

Modeling and Study of Fracture and Delamination in a Packaging Laminate

De-Feng ZHANG^{1,2}, Md. Shafiqul ISLAM¹, Eskil ANDREASSON¹,
 Sharon KAO-WALTER^{1,3,a*}

¹Dept. of Mech. Eng., Blekinge Institute of Technology, SE 371 79, Karlskrona, Sweden

²College of Mech. Eng., Quzhou University, Quzhou, China

³Fac. of Mech. & El. Eng., Shanghai Second Polytechnic University, Shanghai, China

^asharon.kao-walter@bth.se

*Corresponding author

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Abstract. In this work, a packaging laminate consisting of LDPE (Low Density Polyethylene), Al-foil (Aluminum foil) is focused, and failure due to necking in substrates and interfacial delamination under loading are considered. A coupled elasto-plasticity damage and fracture constitutive model is combined. The proposed constitutive model is incorporated into the FEM code ABAQUS and utilized to simulate a uniaxial tension in the laminate with an interfacial pre-crack. The simulation results show deformation of the laminate agrees well with theoretical results. The new combined constitutive model is proper to study the failure due to necking and interfacial delamination in the laminate. And the interfacial delamination mode in pre-crack tip could be influenced by fracture toughness ratio of mode I, II.

Introduction

Liquid food packaging becomes an important part in our daily life because it aids liquid food distribution, allows consumers to have more choice in the foods available and reduces wastes. Liquid food packages are often made of composites in order to meet a variety of functional requirements. In this work, a laminate consisting of LDPE (Low Density Polyethylene), Al-foil (Aluminum foil) is studied. In this laminate, each layer contributes with certain properties to the complete material structure. The LDPE layer is used to avoid the direct contact of liquid food to the Al-foil; the Al-foil is beneficial to prevent oxygen and light from reaching the food product from the outside; both the LDPE and Al-foil layers are bonded together. During production, the laminate goes through different processes such as printing, coating, creasing, laminating, perforation etc. To become a liquid food package, it also needs to be formed, folded, filled, etc. Before reaching the consumer, it has to tolerate loading during transport and distribution. In this work, the laminate has been loaded to extreme loading way beyond normal loading conditions to provoke defects such as failure due to necking in substrates, and interfacial delamination, as shown in Fig.1.

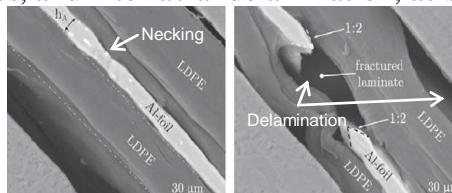


Fig.1 Micrographs of necking and delamination in LDPE, Al-foil packaging laminates [1].

When necking and delamination appears, mechanical toughness of laminate is changed significantly. It is necessary to study and understand the influence of different mechanisms of those defects on property of packaging material. It poses a challenge to researcher. Therefore, the intention in this work is to develop the corresponding theoretical model to analyze failure due to necking in LDPE and Al-foil layers, and delamination in LDPE/Al-foil interface. The proposed

model is then used to study of failure due to necking and interfacial delamination in the packaging laminate with an interfacial pre-crack under unaxial loading.

Theoretical and Numerical Modeling

As shown in Fig.1, the failure due to necking in LDPE/Al-foil packaging laminate under loading mainly refers to both aspects, necking in LDPE and Al-foil, and interfacial delamination. In order to simulate necking and delamination of the laminate, a theoretical model should be created to capture accurately the materials responds during loading at first. After that, the developed model will be incorporated into the commercial finite element packages ABAQUS to fulfill its application.

