THE MECHANICS OF INTERFACE FRACTURE IN LAYERED COMPOSITE MATERIALS: (4) BUCKLING DRIVEN DELAMINATION OF THIN LAYER MATERIALS

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ABSTRACT

Analytical theories were developed for studying post-local buckling-driven delamination of thin layer materials under in-plane compressive stresses which can arise from externally applied mechanical loads, thermal stresses due to mismatch of coefficients of thermal expansion between the thin layer material and the thick substrates, the intercalation stresses due to electrochemical lithiation and delithiation, and etc. The development was based on three mixed mode partition theories. They are Euler beam or classical plate, Timoshenko beam or shear deformable plate [1-5] and 2D-elasticity [6-8] theories. Independent experimental tests [9] show that, in general, the analytical partitions based on the Euler beam or classical plate theory predicts the propagation behaviour very well and much better than the partitions based on the Timoshenko beam and 2D-elasticity theories.

1 INTRODUCTION

Thin layer/substrate composite material systems are commonly seen in many engineering applications, such as thermal barrier coating system in aero engines, erosion resistance coating system in oil transportation pipes, thin film electrodes in batteries, and etc. The thin layer is often sustain substantial in-plane residual stresses in service condition, such as mechanical stresses due to release of pre-strains in the substrate, thermal stresses due to mismatch of thermal expansion coefficients, intercalation stresses in thin film electrodes [10] due to electrochemical lithiation and delithiation, and other diffusion induced stresses. The compressive residual stresses can cause buckling-driven delamination which has to be considered for reliable design of such thin layer/substrate composite material systems. The study aims to develop analytical theories to predict the buckling driven delamination behaviour of thin layer/substrate composite material systems under in-plane compressive stresses.

2 THEORY

Fig. 1 illustrates two typical buckling driven delaminations of thin layer materials, which are often used in experimental tests to determine the fracture toughness of the film/substrate interfaces and also often occur in practice. The thin layer materials are under in-plane compressive stresses which can arise from externally applied mechanical stresses, thermal stresses due to mismatch of coefficients of thermal expansion between the thin layer material and the thick substrates, the intercalation stresses due to electrochemical lithiation and delithiation, and etc. The present work focuses at the buckling driven delamination with straight edges as shown in Fig. 1(a), which can be readily extended to study the buckling driven delamination with circular edge as shown in Fig. 1(b).

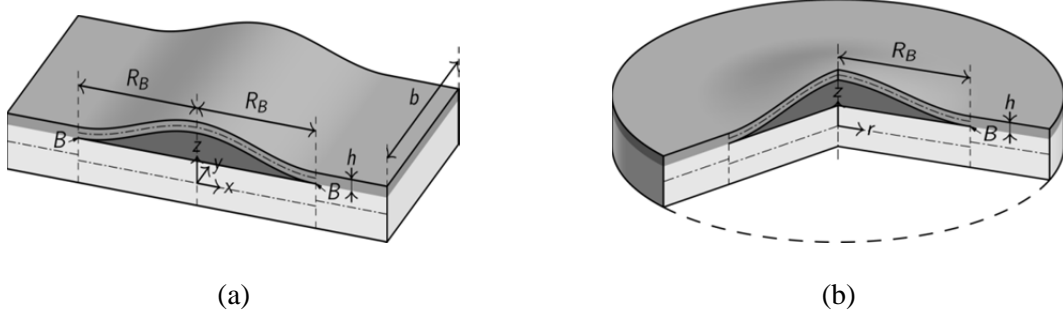(a)   (b)

Figure 1: Buckling driven delamination of thin layer materials (a) with straight edges and (b) with circular edge.

The buckled mode shape of the delamination with straight edges in Fig. 1 (a) is assumed to be [11]

$$w(x) = \frac{A}{2}\left[\cos\left(\frac{\alpha\pi x}{R_B}\right) - \cos(\alpha\pi)\right] \tag{1}$$

where α is the correction factor for the quality of the clamped end condition at the crack tip B, which equals to 1 when the thickness h of the thin layer material is very small in comparison with the thickness of the substrate, and A, R_B are the amplitude and half buckling width, respectively. The energy release rates (ERR) G_I and G_{II} at the crack tip B are determined in the following as they control the delamination propagation behaviour.

