1 Introduction

A self-folding structure is a reconfigurable structure that can change its configuration under certain stimulating conditions [1]. Such structures can be beneficial for many applications, e.g., biomedical devices for drug delivery, robotic sensors, solar cells, micro-electromechanical systems, etc. (refer to Refs. [2–7]). Related to self-folding structures, a paper crafting art called origami studies the folding of a two-dimensional (2D) paper into a three-dimensional (3D) structure along predefined hinge patterns [8–10]. Extensive origami research has been conducted including the origami design and tessellation methods [11–13], folding kinematics [14], and applications such as solar arrays and radio apertures [15,16]. A key technique in an origami design is the folding mechanism. The folding of predefined hinge patterns can be realized manually [17] or by the use of robotic devices [18]. Origami structures can also change their shapes by using self-folding mechanisms that are stimulated by conditions such as thermal or humidity changes [19–21]. Consequently, a desired 3D structure can be directly constructed by self-folding a carefully designed 2D origami sheet.

Figure 1 shows three self-folding mechanisms that are widely used: (i) Figure 1(a) shows an approach based on shape memory materials that can change their shapes under certain stimulating conditions [1]. Such capability can be beneficial for a wide variety of applications including biomedical and electronic products. In this paper, a novel fabrication approach based on a three-dimensional (3D) printing process is presented for fabricating self-folding structures that can be actuated in a heating environment. The thermo-actuating structures that are designed and fabricated by our method are two-dimensional (2D) origami sheets, which have multiple printed layers. The middle layer of an origami sheet is a prestrained polystyrene film with large shrinkage ratios when heated. Both its top and bottom surfaces are covered with cured resin that is printed in designed shapes. A foldable hinge is achieved by constraining the shrinkage of the film on one side while allowing the shrinkage of the film on another side when the origami sheet is exposed to a heating environment. Various experimental tests are performed to verify the self-folding performance of the designed and fabricated origami sheets. Techniques on improving folding angle control are also discussed with possible applications.

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sheets. Such 3D fabrication capability can significantly expand the possible shapes that can be achieved by self-folding structures.

The rest of the paper is organized as follows. Section 2 discusses the self-folding mechanism based on a bilayer structure. Section 3 presents the origami structure design and fabrication approaches. Section 4 presents the models between hinge design parameters and related self-folding angles. Section 5 presents the fabrication process of 2D origami sheets based on the MIP-SL process. Section 6 presents calibration experiments and related techniques for controlling the folding angle of each hinge. Based on them, test cases with more complex self-folding structures are presented in Sec. 7. Finally, conclusions are drawn in Sec. 8 with future work.

## 2 Folding Mechanism Analysis

The folding of a bilayer structure is realized either through the inhomogeneous expansion or contraction of materials with different volumetric shrinkage ratios in different directions. For a direction that needs to be folded, a different shrinking behavior is required along that direction [21,22]. For example, for a structure that is required to be folded in the $Z$ axis, the desired folding will be generated only if the shrinking ratio increases along the $Z$ axis (refer to Fig. 2(b)). If the material has the same shrinkage ratio along the $Z$ axis, the structure will uniformly shrink with no folding effect (refer to Fig. 2(a)).

In our method, a bilayer structure is used to realize the desired self-folding of hinges in a 2D origami sheet. In the structure, a prestrained polystyrene film (e.g., the Shrinky-Dinks film used in Ref. [27]) is used as the active material to provide the energy that is required for folding. Another material, photocurable resin, is printed on the polystyrene film to work as the passive material to control the folding behavior. Note that, in order to realize the bending of the structure, the passive material needs to constrain the active material such that the shrinkage ratio of the polystyrene film will change along the $Z$ axis. Such bottom constraining effect is illustrated in Fig. 2(c), in which the top portion of the polystyrene film is exposed to a preheated oven with a temperature that is higher than the glass transition temperature of the film. Consequently, the top portion will shrink; however, the printed passive material can stop the bottom portion of the film from shrinking, which leads to the bending of the structure. To ensure the bottom constraining effect, photocurable resin needs to be well cured such that it can strongly attach to the film; otherwise, the cured resin may detach from the film when the film begins to shrink under a raised temperature.

In addition to constraining volumetric shrinkage, the printed passive material also blocks heat transfer from the heating environment to the bottom portion of the polystyrene film. Hence, the top and bottom portions of the film may have varying temperatures due to different heat transfer rates. We believe both effects contribute to the self-folding of bilayer structures while the bottom constraining effect plays a major role. This is because the bilayer structure will still fold even in situations where the samples are put in an oven with gradually increased temperatures (i.e., there is little temperature difference throughout the whole structure during the heating process).

