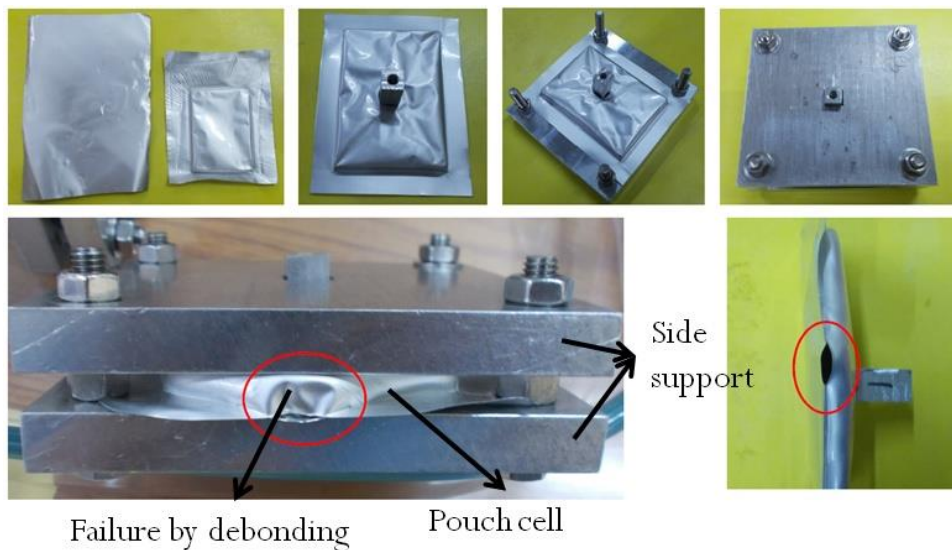


Figure7. Burst test of pouch cell.

6. CONCLUSIONS

Experimental characterization (lap shear, t-peel and tensile) of bonded laminate/films are carried out. UTS of laminate is obtained from lap shear and tensile tests. Fracture energy (mode - I) is obtained from t-peel tests. This is used as input for the cohesive zone model. Structural analysis is carried out for the pouch cell to estimate its pressure capacity.

Tensile strength from lap shear test and tensile test results are close. This indicates robust heat sealing (bond) of pouch cells (cohesive fracture in a lap shear test indicates good process control).

FEA is carried out for the pouch cells under internal pressure and a sufficient margin exists for the cell at 2 bar. A pressure capacity of 6.4 bar is estimated for the pouch cell in assembly condition. However, the average failure pressure from tests is 13.5 bar.

The difference in predicted failure pressure and actual failure pressure is due to the high nonlinear behavior in the test. This could not be captured in the analysis due to non-convergence in finite element solution. Further, few assumptions are made in the CZL used in the finite element model. Christopher's thesis [10] provides insights into the procedure for the extraction of cohesive zone law from peel tests. Tests have to be performed to extract the CZL for a better understanding of the mechanics of laminated interfaces.

Acknowledgment

Authors would like to acknowledge, GD, SDEG and, DD, STR for constant and continuous encouragement in reviewing this technical paper.

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