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Transition among failure modes of the bending system with a stiff film on a soft substrate

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Growing interest is being attracted by stretchable and flexible electronics recently due to their attractive characteristics, commercial potentials, and engineering challenges. In comparison with the system on a macroscopic scale, different failure modes are observed in a system with a thin film bonded on an elastomeric substrate. Furthermore, the experimental observations reveal that failure modes occur in turn with the increasing of thickness ratio of the film to substrate. In this paper, theoretical analysis is performed on the failure mechanism in this system with the focus on transitions among these failure modes based on the theory of fracture mechanics. The present theoretical predictions are coincident with related experiment results and can be used to guide the related structural design. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4905697]

Stretchable and flexible electronics,[1] which offer performance of conventional wafer-based devices as a soft machine with inorganic thin films bonded onto an elastomeric substrate, are promising to enable many new applications, such as flexible displays,[2] conformable skin sensors,[3,4] electronic eye cameras,[5,6] and smart surgical and diagnostic implements.[7] Due to conspicuous engineering challenges in the large mismatch of mechanical properties between the soft substrate and stiff electronic films, many efforts have been taken to explore the mechanism in the design, processing, and integration. For example, research topics range from the structure design[8–10] including wavelength, the amplitude, the energy, the maximum strain, edge effects, and so on in the related buckled structures, wrinkled structures, wavy structures, precisely controlled buckled structures, or island-bridge structures, to processing techniques including encapsulation,[11] transfer printing,[12] and flipping over,[13] to fabrication,[14] and to integration.[15]

Obviously, system failure is an important problem for both stretchable and flexible electronics and the system on the macroscopic scale to insure its safeness, and there are distinct characteristics for the former in comparison with the latter. Unfortunately, comparing with the abundant works on that of macroscopic scale, only few researches[16–21] have been performed on the system failure in stretchable and flexible electronics. Recently, an interesting experimental phenomenon[16] was observed that with the increase of thickness ratio of film to substrate, several failure modes occurred, as shown in Fig. 1, which was explained based on strength theory.[16,17] Considering that once a defect exists or emerges, it will easily induce failures in the device during producing and operating. Therefore, it is valuable to investigate the fundamental facture mechanics buried in the experiments. Using the mixed-mode fracture theory of layered structures,[22] an analytical slipping model was established,[18] which was used to obtain a slippage toughness measurement method,[20] and the comparison was made between slippage and delamination.[21] This paper aims at exploring the mechanism of transitions among these failure modes with the increasing of thickness ratio of film to substrate by using the mixed-mode fracture theory of layered structures.

Fig. 1 shows a schematic illustration of the bending test for a thin electronic film bonded on an elastomeric substrate, which is a typical structure in stretchable and flexible electronics. The right lateral of the substrate is free on which compression is loaded by moving a free baffle toward the left fixed lateral. As the substrate is soft enough compared to the film, out-plane buckling will take place to minimize the energy, which is the reference configuration in this paper, as shown in Fig. 1(a). It is shown that four failure modes such as rupture, slippage, delamination in slipping zone, and delamination occur in turn with the increase of the thickness ratio of film to substrate. Among these four modes, the first failure mode occurs in the film, and the latter three appear on the interface. The competition among these four failure modes determines which one happens in a structure and how it induces the failure of the structure, which is the topic of the present analysis.

Considering the character of slipping failure that it does not lead to the loss of the carrying capacity of the structure completely, the continuity requirement of out-plane displacement w through the upper and lower surfaces of the slipping crack presents as $w^{\text{inter}-s} = w^{\text{inter}-f}$, where $w^{\text{inter}-s}$ and $w^{\text{inter}-f}$ denote displacements on the interface in the substrate and the film, respectively. And because of the continuity of boundary condition of χ_x, one can get $M_x^f/D_f = M_x^s/D_s$, where M_x^f, D_f and M_x^s, D_s are the bending moments and the flexural rigidities of the film and the substrate, respectively. Then, the analytical model of slipping failure can be established. Noting that the continuity requirements are free of