2.1 Euler beam or classical plate partitions

According to Euler beam or classical plate partition theory [1-5], the ERR partitions are given as

$$G_{IE} = c_{IE}\left(M_{1B} - \frac{N_{1Be}}{\beta}\right)\left(M_{1B} - \frac{N_{1Be}}{\beta'}\right) \tag{2}$$

$$G_{IIE} = c_{IIE}\left(M_{1B} - \frac{N_{1Be}}{\theta}\right)\left(M_{1B} - \frac{N_{1Be}}{\theta'}\right) \tag{3}$$

where (θ, β) and (θ', β') are the two sets of orthogonal pure modes which are

$$(\theta, \beta) = \left(-\frac{6}{h}, \frac{2}{\lambda h}\right) \tag{4}$$

$$(\theta', \beta') = (0, \infty) \tag{5}$$

and

$$c_{IE} = \frac{6}{Eh^3} \tag{6}$$

M_{1B} and N_{1Be} are the crack tip bending moment and effective axial force per unit width, respectively. The parameter λ is given as

$$\lambda = \frac{\eta\gamma}{1 + \eta\gamma}, \eta = \frac{E_s}{E}, \gamma = \frac{h_s}{h} \tag{7}$$

E, h, E_s and h_s are the Young's modulus of the thin layer materials, the thickness of the thin layer,

the Young's modulus of the substrate material and the thickness of the substrate, respectively. When $\gamma = h_s / h$ is very big, the parameter λ approaches to 1. For convenience, the partitions are also given below in terms of the critical buckling strain ε_c and the residual compressive strain ε_0.

$$G_{IE} = Ehc_\alpha \sqrt{\varepsilon_c}\, \varepsilon_a \left(2c_\alpha \sqrt{\varepsilon_c} - \sqrt{3}\lambda\sqrt{\varepsilon_a}\right) \tag{8}$$

$$G_{IIE} = Eh\lambda\varepsilon_a^{3/2}\left(\sqrt{3}c_\alpha \sqrt{\varepsilon_c} + 1/2\sqrt{\varepsilon_a}\right) \tag{9}$$

where the critical local-buckling strain ε_c is

$$\varepsilon_c = \frac{(\alpha\pi)^2}{12}\left(\frac{h}{R_B}\right)^2 \tag{10}$$

and the additional compressive strain beyond ε_c is

$$\varepsilon_a = \varepsilon_0 - \varepsilon_c \tag{11}$$

ε_0 is residual compressive strain. It can be produced by externally applied mechanical strain, thermal strain due to mismatch of coefficients of thermal expansion between the thin layer material and the thick substrates, the intercalation stain due to electrochemical lithiation and delithiation, and etc. The parameter c_α is close to 1 for large $\gamma = h_s / h$. Note that when $\sqrt{\varepsilon_a} > \left(2c_\alpha \sqrt{\varepsilon_c}\right)/\left(\sqrt{3}\lambda\right)$, the crack tip normal stress becomes compressive, and so G_{IE} is taken to be zero with $G_{IIE} = G$.

2.2 Timoshenko beam or shear deformable plate partitions

According Timoshenko beam or shear deformable plate partition theory [1-5], the ERR partitions are

$$G_{IT} = c_{IT}\left(M_{1B} - \frac{N_{1Be}}{\beta}\right)^2 \tag{12}$$

$$G_{IIT} = c_{IIT}\left(M_{1B} - \frac{N_{1Be}}{\theta}\right)^2 \tag{13}$$

where

$$c_{IT} = \frac{6}{(1+3\lambda)Eh^3} \tag{14}$$

$$c_{IIT}\, \frac{6}{\left(1+1/(3\lambda)\right)Eh^3} \tag{15}$$

In terms of the critical buckling strain ε_c and the additional compressive strain ε_a, they become

$$G_{IT} = \frac{1}{2(1+3\lambda)}Eh\varepsilon_a\left(2c_\alpha \sqrt{\varepsilon_c} - \sqrt{3}\lambda\sqrt{\varepsilon_a}\right)^2 \tag{16}$$

$$G_{IIT} = \frac{\lambda}{2(1+3\lambda)}Eh\varepsilon_a\left(2\sqrt{3}c_\alpha \sqrt{\varepsilon_c} + \sqrt{\varepsilon_a}\right)^2 \tag{17}$$

Again note that when $\sqrt{\varepsilon_a} > \left(2c_\alpha \sqrt{\varepsilon_c}\right)/\left(\sqrt{3}\lambda\right)$, the crack tip normal stress becomes compressive, and

so G_{IT} is taken to be zero with $G_{IIT} = G$.