In engineering, necking is a mode of tensile deformation where relatively large amounts of strain localize in a small region of the specimen or structure [2]. Because the local strains in the neck are large, necking is often closely associated with yielding, a form of plastic deformation associated with ductile materials, often metals or polymers [3]. In another words, material necking, i.e. strain localization, is the comprehensive results of stress concentration and material degradation i.e. softening. Softening refers to the degradation of material stiffness. Therefore, all these deformation mechanisms, such as elastic deformation, plastic flow, strain hardening, and softening should be considered. The corresponding theories should also be employed in constitutive model to describe material behavior correctly during deformation.

Interfacial delamination is one of the most common failure modes for composite structures because the remote loadings applied to composite components are typically resolved into interfacial tension and shear stresses at discontinuities that create interfacial delamination [4-6]. As described above, interfacial delamination does occur in packaging material studied here. Therefore, it becomes another important physical mechanism to influence mechanical toughness. To characterize the onset and propagation of interfacial delamination, damage mechanics or fracture mechanics could be utilized.

Elasto-Plasticity Damage Mechanics. Material necking is due to the stress concentration and material damage of stiffness. Stress concentration could be caused by various defects, such as cracks, inclusions, and so on. Softening refers to the degradation of material stiffness. In this work, an elasto-plasticity damage constitutive model is suggested to demonstrate the failure due to necking of substrates, LDPE and Al-foil.

In the constitutive model, linear elastic model based on Hooke's Law is used to describe material elastic behavior. The von Mises yield criterion, isotropic hardening, and associated flow-rule, to reveal material plastic flow. The elasto-plasticity constitutive model is related to equation (1) to (6).

$$\dot{\sigma} = \mathbf{D}_{ep} : \dot{\varepsilon} \quad (1)$$

$$\mathbf{D}_{ep} = \mathbf{D}_{el} + \mathbf{D}_{pl} \quad (2)$$

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{pl} \quad (3)$$

$$\sigma = \mathbf{D}_{el} : (\varepsilon - \varepsilon_{pl}) = \mathbf{D}_{el} : \varepsilon_{el} \quad (4)$$

$$f(\sigma, \varphi) = f(\sigma) - \varphi = q - (\sigma_0 + \varphi) = 0 \quad (5)$$

$$\dot{\varepsilon}_{pl} = \lambda \frac{\partial f(\sigma, \varphi)}{\partial \sigma} = \dot{\varepsilon}_{pl} \mathbf{n} \quad (6)$$

Here, $\dot{\sigma}$ and $\dot{\varepsilon}$ are total stress rate and strain rate, \mathbf{D}_{ep} , \mathbf{D}_{el} , \mathbf{D}_{pl} are material elasto-plasticity, elastic and plastic stiffness, respectively, and $\dot{\varepsilon}_{el}$ and $\dot{\varepsilon}_{pl}$ are elastic rate and plastic (inelastic) strain rate.

Equation (5) is von Mises yield criterion with isotropic hardening, and $q = \sqrt{(3/2)\mathbf{s} : \mathbf{s}}$ is the von Mises equivalent stress, \mathbf{s} is the deviatoric stress, σ_0 is the yield stress, φ represents one or more hardening parameters. Equation (6) is associated flow-rule since von Mises yield function $f(\sigma)$ is

used to be as flow potential, and $\mathbf{n} = 3\mathbf{s}/2q$ represents the direction of the plastic flow, $\dot{\varepsilon}_{pl}$ is equivalent plastic strain rate.

Damage mechanics is concerned with damage of materials that is suitable for making engineering predictions about the initiation, propagation, and fracture of continuum materials or interfacial delamination of composites without resorting to a microscopic description that would be too complex for practical engineering analysis [7]. In this work, damage mechanics will be employed to describe damage both in LDPE, Al-foil layers. A damage criterion is composed by damage initiation and damage evolution. Most of the work on damage mechanics uses state variable to represent the effects of damage on material stiffness [8]. By using a damage state variable, the flow stress after damage could be reevaluated by equation (7).

$$\sigma = (1 - D)\bar{\sigma} \quad (7)$$

Where σ , $\bar{\sigma}$ are flow stress of damaged and undamaged substrates respectively, D is a scalar damage state variable, representing the overall damage of materials. When $D=1$, material point has completely failed, namely fracture occurs.

