

Coupled Wrinkling and Bending in Strain-Mismatched Tri-Layer Structures

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ABSTRACT: Wrinkled structures have been widely used to accommodate large deformation through reversible geometric transformations. In this study, we investigate coupled wrinkling and bending in a strain-mismatched tri-layer structure composed of a thin film sandwiched between two pre-strained elastomeric substrates. Upon release of the pre-strain, mismatch-induced compressive stress leads to simultaneous global bending of the structure and localized wrinkling of the film. The bending curvature is governed by the thickness ratio of the substrates, while the onset of wrinkling is determined by the normalized film stiffness. A theoretical model based on energy minimization describes the bending curvature, and a linear buckling analysis provides the critical wrinkling condition. Experimental observations and finite element simulations show good agreement with the theoretical predictions. The results provide a mechanical framework for understanding and designing coupled bending-wrinkling behavior in multilayer soft structures.

Key Words: Wrinkling, Buckling instability, Multilayer structures, Bending curvature

1. INTRODUCTION

Wavy electrode structures have garnered significant attention in the field of stretchable electronics due to their ability to undergo reversible unfolding and folding. By effectively mitigating residual strain to ensure structural integrity under extreme deformation, these wavy geometries have been widely adopted across stretchable electronics [1,2], surface engineering [3,4], wearable sensors [5,6], and smart displays [7,8]. Such wavy structures are primarily designed as either vertical serpentine geometries or wrinkling-type architectures. The former relies on pre-designed curvilinear patterns produced by screen printing [9,10] or 3D printing [11]; in contrast, the latter is mechanically generated by buckling within thin film/substrate systems through a pre-stretch and release process [12,13].

Recently, conformal stretchable electronics designed to wrap non-planar surfaces, including spherical, cylindrical, and other curved geometries, have attracted significant attention [14–

16]. For these applications, electrode layers must satisfy stringent mechanical requirements, including high stretchability, enhanced bendability, and cyclic repeatability, to ensure long-term stability for elastic deformations. To address the requirements, conventional strategies typically rely on precise neutral-axis engineering, which is achieved through multi-layered composite structures incorporating encapsulation or adhesive interlayers [17,18]. However, these multilayer configurations increase structural complexity, thereby complicating the packaging process and inevitably increasing the overall device thickness, which makes it challenging to simultaneously achieve structural optimization and high performance under repeated bending and stretchability.

Despite the growing relevance of such multilayer systems, the coupled mechanics of wrinkling and global bending in trilayer or multilayer structures remains largely unexplored. While wrinkling in simple bilayer systems has been extensively studied—from critical buckling conditions [19,20] to post-buckling behavior and substrate pre-stretch effects [21,22]—

Received 10 April 2026, received in revised form 21 May 2026, accepted 2 June 2026

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these models predominantly assume semi-infinite substrate geometries where global bending is inherently absent. As substrates have become thinner in pursuit of lightweight designs, bending-induced curvature has grown in significance, driving the adoption of trilayer configurations with additional encapsulation or upper substrate layers [23,24]. Although wrinkling in such trilayer structures has been investigated through parametric theoretical and numerical analyses [25–29], the majority assume flat or semi-infinite conditions, leaving the effect of global bending under finite substrate thickness largely unaddressed. While a few bilayer studies have considered finite-thickness effects and the interplay between wrinkling and global bending [30–32], this coupled behavior in trilayer or multilayer structures remains insufficiently explored. The present study addresses this gap by examining the coupled evolution of global bending and local wrinkling in strain-mismatched tri-layer structures with finite substrate thickness.

In this study, we consider a strain-mismatched tri-layer structure in which a thin film is sandwiched between two pre-stretched elastomeric substrates. Upon release of the pre-strain, the mismatch between the layers gives rise to coupled global bending and localized wrinkling. We focus on how the substrate thickness ratio and the normalized film stiffness govern the resulting deformation modes. To this end, a theoretical framework based on energy minimization is formulated to describe the global bending, and a linear buckling analysis is employed to characterize the onset of wrinkling. In addition, finite element simulations and experiments are conducted to examine the deformation behavior under varying geometric and material parameters.