2.3 2D elasticity partitions

By ignoring the material mismatch the 2D elasticity partition theory [6-8] gives the following partitions

$$G_{I2D} = c_{I2D}\left(M_{1B} - \frac{N_{1Be}}{\beta_{2D}}\right)^2 \tag{18}$$

$$G_{II2D} = c_{II2D}\left(M_{1B} - \frac{N_{1Be}}{\theta_{2D}}\right)^2 \tag{19}$$

where

$$(\theta_{2D}, \beta_{2D}) = \left(-\frac{2.697}{h}, \frac{4.450}{\lambda h}\right) \tag{20}$$

$$c_{I2D} = \frac{4.450^2\left(12 + 2.697^2\lambda\right)}{12\left(4.450 + 2.697\lambda\right)^2}\frac{6}{Eh^3} \tag{21}$$

$$c_{II2D} = \frac{2.697^2\left(12\lambda + 4.450^2\lambda\right)}{12\left(4.450 + 2.697\lambda\right)^2}\frac{6}{Eh^3} \tag{22}$$

In terms of the critical buckling strain ε_c and the additional compressive strain ε_a, they become

$$G_{I2D} = \frac{12 + 2.697^2\lambda}{6\left(4.450 + 2.697\lambda\right)^2}Eh\varepsilon_a\left(4.450c_\alpha\sqrt{\varepsilon_c} - \sqrt{3}\lambda\sqrt{\varepsilon_a}\right)^2 \tag{23}$$

$$G_{II2D} = \frac{\left(12\lambda + 4.450^2\right)\lambda}{6\left(4.450 + 2.697\lambda\right)^2}Eh\varepsilon_a\left(2.697c_\alpha\sqrt{\varepsilon_c} + \sqrt{3}\sqrt{\varepsilon_a}\right)^2 \tag{24}$$

Again note that when $\sqrt{\varepsilon_a} > \left(4.450c_\alpha\sqrt{\varepsilon_c}\right)/\left(\sqrt{3}\lambda\right)$, the crack tip normal stress becomes compressive, and so the G_{I2D} is taken to be zero and $G_{II2D} = G$.

3 EXPERIMENTAL ASSESSMENTS

In this Section experimental results are used to assess which above ERR partitions gives the best predictions for the mechanical behaviour of buckling driven delamination. A linear failure criterion was used for the relatively low interface fracture toughness in consideration. Fig. 2 shows the comparison between the analytical predictions and experimental test [9] for case 1 specimen. The thickness of the thin layer is 0.518 mm and the thickness of the substrate is 2.072 mm. It is seen that the two beam partition theories predict the propagation behavior very well and much better than the 2D elasticity partition theory does. The delamination propagation is indeed the pure mode II propagation predicted by the two beam partition theories. It is now clear that the 2D elasticity partition theory does not provide the right partition for predicting the propagation behaviour of buckling-driven delamination for Case 1. The question of which beam partition theory provides the right partitions when the propagation is not pure mode II, however, still needs to be answered. Fig. 3 shows the comparison between the analytical predictions and experimental test [9] for case 2 specimen. The thickness of the thin layer is 0.508 mm and the thickness of the substrate is 2.032 mm. It is observed that the analytical theory based on the classical partition theory predicts the propagation behaviour very well and much better than the analytical theories based on the shear deformable and 2D-elasticity partition theories.
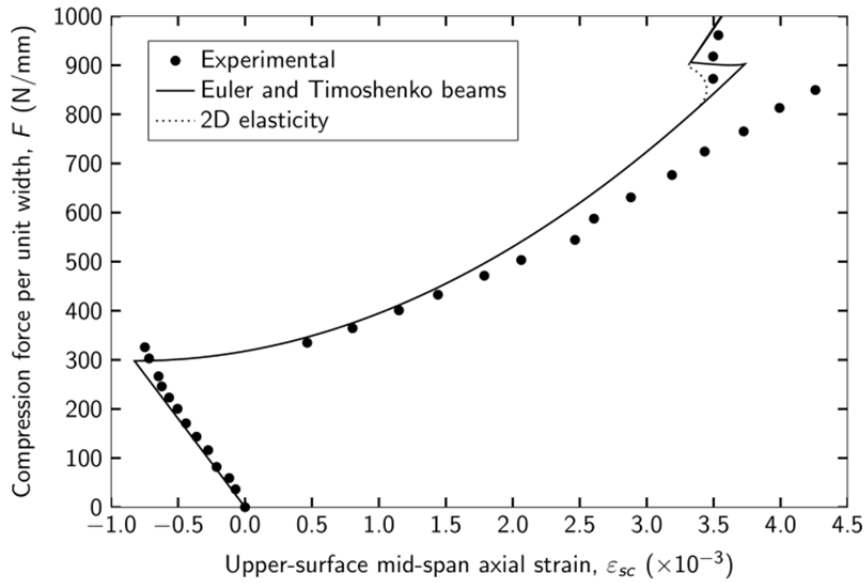
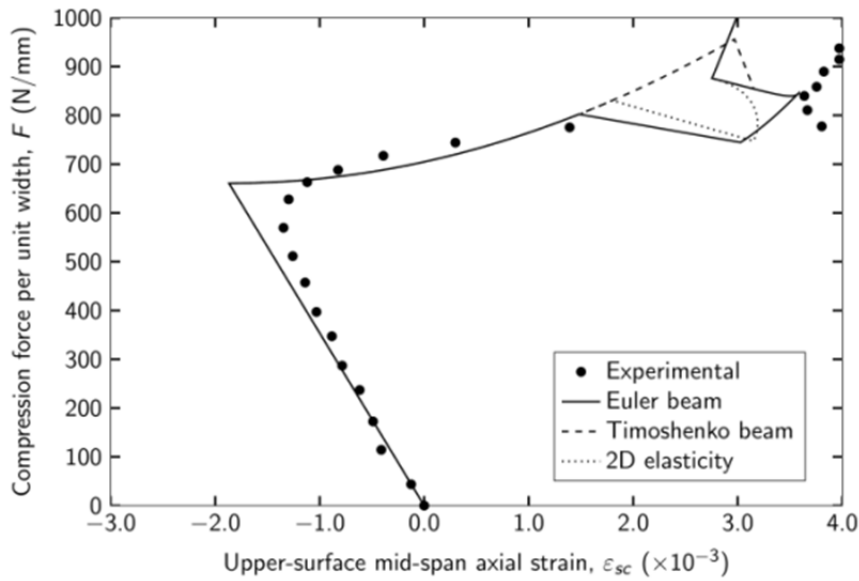Figure 2: Compression force per unit width F vs. upper-surface mid-span strain ε_{sc} for case 1 specimen.