Fracture Mechanics. In this work, fracture mechanics will be used to depict interfacial delamination. The energy criterion and the stress intensity approach are the two most common approaches to the fracture analysis. Here, the energy criterion which was proposed by Griffith will be adopted [9] and a 2D fracture mode-mix criterion based on power law [10] is used.

$$f = \left(\frac{G_I}{G_{Ic}}\right)^{am} + \left(\frac{G_{II}}{G_{IIC}}\right)^{an} \geq 1 \quad (8)$$

Where f is effective energy release rate ratio. Once equation (8) satisfies, interfacial delamination occurs.

In equation (8), G_I , G_{II} and G_{Ic} , G_{IIC} are strain energy release rate and fracture toughness of mode I, II, am , an are relevant parameters respectively. In this work, am , an , are 1.

Numerical Modeling. As described above, the failure of laminate under loading mainly refers to two aspects, failure due to necking in substrates, and interfacial delamination induced by the mixed-mode cracking of mode I, II. By means of related theories including continuum mechanics, damage mechanics, or fracture mechanics, a coupled elasto-plasticity damage and fracture constitutive model, governed by equation (1) to (8), is therefore formulated and could be used to capture correctly the two kinds of material behavior.

In this work, ABAQUS is employed to handle the constitutive model. In ABAQUS, all the behaviors described by equation (1) to (7), i.e. elastic behavior, plastic flow and softening due to damage, can be utilized in the fundamental function module of ABAQUS [11]. VCCT (Virtual Crack Closure Technique) available in ABAQUS, is used to model the interfacial delamination.

Simulation of a Uniaxial Tension

Since the theoretical model of LDPE/Al-foil packaging laminate under loading is combined and the constitutive model can be realized by fundamental function and VCCT technique in ABAQUS. Then, the combined model is used to simulate a uniaxial tension in the laminate with an interfacial pre-crack to validate the model and study the fracture in LDPE, Al-foil layers and interfacial delamination.

Information and Parameters. Here, a uniaxial tension in the laminate with an interfacial pre-crack is carried out by ABAQUS. The laminate is composed of a two layer composite build up by LDPE and Al-foil. Fig.2 illustrates the basic information. The interfacial pre-crack is regarded as imperfect bonding and is assumed in the center with a total length of 0.005 mm, shown by the thick blue line at the middle of interface. Therefore, stress concentration and necking will arise around it in the uniaxial tension simulation. Two simulation results under different amount of displacements, 0.004 and 0.005 mm, are used to compare with theoretical case [12].

To model elasto-plastic behavior of laminate described in ABAQUS, the Young's modulus of LDPE and Al-foil are 34201, 136.63 MPa respectively and Poisons ratio of both material is the same value, 0.3. The plasticity values are shown in Fig. 3.

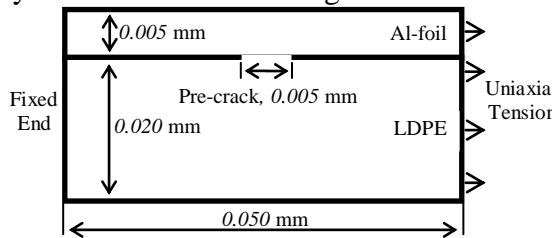


Fig.2 2D model of the packaging laminate

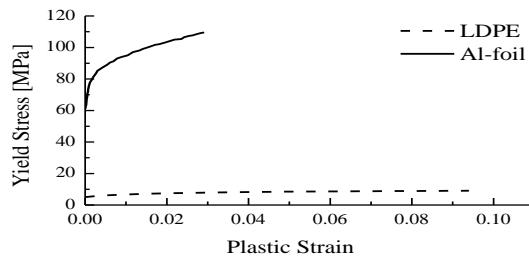


Fig.3 Plasticity value of LDPE and Al-foil.