2. MATERIALS AND METHODS

2.1 Wrinkling and global bending in a tri-layer composite

Fig. 1 schematically illustrates the fabrication process of the tri-layer composite exhibiting bending and wrinkling. In Fig. 1(a), the upper and lower substrates are pre-stretched by an applied pre-strain, ϵ_{pre} . Both substrates are fabricated from Ecoflex 00-30 (Smooth-On, Inc.), a two-part silicone elastomer consisting of Part A (base) and Part B (catalyst). The two parts were mixed in a 1:1 ratio by weight, poured into a mold of the desired geometry (dog-bone shape), and cured at room temperature for approximately 4 hours.

The film layer with an initial length of ($L_0 = 50$ mm) is then formed between the upper and lower substrates by coating it onto the pre-stretched lower substrate. Specifically, a prepolymer solution of vinylpolysiloxane (VPS-32, Zhermack) was prepared at a 1:1 base-to-catalyst ratio by weight. Prior to deposition, a masking tape was applied to the pre-stretched substrate to confine the coating area to the initial gauge length L_0 , ensuring that the film was formed only within the intended region. The prepolymer solution was then deposited onto the exposed area and spin-coated at 600 rpm for 60 s, yielding a

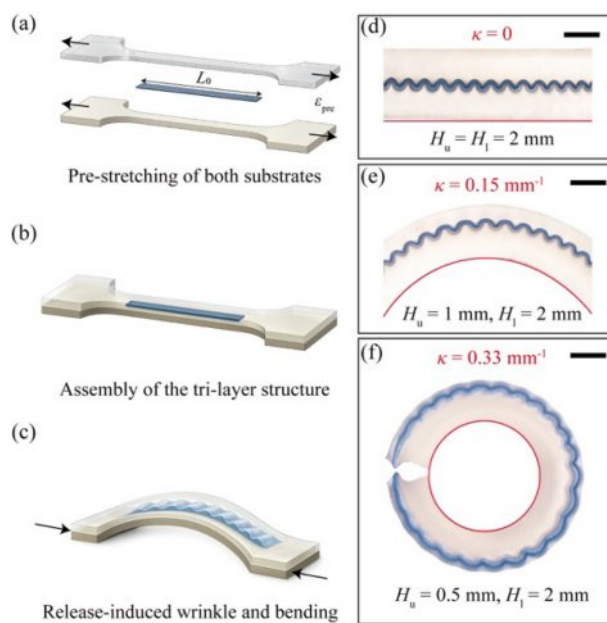


Fig. 1. Experimental process and global bending coupled with wrinkling. (a–c) Pre-stretching, assembly, and release processes are used to induce buckling for wrinkling and curvature in the tri-layer composite. (d–f) Optical images of the experimental results showing wrinkling behavior with varying bending curvature controlled by the upper-substrate thickness

uniform film thickness of approximately 180 μm . The masking tape was then carefully removed, and the film was subsequently allowed to partially cure for ~ 15 min at room temperature.

The elastic moduli of VPS-32 and Ecoflex-0030 were determined from the uniaxial tensile tests described in Section 2.2, yielding $E_f \approx 0.864$ MPa and $E_s \approx 0.148$ MPa, respectively. The Poisson's ratio was assumed to be $\nu = 0.49$ for all layers.

In Fig. 1(b), after the prepolymer solution had partially cured, the upper substrate was attached. At this partially cured stage, the film layer exhibited sufficient adhesion to achieve perfect bonding with both the lower and upper substrates. Since VPS-32 and Ecoflex-30 are both siloxane-based elastomers, favorable interfacial compatibility during curing contributed to strong bonding between the layers. No additional external pressure was applied during the bonding process in order to avoid unintended changes in the film thickness. The upper substrate was placed on the partially cured VPS-32 layer and bonded during the subsequent curing process. Moreover, no visible interfacial delamination was observed during the experiments, even under the largest pre-strain. This supports the perfect interfacial bonding throughout the deformation range.

In Fig. 1(c), after ~ 30 min, the VPS-32 film was fully cured. Subsequently, the pre-strain applied to both substrates was simultaneously released, generating compressive stress during

relaxation. This compressive stress induced wrinkling of the film layer, together with global bending of the entire structure.