Figure 3: Compression force per unit width F (N/mm) vs. upper-surface mid-span strain ε_{sc}.

4   CONCLUSIONS

Mechanical models have been developed for studying buckling driven delamination of thin layer materials under in plane compressive stress arising from mechanical, thermal and electrochemical actions. In both test cases, the thin layers have macroscopic thicknesses. The Euler beam or classical plate partition theory [1-5] predicts the delamination behaviour very well due to the global nature of the theory. Whilst the Timoshenko beam or shear deformable plate and 2D elasticity partition theories perform less well due to their local nature.

REFERENCES

[1] S. Wang S and C.M. Harvey, A theory of one-dimensional fracture. *Composite Structures*, **94**, 2012, pp.758–767 (doi: 10.1016/j.compstruct.2011.09.011). Also a plenary lecture at the 16th International Conference on Composite Structures (ICCS16), 28–30 June 2011, Porto, Portugal.

[2] S. Wang and C.M. Harvey, Mixed mode partition theories for one dimensional fracture, *Engineering Fracture Mechanics*, **79**, 2012, pp. 329-352 (doi: 10.1016/j.engfracmech.2011.11.013).

[3] C.M. Harvey and S. Wang, Mixed mode partition theories for one dimensional delamination in laminated composite beams, *Engineering Fracture Mechanics*, **96**, 2012, pp. 737-759
(doi: 10.1016/j.engfracmech.2012.10.001).

[4] C.M. Harvey and S. Wang, Experimental assessment of mixed-mode partition theories, *Composite Structures*, **94**, 2012, pp. 2057-2067 (doi: 10.1016/j.compstruct.2012.02.007).

[5] C.M. Harvey, M.R. Eplett and S. Wang, Experimental assessment of mixed-mode partition theories for generally laminated composite beams, *Composite Structures*, **124**, 2015, pp. 10-18
(doi: 10.1016/j.compstruct.2014.12.064).

[6] J.W. Hutchinson, Z. Suo, Mixed mode cracking in layered materials, *Advances in Applied Mechanics*, **29,** 1992, pp. 63-191 (doi:10.1016/S0065-2156(08)70164-9).

[7] C.M. Harvey, J.D. Wood, S. Wang and A. Watson, A novel method for the partition of mixed-mode fractures in 2D elastic laminated unidirectional composite beams, *Composite Structures* **116**, 2014, pp. 589-594 (doi: 10.1016/j.compstruct.2014.05.041).

[8] J.D. Wood, C.M. Harvey and S. Wang, Partition of mixed-mode fractures in 2D elastic orthotropic laminated beams under general loading, *Composite Structures*, **149**, 2016, pp. 239-246 (doi: 10.1016/j.compstruct.2016.04.016).

[9] Z. Kutlu and F.K. Chang, Composite panels containing multiple through-the-width delaminations and subjected to compression: Part II: experiments and verification, Composite Structures, 31, 1995, pp. 297-314 (doi: 10.1016/0263-8223(95)00093-3)

[10] V.A. Sethuraman, M.J. Chon, M. Shimshak, V. Srinivasan and P.R. Guduru, In situ measurements of stress evolution in Silicon thin films during electrochemical lithiation and delithiation, **195**, 2010, pp. 5062-5066 (doi: 10.1016/j.jpowsour.2010.02.013).

[11] S. Wang, C.M. Harvey, B. Wang and A. Watson, Post-local buckling-driven delamination in bilayer composite beams, *Composite Structures*, **133**, 2015, pp. 1058-1066
(doi: 10.1016/j.compstruct.2015.08.012).