In this work, the ductile damage model in ABAQUS is adopted to depict damage mechanism, the fracture strain, stress triaxiality and strain rate in the model, are required to define damage initiation. Moreover, a linear damage evolution law based on energy is also used to define the post-damage material behavior. All the related parameters are listed in Table 1. Parameters of ductile damage model in substrates.

Tab.1 Parameters of ductile damage model in substrates.

Material	Fracture Strain	Stress Triaxiality	Strain Rate	Fracture Energy (N/mm)
Al-foil	0.036	-5	0	1
	0.036	5	0	
LDPE	0.90	-5	0	0.01
	0.90	5	0	

VCCT technique in ABAQUS is used to model interfacial delamination. For VCCT technique, power law expressed by equation (8) is adopted to work as the interface debonding criterion. The fracture toughness, G_{Ic} , G_{IIc} and a_m , a_n should be specified to define the fracture criterion. In this work, a set of normalized parameters of G_{Ic}/G_{IIc} are used to validate the model and analyze the delamination mode of pre-crack tip.

Fig.4 displays the FEM model based on VCCT. In this model, the interfacial pre-crack can be realized by initial debonding part of Slave-Master Contact Pair, shown as a white line. In order to activate the crack propagation capability, a small-sliding, slave-master contact surfaces in ABAQUS/Standard is used. Moreover, an initial contact condition is used to identify which part of the slave surface is initially bonded and will debond once the fracture criterion is met. In the model, the four-node quadrilateral plane strain elements, type CPE4, are used in both substrates, and matching elements along the interface.

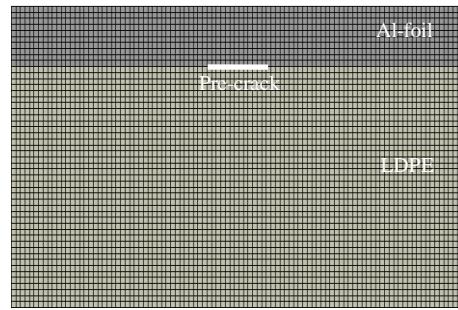


Fig.4 FEM model based on VCCT technique

Simulation Results and Analysis

In this work, a uniaxial tension of the packaging laminate with an interfacial pre-crack is simulated by the FEM model. A displacement boundary condition on the right side of the specimen is applied when the clamp is moved in tension. Meanwhile, all DOF (Degree of Freedom) of the left side are constrained, i.e. encasted in ABAQUS, as a fixed end. The material model is elasto-plasticity associated with damage consisting of von Mises yield criterion, isotropic hardening and associated flow-rule for both materials. The property of interface is defined respectively according to the principle described above.

Fig.5 (a) shows the deformation results of simulation without interfacial delamination. For the comparison, the theoretical analysis results, in which interfacial delamination is not considered, are also presented by using slip-line theory from [12], in Fig.5 (b). Simulation results are closely consistent with that of theoretical analysis. That means material behaviors, including elastic deformation, plastic flow, strain hardening; softening could be captured accurately by the model.

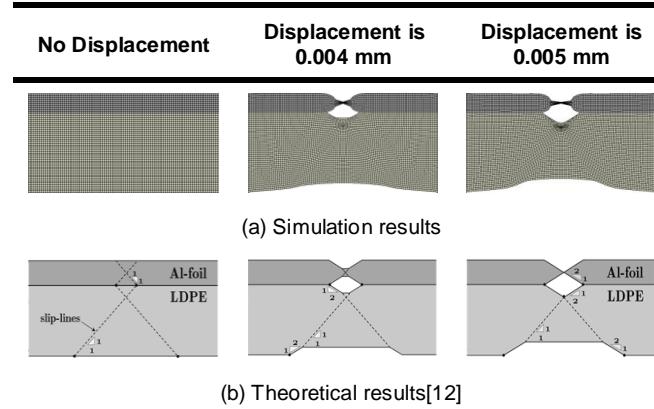


Fig.5 Deformation results of simulation and theoretical analysis

Fig.6 shows interfacial pre-crack extends progressively along the interface during uniaxial tension. In ABAQUS, the fracture energy release rate G_I , G_{II} could be computed by using VCCT technique and used to get effective energy release rate ratio f by equation (8). For instance, the G_I , G_{II} in interfacial pre-crack tip are 0.00031554, 0.00011331 by calculation, and then