In Figs. 1(d to f), optical images of the tri-layer composite exhibiting global bending coupled with wrinkling are presented. The thickness of the upper substrate (H_u) varied as 2, 1, and 0.5 mm, while the thickness of the lower substrate (H_l) was fixed at 2 mm. In all cases, the applied pre-strain was maintained at $\varepsilon_{\text{pre}} \approx 1.1$ (110%). In Fig. 1(d), under the symmetric condition where the upper and lower substrate thicknesses are identical, the bending curvature (κ) is zero because the neutral axis is located at the center of the structure and coincides with the film layer. In Figs. 1(e) and 1(f), under asymmetric conditions ($H_l > H_u$), κ gradually increased as the thickness of the upper substrate decreased. Furthermore, the film layer exhibited wrinkling with smaller amplitudes and longer wavelengths as the upper substrate became thinner.

2.2 Constitutive models

To analyze the wrinkling and bending behavior, constitutive models were employed for each layer. The film layer (VPS-32) was modeled using a Neo-Hookean constitutive law, whereas the substrate (Ecoflex 00-30) was described by an Ogden model. The Neo-Hookean model was selected for VPS-32 because the film was deposited onto the substrates while they were held in the pre-stretched state and its measured stress-

strain response was adequately captured by the Neo-Hookean model. In contrast, the Ogden model was adopted for Ecoflex-0030 to represent its highly nonlinear behavior under large pre-strains. Under uniaxial tension and the incompressibility assumption, the Neo-Hookean model is given by

$$\sigma_e = 2\bar{C}_1(\Lambda - \Lambda^{-2}), \quad (1)$$

where $\bar{C}_1$ is the half shear modulus as a material constant, σ_e is the engineering stress, and Λ is the stretch ratio ($1 + \varepsilon$). The Ogden model can be written as

$$T_{11} = \sum_{i=1}^3 \mu_i \left(\Lambda^{\alpha_i} - \Lambda^{-\left(\frac{\alpha_i}{2}\right)} \right), \quad (2)$$

where T_{11} is the Cauchy stress as $T_{11} = \sigma_e \cdot \Lambda$. For the tensile test, specimens were prepared in accordance with ASTM D412 Type C standard. Uniaxial tensile tests were performed using a universal testing machine (Instron 5943, Instron Corp., USA). The strain rate was set to 500 mm/min, which is commonly adopted for the mechanical characterization of soft materials.

Figs. 2(a) and 2(b) show the constitutive model fitting results for VPS-32 and Ecoflex-0030, respectively. According to Eq. (1), $\bar{C}_1$ of VPS-32 was 0.144 MPa, and the Ogden coefficients of Ecoflex-0030 are written in the caption of the figure. The Ogden model parameters ($a_{1,2,3}$ and $\mu_{1,2,3}$) listed in the caption of Fig. 2 were determined by least-squares fitting of the Ogden model (Eq. 2) to the uniaxial tensile test data obtained in this study.

Since the present study focuses on quasi-static equilibrium deformation, the materials were modeled as hyperelastic solids and viscoelastic effects were not considered.

3. THEORETICAL INVESTIGATIONS

3.1 Global bending

To elucidate the coupled mechanics of wrinkling and global bending in the proposed tri-layer structure, theoretical models were developed to describe the elastic deformation under substrate pre-strain release. In Fig. 3(a), the film layer, upper and lower substrates have elastic moduli, thicknesses, and Poisson's ratios of (E_f, H_f, ν_f), (E_u, H_u, ν_u), and (E_l, H_l, ν_l), respectively. The materials are assumed to be nearly incompressible.

Accordingly, the Poisson's ratios are taken as 0.49 to ensure numerical stability while approximating the incompressible limit. In Fig. 3(b), the upper and lower substrates were pre-stretched by the same applied pre-strain, ε_{pre} , and the film layer was sandwiched between them. In Fig. 3(c), the compressive stress generated by the release of the pre-stretched substrates induces buckling deformation, accompanied by wrinkling and global bending of the structure. Here, the wrinkling profile is characterized by the amplitude (A), wavelength (λ), and the bending curvature is κ .