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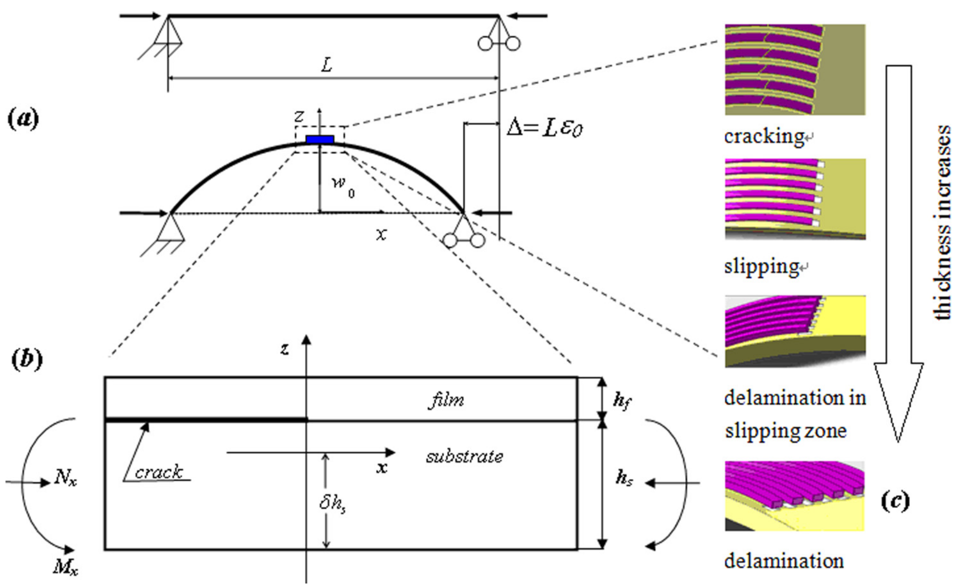

FIG. 1. Schematic illustration of proposed model in bending test. (a) The initial equilibrium configuration of the set before loaded and the reference configuration of the set with the substrate buckled when applying the loading; (b) the present analyzed model of a film on a substrate with a kind of crack on the interface or in the film; and (c) the transitions of the failure modes with the increasing of film thickness.

force and moment through the upper and lower surface of the delaminating crack if it occurs on the interface, the analytical model of delaminating failure can be established. As for the delamination in slipping zone, the related analytical model can be established by combining the interface slipping boundary conditions with the delaminating crack surface conditions. For the first failure mode, rupture of the thin film, we adopt the same analytical model in Ref. 23. Thus, based on the mixed-mode fracture theory of layered structure, the energy release rates for the three interface failure models can be obtained as

$$G_{del-adh} = \frac{1}{2\bar{E}_s}\frac{N_x^2}{h_s}\left[\frac{t\eta}{1+t\eta} + 12\left(\frac{w_0}{h_s}\right)^2 - \frac{12}{(1+t\Sigma)\Delta_3}\left(\frac{w_0}{h_s}+\frac{\Delta_1}{2}\right)^2\right], \quad (1)$$

$$G_{slip-adh} = \frac{1}{2\bar{E}_s}\frac{N_x^2}{h_s}\left[\frac{t\eta}{1+t\eta} + \frac{12}{1+t\eta^3}\frac{w_0^2}{h_s^2} - \frac{12}{(1+t\Sigma)\Delta_3}\left(\frac{w_0}{h_s}+\frac{\Delta_1}{2}\right)^2\right], \quad (2)$$

$$G_{del-slip} = \frac{1}{\bar{E}_s}\frac{N_x^2}{h_s}\left(\frac{w_0}{h_s}\right)^2\frac{6\times t\eta^3}{1+t\eta^3}, \quad (3)$$

where $G_{del\text{-}adh}$, $G_{slip\text{-}adh}$, $G_{del\text{-}slip}$ denote the energy release rates for the failure mode of delamination, slippage, and delamination in slipping zone. $\bar{E}_f$ and $\bar{E}_s$ are the plane-strain modulus of the film and the substrate, $\eta = h_f/h_s$ and $t = \bar{E}_f/\bar{E}_s$ are the thickness and the modulus ratios of film to substrate, respectively, in which h_f and h_s are the thickness of the film and the substrate, respectively. $w_0 = \frac{2}{\pi}L\sqrt{\frac{dL}{L} - \frac{\pi^2 h_s^2}{12L^2}}$ is the deflection of the substrate at the center, where L, dL/L denote the initial lengths, the applied strain; $\triangle_1 = t\eta(1+\eta)/(1+t\eta)$, $\triangle_2 = \eta(\eta^2 + 3/(1+t\eta)^2)$, $\triangle_3 = 1 + 3t^2\eta^2/(1+t\eta)^2$, $\sum = \triangle_2/\triangle_3$, and N_x is the axial force determined at the substrate center. For the rupture of the thin film, by using the solutions in Ref. 23, we can easily obtain the related solution of energy release rate for the present layered structure.