## 3 Self-folding Origami Structure Design and Fabrication

Based on a bilayer structure as discussed in Sec. 2, two types of hinge designs (refer to Fig. 3) are explored for a self-folding origami structure. Figure 3(a) shows a partial film design, in which only the hinge portions incorporate the bilayer structure while all the other portions are made by 3D printing processes. Figure 3(b) shows a sandwiched film design by incorporating the bilayer structure in the whole origami structure. In the sandwiched design, the polystyrene film will be used as the middle layer not only in the hinge portions but also in all other areas. To achieve desired folding, the top and bottom resin layers in such a design are cured.
in designed shapes and thicknesses on the polystyrene film in order to define the related hinges in the self-folding structure.

Although the two origami structure designs are based on the same self-folding mechanism, they will have quite different fabrication complexity. In the partial film design model, every hinge has a piece of polystyrene film to be embedded in. During the fabrication process, the film portion related to a hinge needs to be cut and inserted at each hinge position precisely. In comparison, in the sandwiched design, a much larger film related to the whole origami structure is used. Each hinge is defined by projection mask images that will cure liquid resin into desired shapes. Hence the hinge portion can have a high resolution (<0.1 mm) [28,29].

The building process can be automated and fast regardless of the number of hinges [30]. Considering the fabrication requirements, the sandwiched structure design is better suited for the self-folding origami structures and further studied.

Figure 4 shows two fabrication approaches for the sandwiched structure design. The first one is a cure-before-cut approach (refer to Fig. 4(a)). The approach is based on using a large piece of polystyrene film that is placed on the building platform. After curing liquid resin on both sides of the film, the extra portion of the film is cut either manually or using a computer numerical control (CNC) cutter. However, edges of the cut film will shrink, which may lead to the separation of the top and bottom film layers along the edges (refer to a test example in Fig. 4(b)).

Another fabrication approach is based on a cut-before-cure approach (refer to Fig. 4(c)). The approach requires drawing the outline of an origami structure (with certain offset distance). Accordingly, the polystyrene film is cut into the drawn shape either manually or using a CNC cutter. The cut film is then placed in the building platform for the liquid resin to be cured on the film. An appropriate offsetting distance can be used in drawing the outline such that the edges of the film will be covered by the cured resin. Figure 4(d) shows a test example based on the cut-before-cure approach. The red line on the test part is the drawn outline for cutting the polystyrene film. In this paper, the cut-before-cure approach is used in all the experimental study (refer to Secs. 6 and 7).

Two portions of a sandwiched structure, hinges and bodies, need to be considered when designing a self-folding structure. The design of the hinge portions requires analytical models and a design method such that each hinge can be self-folded to a desired angle when the origami sheet is exposed to a heating environment. The hinge design is discussed in more details in Sec. 4.

4 Hinge Design and Self-Folding Angle Analysis

4.1 Shrinkage of Polystyrene Film. The prestrained polystyrene film shrinks in the XY plane and expands in the Z axis when heated. The shrinkage behavior varies with the set temperatures. We investigate two types of polystyrene films, one is transparent and another is white (as shown in Figs. 5(a) and 5(b), respectively).
respectively). The shrinkage ratios of the two films are found to be similar.

Figure 5(c) shows the shrinkage of the transparent film in the \( XY \) plane under different temperatures. The original dimension is 100 \( \times \) 100 mm. Multiple identical samples are made for the tests (one sample is shown in Fig. 5(a)). Each sampling point in the plot is generated by positioning the samples in an oven with a pre-set temperature (e.g., 98 \(^{\circ}\)C or 130 \(^{\circ}\)C) for a certain time period. The samples are then taken out and the shrunk lengths in the \( X \) axis are measured.

Based on the length measurement results, the film starts to shrink at \( \approx 98^{\circ} \)C. The film shrinkage in the \( XY \) plane then starts to grow rapidly and becomes stable around 120 \(^{\circ}\)C. Note that the polystyrene film will become soft around 130 \(^{\circ}\)C, which sets the maximum temperature that the film can be used in a heated environment. The maximum shrink length is about 43% of the original length. It takes 5–10 s for the film to be totally transformed. The film's shrinkage ratio in the \( XY \) plane is fixed when the samples are heated under a temperature between 98 \(^{\circ}\)C and 120 \(^{\circ}\)C for a certain time. Assume \( \lambda \) denotes the shrinkage ratio in the \( XY \) plane, which is measured as the shrunk length over the original length. Denote \( \mu \) as the transferred mass ratio of the film, which is the mass of the material that deforms over the total mass of the material. To better control the bending behavior of a designed origami structure, the heating time \( t \) is set to be long enough in our study. That is, it is assumed the film is totally transformed by exposing it for a long enough time.