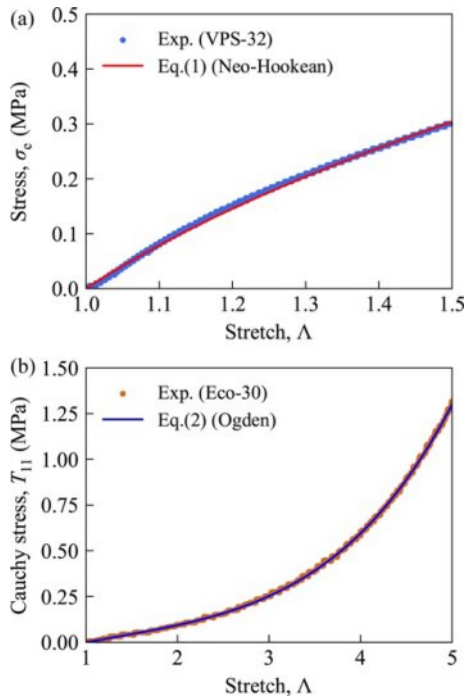


Fig. 2. Constitutive fitting results of the hyperelastic materials. (a) Neo-Hookean fitting model of the film layer as VPS-32. (b) Experimental Cauchy stress-stretch response of Ecoflex-0030 fitted with the Ogden model in Eq. (2), using the fitted parameters $a_1 = -0.2957$, $a_2 = 1.011$, $a_3 = 4.323$, $\mu_1 = -0.3346$ MPa, $\mu_2 = 0.08142$ MPa, and $\mu_3 = 0.0009939$ MPa

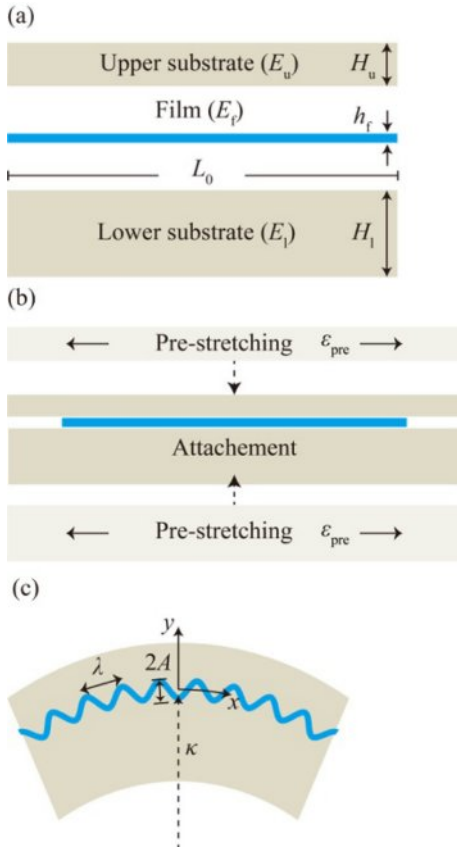


Fig. 3. Schematic diagram of the buckling-induced global bending and wrinkling. (a) Initial configuration of the tri-layer structure consisting of the upper substrate, film layer, and lower substrate. (b) Pre-stretching of the upper and lower substrates to the same applied strain, followed by assembly with the film layer. (c) Release-induced buckling deformation, resulting in simultaneous wrinkling, is characterized by amplitude and wavelength (A, λ) and global bending curvature (κ)

The global bending curvature is determined by minimizing the bending energy stored in the film and the substrates after release of the pre-strain. The total bending energy consists of contributions from the film ($U_{b, \text{film}}$) and from the upper and lower substrates ($U_{b, \text{subs}}$). The bending energy stored in the film is expressed as

$$U_{b, \text{film}} = \frac{1}{2} \bar{E}_f h_f \varepsilon_f^2 \quad (3)$$

and

$$U_{b, \text{subs}} = \frac{1}{2} \bar{E}_l \int_{-H_l}^0 \varepsilon_s^2 dy + \frac{1}{2} \bar{E}_u \int_0^{+H_u} \varepsilon_s^2 dy, \quad (4)$$

where ε_f is the membrane strain in the film, ε_s is the strain in each substrate ($\varepsilon_s = \varepsilon_{pre} + \varepsilon_f + \kappa y$), and $\bar{E}$ is the plane-strain modulus given by $\bar{E} = E / (1 - \nu^2)$ where ν is the Poisson's ratio. Here, the major dimensionless parameters are