$$f = (G_I/G_{IC})^l + (G_{II}/G_{IIC})^l = (0.00031554/0.0005) + (0.00011331/0.0005) = 1.08433 \quad (9)$$

That means the fracture criterion based on power law is satisfied, therefore interfacial delamination initiates, as shown in Fig.6. The case without delamination at crack tip is also provided for the purpose of comparison.

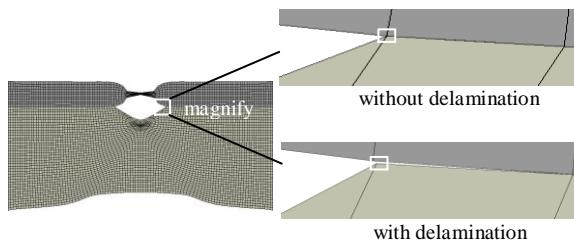


Fig.6 Interfacial delamination at interfacial pre-crack tip

Fig.7 shows the influence mechanism of fracture toughness on interfacial delamination in pre-crack tip. The mode I of delamination is prominent, i.e. $(G_I/G_{IC})/f = 1$, when interfacial fracture toughness of mode I, II is equal, $G_{IC}/G_{IIC} = 1$. The $(G_I/G_{IC})/f$ is decreasing progressively from 1 to around 0.6 with the increasing of G_{IC}/G_{IIC} . It means the mode II turns to be important with increasing of fracture toughness ratio, G_{IC}/G_{IIC} .

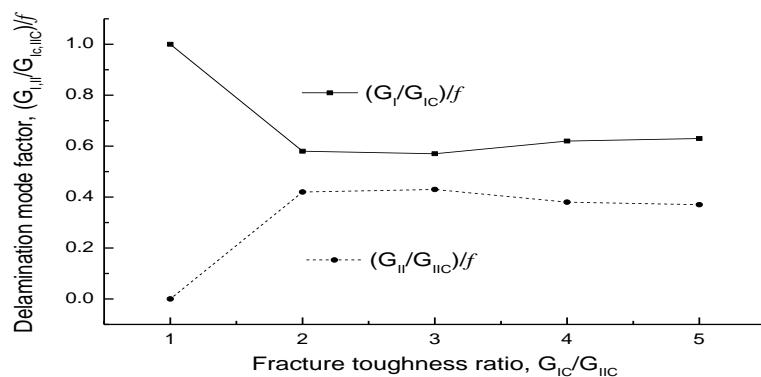


Fig.7 Influence curve of fracture toughness on interfacial delamination in crack tip

Conclusion

In this work, a coupled elasto-plasticity damage and fracture constitutive model is combined to describe failure due to necking in substrates and interfacial delamination of a packaging laminate during loading. The proposed model is incorporated into the FEM code ABAQUS and employed to simulate a uniaxial tension in the laminate with an interfacial pre-crack. The study results are concluded as follows:

(1) The new combined constitutive model is proper to study the failure due to necking in substrates and interfacial delamination in the laminate. The deformation in simulation agrees well with theoretical results. Material behaviors, including elastic deformation, plastic flow, strain hardening, softening and interfacial delamination could be captured accurately by this model.

(2) The interfacial delamination mode in pre-crack tip could be influenced by the ratio of fracture energy of mode I, II. The mode I of delamination is prominent when interfacial fracture toughness of mode I, II is equal. The mode II turns to be important with relative decreasing of its fracture toughness.

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