4.2 Design Parameters of the Origami Structure. Figure 6 shows a detailed design of a hinge used in the sandwiched structure design. The design parameters of a self-folding origami sheet include:

1. The dimensions of the body portion include length \( S_1 \) and \( S_2 \), width \( a \), thickness \( c \), top layer thickness \( d_1 \), and bottom layer thickness \( d_2 \);
2. The dimensions of the hinge portion include length \( L \), width \( b \), thickness of the film \( h \), and thickness of the constraint resin layer \( d \);
3. The mass of the two neighboring body portions is denoted as \( M_1 \) and \( M_2 \); in addition, the mass of the polystyrene film in the hinge portion is denoted as \( m_1 \), and the mass of the constraint resin in the hinge portion is denoted as \( m_2 \).

4.3 Hinge Folding Analysis. To determine an appropriate value of each design parameter, the folding process is analyzed for establishing related deformation models. Note that the thermal analysis is not performed since time parameter \( t \) is set to be sufficiently long in the experiments. As discussed in Sec. 4.1, when the origami structure is put in a heated environment with a raised temperature (e.g., 120 \(^{\circ}\)C), the polystyrene film will go through the shrinking process and release the transformation energy that will deform the coated constraint resin layer on the film. The energy will also overcome the gravitational potential energy of neighboring body portions if they are raised up in the \( Z \) axis.

In our analysis, we assume the bonding between the film and the constraint resin layer is sufficiently strong such that the interface will have the same length during the folding process. For the purpose, liquid resin should be sufficiently cured to ensure strong bonding between cured resin and the film.

Due to the small size of the hinge (\( \approx 1 \) mm), the hinge portion will be bent into an arc shape (refer to Fig. 7). Accordingly, the geometric relationship of the deformed hinge is given as

\[
z\bar{R} = L, \quad z(R + d) = L_1
\]
The maximum strain of the constraint layer is

\[ \epsilon_{\text{max}} = \frac{L_1 - L}{L} = \frac{2d}{L} \]  

Thus, the maximum stress in the constraint resin layer is

\[ \sigma_{\text{max}} = E^T \epsilon_{\text{max}} = \frac{E^T 2d}{L} \]  

where \( E^T \) is the flexural modulus of the cured resin under temperature \( T \).

Hence, one of the design criteria to make sure the deformed constraint layer will not break is

\[ \sigma_{\text{max}} = \frac{E^T 2d}{L} < \sigma_{\text{resin}} \]  

As mentioned before, the energy conservation function during the bending movement is

\[ \Delta Q = \Delta E_d + \Delta E_g \]  

where \( \Delta Q \) is the energy released from the polystyrene film; \( \Delta E_d \) is the energy used in generating the deformation of the constraint resin layer; and \( \Delta E_g \) is the energy used to overcome the gravitational potential energy of the load (e.g., raising up \( M_2 \) in Fig. 7):

1. For a fixed temperature \( T \), the mass shrinking ratio \( \mu \) is fixed. Denote \( q \) as the unit releasing energy of the polystyrene film (\( q \) is in a range of 2–3 J/g). Denote \( \rho \) as the density of the film, then

\[ \Delta Q = \mu m_1 q = \mu p(Lhb)q \]  

2. Since \( S_2 \gg L \), a simple model for the increased gravitational energy for \( m_1 \) and \( M_2 \) is

\[ \Delta E_g = \frac{M_2 g S_2 \sin \alpha}{2} \]  

The magnitude of \( \Delta E_g \), when compared to the other two terms in the equation, is usually multiple orders of magnitudes smaller (refer to an example in Sec. 4.3.1).

3. Depending on the bending angles, there are two types of models for calculating \( \Delta E_g \). The first one is to treat the deformation as a large elastic deflection of a "wide" beam, which is appropriate for modeling small elastic deformation of the constraint resin layer. The second one is to treat the deformation of the constraint resin layer as the plastic deformation. For different constraint materials and folding angles, either elastic or plastic deformation can be used. Both types of models are considered in our study. They are discussed in details as follows.