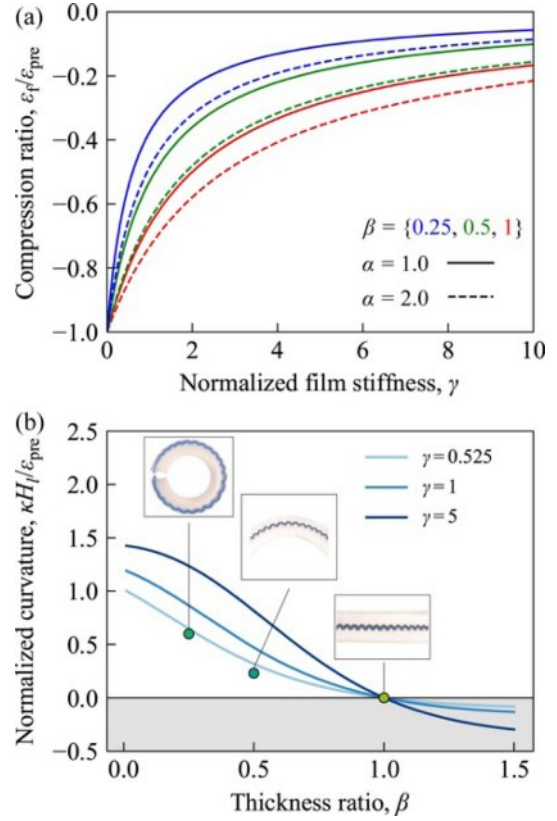


Fig. 4. Compression ratio and normalized curvature in the tri-layer composite. (a) Variation of the normalized membrane compression with γ for different combinations of α and β . (b) Normalized curvature as a function of β for $\gamma = 0.525$ (our exp.). The inset images show representative deformation modes at different β , and the shaded region indicates negative curvature ($\kappa < 0$)

$$\alpha = \frac{\bar{E}_u}{\bar{E}_l}, \quad \beta = \frac{H_u}{H_l}, \quad \gamma = \frac{\bar{E}_f h_f}{\bar{E}_l H_l} \quad (5)$$

where α, β , and γ denote the modulus ratio between the upper and lower substrates, the thickness ratio of the two substrates, and the normalized film stiffness relative to the lower substrate, respectively. Minimizing the total bending energy ($U_b = U_{b, \text{film}} + U_{b, \text{subs}}$) with respect to ε_f and κ ($\partial U_b / \partial \varepsilon_f = 0$, $\partial U_b / \partial \kappa = 0$) yields

$$\frac{\varepsilon_f}{\varepsilon_{pre}} = -\frac{D_0(\alpha, \beta)}{D(\alpha, \beta, \gamma)}, \quad (6)$$

and

$$\frac{\kappa H_l}{\varepsilon_{pre}} = -6 \frac{\gamma(\alpha \beta^2 - 1)}{D(\alpha, \beta, \gamma)}. \quad (7)$$

In Eqs. (6) and (7), the functions $D_0(\alpha, \beta)$ and $D(\alpha, \beta, \gamma)$ are

defined as

$$\begin{cases} D_0(\alpha, \beta) = 4(1 + \alpha\beta)(1 + \alpha\beta^3) - 3(\alpha\beta^2 - 1)^2 \\ D(\alpha, \beta, \gamma) = 4(1 + \alpha\beta + \gamma)(1 + \alpha\beta^3) - 3(\alpha\beta^2 - 1)^2 \end{cases} \quad (8)$$

Eqs. (6) and (7) indicate the compression ratio ($\varepsilon_f/\varepsilon_{\text{pre}}$) of the membrane strain to the applied pre-strain and the normalized curvature, respectively.

Fig. 4(a) shows how the membrane strain transferred from the applied ε_{pre} varies with α , β , and γ . As γ decreases, the compression ratio ($\varepsilon_f/\varepsilon_{\text{pre}}$) approaches -1, indicating efficient transfer of the applied pre-strain to the film. In contrast, as γ increases, $\varepsilon_f/\varepsilon_{\text{pre}}$ approaches 0, implying a smaller compressive strain in the film. Likewise, as β decreases, meaning that the upper substrate becomes thinner, the membrane strain in the film also decreases. If the membrane strain is too small, the criterion for local buckling is not satisfied, and the structure undergoes pure bending without wrinkle formation.

Fig. 4(b) compares the normalized curvature obtained from the theoretical model with the experimental results. The VPS-32 film layer was assumed to E_f of 864 kPa, while the elastic moduli of Ecoflex-0030 for the upper and lower substrates ($E_u = E_l = 148$ kPa) were obtained from the initial slope of the Ogden model. Given that $H_l \approx 2$ mm, and $h_f \approx 180$ μm , γ for our case is approximated to 0.525.