In the system with a thin silicon film ($E_f = 130$Gpa, $\nu_f = 0.27$) on a PET substrate ($E_s = 4.0$Gpa, $\nu_s = 0.44$) just as given in Ref. 16, the thickness of thin film, i.e., silicon, is $\sim$1000 times as small as a typical elastomer, $\eta \ll 1$. And considering in some extreme mismatch structures when $t\eta \ll 1$, the energy release rates $G_{del\text{-}adh}$ and $G_{slip\text{-}adh}$ are equal to each other and their expressions can be simplified as

$$G_{del-adh} = G_{slip-adh} = \frac{1}{2\bar{E}_s}\frac{N_x^2}{h_s}t\eta\left(1 - 12\frac{w_0}{h_s}\right) \quad (4)$$

and

$$G_{del-slip} \ll G_{del-adh}, \quad \text{and } G_{slip-adh}. \quad (5)$$

Noting that only the buckled structures are studied in this paper, the above solutions shows that for the structure with $\eta \ll 1$ and $t\eta \ll 1$, once it is buckled with the increasing of applied displacement loading dL, the energy release rates $G_{del\text{-}adh}$ and $G_{slip\text{-}adh}$ reach to the same maximum values and the system is at the most dangerous state at this time. It also can be found that the delaminating failure, including the delaminating failure in slipping zone, on the interface cannot take place in such structures considering that the critical values of energy release rates of delamination $G_c|_{del-adh}$ are larger than those of slipping $G_c|_{slip-adh}$ in a structure, $G_c|_{del-adh} > G_c|_{slip-adh}$, which is consistent with the experimental phenomenon that film rupture occurs for the structures with $\eta = 0.57 \times 10^{-3}$ and $t\eta = 0.016$, and slipping failure occurs for the structures with $\eta = 0.014$, $t\eta = 0.396$; $\eta = 0.05$, $t\eta = 1.413$, etc.

In the stretchable and flexible electronics with a Si film ($E_f = 130$ GPa, $\nu_f = 0.27$) on a PDMS substrate ($E_s = 2.0$ MPa, $\nu_s = 0.45$), there are $\eta \ll 1$ and $t\eta^3 \ll 1$ in general. Thus, $G_{del\text{-}slip} \ll G_{del\text{-}adh}$ and $G_{slip\text{-}adh}$. The variations of energy release rate G with the deflection of the substrate w_0 are obtained in Fig. 2. Fig. 2(a) gives the variations of three kinds of energy release rate, $G_{del\text{-}adh}$, $G_{slip\text{-}adh}$, and $G_{del\text{-}slip}$, with the deflection of the substrate w_0 for the case of $\eta = 1.0 \times 10^{-4}$,

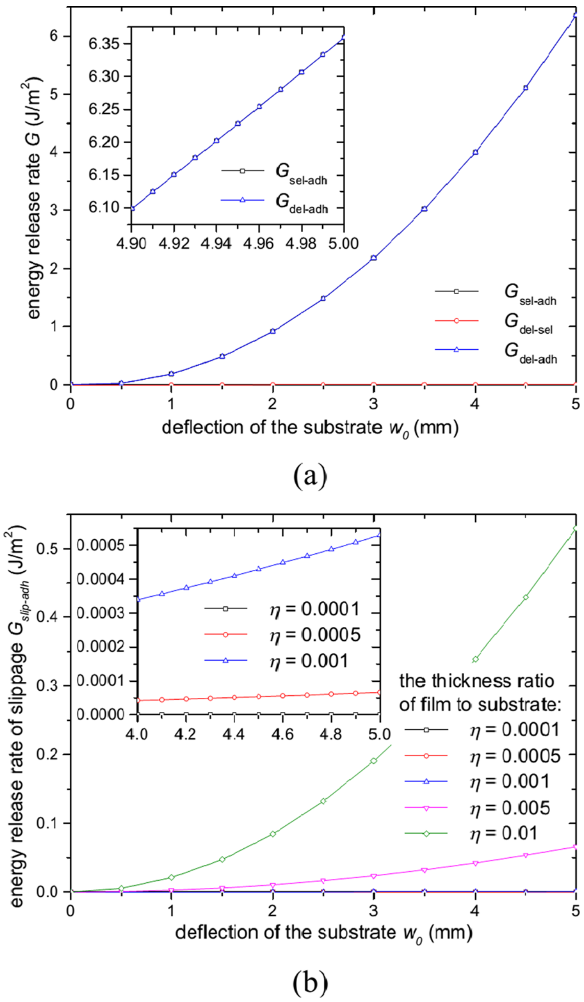

FIG. 2. The variations of energy release rate G with the deflection of the substrate w_0. (a) Three kinds of energy release rate, $G_{slip\text{-}adh}$, $G_{del\text{-}slip}$, $G_{del\text{-}adh}$, vs the deflection of the substrate w_0 when the thickness ratio of film to substrate $\eta = 1.0 \times 10^{-4}$. (b) The energy release rate $G_{slip\text{-}adh}$ vs the deflection of the substrate w_0 for different film thickness, namely, $\eta = 1.0 \times 10^{-4}$, 5.0×10^{-4}, 1.0×10^{-3}, 5.0×10^{-3}, and 1.0×10^{-2}, respectively.