4.3.1 Modeling Using the Assumption of Elastic Deformation. Since the magnitude \( b \gg L \) in a hinge, the elastic deformation is modeled as large deflections of a wide beam. That is

\[ \Delta E_d = \frac{1}{2} M x, \quad M = \frac{E^T I}{R(1 - \nu^2)} \]  

where \( M \) is the moment that is required to bend the structure; \( E^T \) is the flexural modulus of the resin material under temperature \( T \); \( \nu \) is the Poisson ratio of the resin material; and \( I = bd^3/12 \). Hence

\[ \Delta E_d = \frac{E^T}{2R(1 - \nu^2))} \frac{bd^3}{12} x = \frac{E^T bd^3}{24(1 - \nu^2)} \frac{x}{R} = \frac{E^T bd^3 x^2}{24(1 - \nu^2)L} \]  

The overall function \( \Delta Q = \Delta E_d + \Delta E_g \) would be

\[ \mu p(Lhb)q = \frac{E^T bd^3 x^2}{24(1 - \nu^2)L} + \frac{M_2 S_2 \sin \alpha}{2} \]  

\( \Delta E_g \) in the last term could be neglected since its magnitude is relatively small compared to the other two terms in the equation. For example, for a test case with \( L = 2 \) mm, \( h = 0.29 \) mm, \( d = 0.33 \) mm, \( b = 10 \) mm, \( p = 10^{-3} \) g/mm, \( q \approx 2.5 \) J/g, \( \mu \approx 0.4 \), \( M_2 = 0.142g \), and \( S_2 = 9 \) mm. Suppose a bending angle \( \alpha \approx 45 \) deg. The term \( \mu p(Lhb)q = 5.8 \times 10^{-3} \) J, while the term \( M_2 S_2 \sin \alpha/2 = 4.5 \times 10^{-6} \) J. Hence, the energy equation can be simplified as follows:

\[ \mu p(Lhb)q = \frac{E^T bd^3 x^2}{24(1 - \nu^2)L} \]  

Accordingly, the relationship between the bending angle and the design parameters of a hinge could be written as

\[ \alpha = K \sqrt{\frac{L^2 h}{d^3}} \]  

where

\[ K = \sqrt{\frac{24(1 - \nu^2) \mu \rho q}{E^T}} \]  

Note that \( K \) is a coefficient related to the temperature and material properties. Physical experiments can be performed to calibrate its value (refer to Sec. 6.1).

4.3.2 Modeling Using the Assumption of Plastic Deformation. Consider the resin material as a perfectly plastic material. Denote \( u \) as the unit energy, which can be calculated as

\[ u = \int \sigma d e = Y e \]  

where \( Y \) is the yield strength of the resin material.

As shown in Fig. 7, the areas in the constraint layer have a radius of \( R + r', r' \in (0, d) \). The strain \( \epsilon = x r'/L \), and \( u = Y e = Y x/L r' \). The unit energy varies along \( r' \). Hence, an integral along \( r' \) could lead to the energy of the deformed hinge. For a small \( \Delta r' \), the energy would be

\[ \Delta U = u \times \Delta V = \frac{Y x}{L} \Delta r' \times x \times (L + x r') = Y x b r' \Delta r' + Y x^2 b L/r^2 \Delta x' \]  

Thus, the total energy required for the plastic deformation is

\[ \Delta E_d = \int_0^d \Delta U = \int_0^d Y x b r' \Delta r' + Y x^2 b L/r^2 \Delta x' = Y x b d^3/2 + Y x^2 b d^3/3L \]  

By neglecting \( \Delta E_g \), the energy equation can be simplified as

\[ \mu p(Lhb)q = \frac{Y x b d^3}{2} + \frac{Y x^2 b d^3}{3L} \]  

The relationship between the bending angle and the design parameters of a hinge could be established as

\[ \alpha = \frac{3L}{4d} \left( \sqrt{1 + \frac{16 \mu \rho q}{3Yd}} - 1 \right), \quad \text{or} \quad \alpha = \frac{3L}{4d} \left( \sqrt{1 + \frac{K' h}{d}} - 1 \right) \]  

where \( K' = 16 \mu \rho q/3Y \).
Since $K' < 1$, Eq. (18) could be approximated using the Taylor equation. That is

$$\sqrt{1 + \frac{K'h}{d}} = 1 + \frac{K'h}{2d} - \frac{1}{8} \left( \frac{K'h}{d} \right)^2 + \frac{1}{16} \left( \frac{K'h}{d} \right)^3 + O\left( \left( \frac{K'h}{d} \right)^4 \right)$$

(19)

For the simplicity, only the first order term in the Taylor equation is considered. Hence

$$x = \frac{3L}{4d} \left( \sqrt{1 + \frac{K'h}{d}} - 1 \right) \approx \frac{3L}{4d} \times \frac{K'h}{2d} = \frac{3K'hL}{8d^2} = K'' \times \frac{hL}{d^2}$$

(20)

where $K'' = 3K'/8$, which could be obtained through calibration experiments (refer to Sec. 6.1).