In Fig. 4(b), the experimental observations ($\gamma = 0.525$) agree well with the theoretical predictions as a function of β . As γ increases, the global bending curvature increases (in Fig. 4(b)), while the membrane strain transferred to the film decreases (in Fig. 4(a)). This indicates that less of the deformation energy induced by pre-stretching is stored as membrane energy, while a larger portion is accommodated by bending energy.

From Eq. (7), the zero-curvature condition ($\kappa = 0$) is obtained when it is satisfied with $\alpha\beta^2 = 1$, which leads to

$$\overline{E}_u H_u^2 = \overline{E}_l H_l^2. \quad (9)$$

Eq. (9) represents the material condition required to eliminate the global bending curvature of the tri-layer composite. This relation indicates that the second-order stiffness of the upper and lower substrate layers must be balanced.

3.2 Linear buckling model of wrinkling

Linear buckling theory is adopted because the analysis focuses on the critical onset of wrinkling, i.e., the bifurcation point at which the initially flat equilibrium configuration first becomes unstable. At this critical point, the wrinkling amplitude is infinitesimally small, and thus a linearized perturbation approach is analytically tractable for predicting the onset condition.

The wrinkling displacement of the film was approximated by a sinusoidal profile, $w = A \cos(kx)$, where x is the coordi-

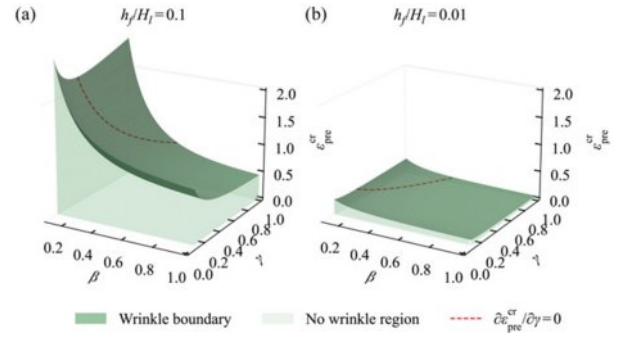


Fig. 5. Critical pre-strain for wrinkles as a function of β and γ for $\alpha = 1$. (a) $h_f/H_l = 0.1$ and (b) $h_f/H_l = 0.01$. The dark green surface denotes the wrinkle boundary, while the light green region indicates the no-wrinkle regime

nate along the curvature line and k is the wavenumber defined as $k = 2\pi/(\lambda(1 + \varepsilon_{\text{pre}}))$. According to von Karman plate theory [33], the strain energy stored in the film layer consists of both membrane energy and bending energy, and is expressed as

$$U_{\text{film}} = \frac{\overline{E}_f h_f}{2} \left(\frac{k^2 A^2}{4} - \varepsilon_{\text{pre}} \right)^2 + \frac{\overline{E}_f h_f^3 k^4 A^2}{48}. \quad (10)$$

The substrate strain energy is obtained from the normal stress acting at the film/substrate interfaces, namely, the interface between the film and the upper substrate and that between the film and the lower substrate. For thin substrates, the corresponding elastic energy contributions [34] are written as

$$\begin{cases} U_{\text{upper}} = -\frac{1}{4} \left[\frac{(1 - \nu_u)^2}{(1 - 2\nu_u)} \right] \overline{E}_u A^2 (H_u)^{-1} \\ U_{\text{lower}} = +\frac{1}{4} \left[\frac{(1 - \nu_l)^2}{(1 - 2\nu_l)} \right] \overline{E}_l A^2 (H_l)^{-1} \end{cases} \quad (11)$$

The equilibrium state of the wrinkling deformation is then determined by minimizing the total energy ($U_{\text{tot}} = U_{\text{film}} + U_{\text{upper}} + U_{\text{lower}}$) with respect to A and k . The normalized wrinkle wavelength and amplitude can be expressed as

$$\begin{cases} \frac{\lambda_c}{h_f} = \frac{2\pi}{(1 + \varepsilon_{\text{pre}})} \left[\frac{12h_f(1 - \nu_u)^2 \overline{E}_u}{H_u(1 - 2\nu_u)\overline{E}_f} + \frac{12h_f(1 - \nu_l)^2 \overline{E}_l}{H_l(1 - 2\nu_l)\overline{E}_f} \right]^{\frac{1}{4}} \\ \frac{A_c}{h_f} = \left[\frac{2}{3} \left(\frac{\varepsilon_{\text{pre}}}{\varepsilon_c} - 1 \right) \right]^{\frac{1}{2}} \end{cases}, \quad (12)$$

where the critical buckling strain ε_c is given by

$$\varepsilon_c = - \left[\frac{(1 - \nu_u)^2 \overline{E}_u h_f}{3(1 - 2\nu_u)\overline{E}_f H_u} + \frac{(1 - \nu_l)^2 \overline{E}_l h_f}{3(1 - 2\nu_l)\overline{E}_f H_l} \right]^{\frac{1}{2}}. \quad (13)$$