which shows that the former two are coincident well with each other while the third $G_{del\text{-}slip}$ is nearly negligible compared to the former two. Fig. 2(b) gives the variation of energy release rate $G_{slip\text{-}adh}$ with the deflection of the substrate w_0 for different film thicknesses, i.e., $\eta = 1.0 \times 10^{-4}$, 5.0×10^{-4}, 1.0×10^{-3}, 5.0×10^{-3}, and 1.0×10^{-2}, respectively. It shows that $G_{del\text{-}slip}$ is a monotonic increasing function of the deflection of the substrate w_0, and it increases with η when $\eta \ll 1$. Based on the present solutions, we obtain $G_{slip\text{-}adh} = 0.56 \times 10^{-3}$ J/m^2 for the case of $L = 12.8$ mm, $h_f = 100\,\mu$m, and $dL/L = 3.5\%$, which agrees well with the FEM result 0.51×10^{-3} J/m^2 given in Ref. 20. For the case of $h_f = 100$ nm and $dL/L = 7.7\%$, the present analytical result of the energy release rate is 1.11 J/m^2, while the related experimental result in Ref. 20 is 0.78 J/m^2 when the Si films are prepared with widths of 5 μm, and lengths of 200 μm. Considering the present analytical solutions are obtained for plane strain state, some modifications are made and the related analytical result of plane stress state is 0.89 J/m^2, which is adequately accurate in comparison with the experimental result. Thus, the above quantitative comparison shows that the present theoretical solutions agree well with the related experimental results and the FEM results.

Flexibility is one of the most important characters and also the basic requirement for applications of stretchable and flexible electronics such as flexible displays and solar cells, conformable sensors, and so on. It can be quantitatively illustrated by the curvature radius R of the structure, and the smaller the curvature radius, the better the flexibility. By using the mixed-mode fracture theory of layered structure, the critical stress intensity factors can be determined. Then, considering $R = L^2/(\pi^2 w_0)$, four curves of the critical radius of curvature R_c versus the thickness ratio η are shown in Fig. 3, in which R_c is the special curvature radius R determined by four failure states. Noting that curvature radius decreases with the applied displacement loading dL, the failure mode will occur at first when its value of R_c is bigger than others among these four curves. Thus, Fig. 3 was divided into four zones according to different failure modes, and they occur in turn with the increase of the film thickness, which agrees well with the experimental observation. By comparing the present solutions with the experimental results, it can also be found that the present solutions can quantitatively explain the experimental results well except the case that slippage takes place at first, then delamination occurs with the increasing load. This might be caused by the influence of the unloading, which is inevitable once failure occurred and is very difficult to be quantitatively studied in the present analysis.

In summary, the failure mechanism in a system with a thin film bonded on an elastomeric substrate is studied and the interfacial energy release rates are obtained by using the mixed-mode fracture theory of layered structure, which are related to three interfacial failure modes. It is demonstrated that the present analysis solutions of energy release rates of $G_{del\text{-}adh}$ and $G_{slip\text{-}adh}$ are consistent well with the related experiment results and the FEM results. Four curves of the critical radius of curvature R_c as the functions of dimensionless film thickness are obtained, which quantitatively

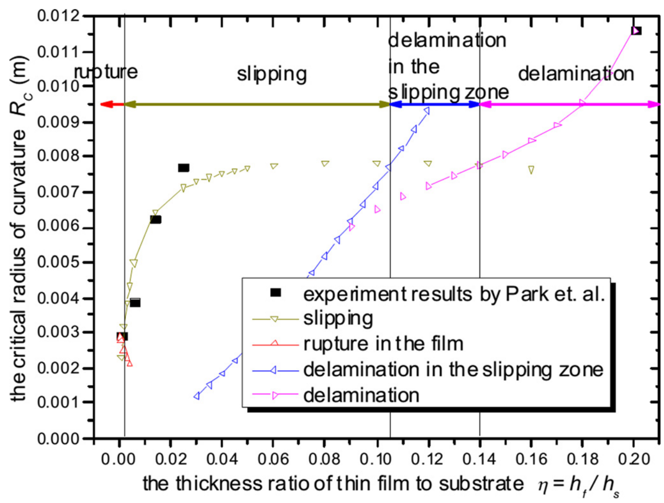

FIG. 3. The critical radius of curvature R_c which is depend on four failure modes: rupture occurred in the film, slippage, delamination in the slipping zone, and delamination occurred on the interface, vs the thickness ratio of film to substrate, which is agreement with the related experimental results (black squares for experiment, lines for present theory models).

illustrate the flexibility of the system. Furthermore, the transitions among these four failure modes occur with the increase of dimensionless film thickness are explored, which are consistent with the related experimental results. The analytical theory proposed in this letter provides interpretable guidelines for the design of stretchable and flexible electronics.

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