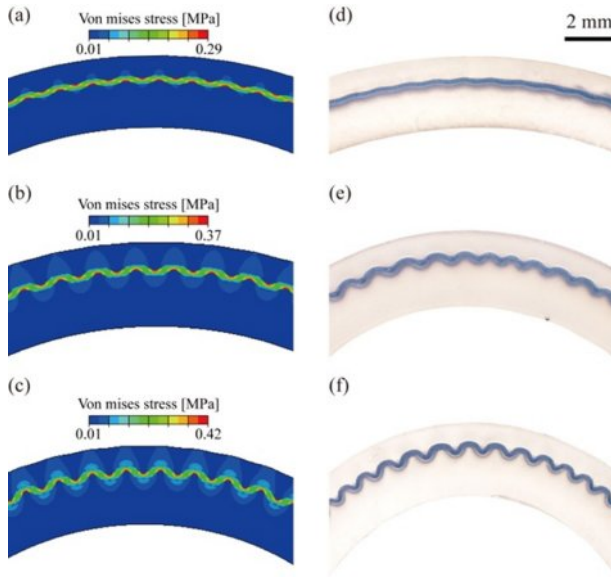


Fig. 6. FEM and experimental results of wrinkle morphology in the strain-mismatched tri-layer composite. (a) $\varepsilon_{\text{pre}} = 0.6$, (b) $\varepsilon_{\text{pre}} = 0.8$ and (c) $\varepsilon_{\text{pre}} = 1.1$ for the FEM simulations. (d) $\varepsilon_{\text{pre}} = 0.6$, (e) $\varepsilon_{\text{pre}} = 0.8$ and (f) $\varepsilon_{\text{pre}} = 1.1$ for the corresponding experimental observations

Table 1. Comparison of A and λ between FEM and experiments under different pre-strains

ε_{pre}		FEM	Exp.		FEM	Exp.
0.6	A (μm)	77	41	λ (μm)	1180	1172
0.8		122	132		1116	1065
1.1		178	171		993	965

In Eq. (12), the critical normalized wavelength and amplitude are expressed for a thin-substrate system with asymmetric substrate thicknesses. Eq. (13) gives the critical buckling strain to obtain the local wrinkles in the film-layer, and it is simplified ($\nu_u = \nu_l = \nu_s$) as

$$\varepsilon_c = - \left[\left(\frac{(1-\nu_s)^2}{3(1-2\nu_s)} \right) \left(\frac{\alpha}{\beta} + 1 \right) \frac{1}{\gamma} \right]^{\frac{1}{2}} \left(\frac{h_f}{H_1} \right). \quad (14)$$

Simultaneous bending and wrinkling can occur only when the bending-induced compressive strain in Eq. (6) exceeds the critical buckling strain in Eq. (14). This condition is expressed as

$$\varepsilon_{\text{pre}}^{\text{cr}} = - \frac{D(\alpha, \beta, \gamma)}{D_0(\alpha, \beta)} \left[\left(\frac{(1-\nu_s)^2}{3(1-2\nu_s)} \right) \left(\frac{\alpha}{\beta} + 1 \right) \frac{1}{\gamma} \right]^{\frac{1}{2}} \left(\frac{h_f}{H_1} \right). \quad (15)$$

Fig. 5 shows Eq. (15) with respect to β and γ for $\alpha = 1$, considering two representative thickness ratios, $h_f/H_1 = 0.1$ (thin-

substrate) and 0.01 (thick-substrate). For $h_f/H_1 = 0.01$, $\varepsilon_{\text{pre}}^{\text{cr}}$ is significantly low for the entire β - γ domain, other than for $h_f/H_1 = 0.1$. Furthermore, the lower β (thinner upper substrate thickness) monotonically needs a higher $\varepsilon_{\text{pre}}^{\text{cr}}$ value to obtain the wrinkling. In contrast, for γ , the local minimum of $\varepsilon_{\text{pre}}^{\text{cr}}$ is determined by derivatives Eq. (15) with respect to γ (red-dashed line).

4. NUMERICAL SIMULATIONS

Numerical simulations were performed to reproduce the experimental observations. Finite element analyses were performed under plane-strain conditions using the commercial software ABAQUS. The tri-layer composite was discretized using four-node hybrid plane-strain elements with reduced integration (CPE4RH). In the model, the initial thicknesses of the upper and lower substrates were set to 1 mm and 2 mm, respectively, and the film thickness was taken as 0.18 mm. The total length of the tri-layer composite was set to 50 mm. The constitutive model of the substrate was described by the Ogden model, whereas that of the film was described by the Neo-Hookean model (see Fig. 2). A mesh convergence study confirmed that an element size of 0.04 mm along the longitudinal and thickness direction was sufficient to obtain sufficiently converged results. The simulations were performed using a nonlinear Static, General step under fully free boundary conditions. To simulate the release of pre-stretch in the experiments, residual stress fields were assigned to the substrates as predefined fields corresponding to the tensile pre-strain applied during stretching. This procedure effectively reproduced the compressive stress state developed in the film after release of the pre-stretch. A small geometric imperfection was further introduced in the form of a sinusoidal perturbation with an amplitude equal to 1% of the film thickness and a wavelength determined from the theoretical prediction.

Fig. 6 shows the evolution of the wrinkling under global bending, together with the corresponding FEM and experimental results. FEM simulations were conducted at ε_{pre} of 0.6, 0.8, and 1.1, with all other parameters held constant. In Figs. 6(a) and (d), at the early stage of ε_{pre} , the onset of wrinkling is observed, characterized by a shallow amplitude and a long wavelength. As ε_{pre} increases, the wrinkling becomes more pronounced, exhibiting a larger amplitude A and a shorter wavelength λ .

Table 1 summarizes the quantitative comparison of A and λ between the FEM and the experimental measurements. The wavelength λ was measured as the average peak-to-peak distance over a minimum of five wrinkle periods, and the amplitude was defined as half the peak-to-valley vertical displacement. In the FEM results, λ and A were extracted from the out-of-plane displacement profile of the film layer using the same definitions.

At $\varepsilon_{\text{pre}} = 0.6$, the FEM-predicted amplitude (77 μm) over-

estimates the experimental value (41 μm). This discrepancy is attributed to the sinusoidal geometric imperfection (1% of film thickness) prescribed in the FEM to trigger wrinkling, which artificially amplifies the wrinkling amplitude near the critical buckling onset. At higher pre-strains ($\epsilon_{\text{pre}} = 0.8$ and 1.1), where wrinkling is well-developed, the relative influence of the initial imperfection becomes less significant, and the FEM results show good agreement with the experiments.

Here, the decrease in λ with increasing ϵ_{pre} can be attributed to the combined influence of two competing effects: the strain-driven compression, which directly promotes wrinkling and reduces the wavelength, and the curvature-induced geometric confinement associated with global bending. Under the present experimental condition ($\beta = 0.5$) the strain-driven effect appears to dominate, resulting in a net decrease in wavelength. However, as β decreases further and the bending curvature increases, the influence of geometric confinement may become more significant.

5. CONCLUSIONS

In this study, we investigated coupled bending and wrinkling in a strain-mismatched tri-layer structure composed of pre-strained elastomeric substrates and a thin intermediate film. A theoretical framework combining energy minimization for global bending and linear buckling analysis for wrinkling was developed, and the predictions were validated through experiments and FEM simulations. The results show that the global bending curvature is governed by the substrate thickness ratio and the applied pre-strain, whereas the onset and wavelength of wrinkling are determined by the normalized film stiffness of the intermediate film. In particular, the strain mismatch is not entirely transferred to the film but is partially relaxed through global bending, leading to a coupled response in which bending and wrinkling compete to accommodate the imposed mismatch.

This coupling provides a useful mechanical perspective for designing multilayer soft structures, where the distribution of strain between global deformation and local instability can be tuned through geometric and material parameters. Such control may be utilized in applications requiring programmed surface morphologies or controlled curvature, for example in soft interfaces, adaptive surfaces, and mechanically tunable layered systems.

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