In Sec. 5, the fabrication process of an origami sheet will be presented. Based on it, the calibration experiments for identifying $K$ and $K'$ are performed, which will be discussed in Sec. 6.

5 Fabrication Process of an Origami Sheet

The cut-before-cure approach, as shown in Fig. 4(c), is used to fabricate a designed self-folding origami sheet. A 3D printing process based on a bottom-up MIP-SL process [30,31] is adopted in curing desired constraint layer on a polystyrene film. In the MIP-SL process, a digital micromirror device (DMD) from Texas Instruments Inc. is used to project designed mask images on the liquid resin. When exposed to the projection light defined by the mask images, liquid resin will be selectively solidified accordingly.

Various modifications have been made in order to embed the polystyrene film in a built 3D structure. Figure 8 shows the experimental setup, which has a modified curing chamber from our previous MIP-SL systems. The curing chamber is designed for coating the polystyrene film with desired photocurable resin layers. The physical structure of the chamber is shown in Fig. 9. The resin curing chamber is made up of two components, one is a transparent coated tank and the other is a cover. The tank is used to hold the resin material. A layer of polydimethylsiloxane (PDMS) film is coated at the bottom of the tank such that the cured layer can be detached from the tank. The cover works as the platform on which the film is attached. Markers for positioning the tank and cover are also added such that the film can be aligned with the projection images during the building process.

The fabrication steps for an origami structure with unidirectional folding (i.e., folding in a single direction) or bidirectional folding (i.e., folding in both directions) are different. Figures 10(a) and 10(b) illustrate the origami sheet designs for the unidirectional and bidirectional folding, respectively. For the origami sheet with unidirectional folding, only three layers are needed...
during the fabrication. Note that the thickness of a constraint resin layer may be different from the thickness of a body layer. In comparison, at least four layers are needed for an origami sheet design with bidirectional folding. In addition, extra layers can be added on the body layers in each side for additional features such as characters or geometric shapes (refer to some test cases in Fig. 19). Figures 10(c) and 10(d) illustrate the origami sheets with one extra layer in both sides for unidirectional and bidirectional folding, respectively.

A detail building process of a bidirectional folding design (refer to Fig. 10(d)) is shown in Fig. 11. A total of six layers are required in the designed origami sheet. During its fabrication, the polystyrene film is first cut into a desired shape based on the outline of the self-folding structure. The cut polystyrene film is positioned with the spacers and glued on the cover. The tank is then filled with liquid resin. The cover is positioned on the tank with a controlled gap distance defined by the spacers. As shown in Fig. 9, a set of position markers can be used for positioning the cover and the tank together. Next, the DMD device projects a planned mask image for 3 s from the bottom of the tank to cure a layer on the film. The cover with the built structure is then detached from the tank. After the structure as well as the cover is cleaned, one spacer is removed and the built sheet is positioned back to the cover. The process repeated for fabricating the next layer. As shown in Fig. 11, Steps (c) and (f) require the flipping of the built origami sheet in order to build layers on another side of the film. After the building process, the fabricated origami sheet is cleaned and positioned in a postcuring chamber for about 20 s to strengthen the attachment between cured resin layers and the polystyrene film.

6 Self-Folding Experiments

6.1 Calibration Experiments. As discussed in Secs. 4.3.1 and 4.3.2, two types of energy models are established based on Table 1 Folding test data based on designs with different \((L, d)\) values

<table>
<thead>
<tr>
<th>(L) (mm)</th>
<th>1.5</th>
<th>3.27</th>
<th>3.42</th>
<th>3.45</th>
<th>5.49</th>
<th>5.03</th>
<th>1.8</th>
<th>3.4</th>
<th>5.08</th>
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<tbody>
<tr>
<td>(d) (mm)</td>
<td>0.11</td>
<td>0.15</td>
<td>0.12</td>
<td>0.18</td>
<td>0.14</td>
<td>0.13</td>
<td>0.24</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>(x) (deg)</td>
<td>100</td>
<td>130</td>
<td>135</td>
<td>97.5</td>
<td>155</td>
<td>165</td>
<td>52.5</td>
<td>82.5</td>
<td>105</td>
</tr>
<tr>
<td>(L) (mm)</td>
<td>5.42</td>
<td>5.6</td>
<td>5.3</td>
<td>3.14</td>
<td>1.64</td>
<td>1.32</td>
<td>3.38</td>
<td>1.45</td>
<td>1.22</td>
</tr>
<tr>
<td>(d) (mm)</td>
<td>0.24</td>
<td>0.26</td>
<td>0.29</td>
<td>0.31</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td>0.4</td>
<td>0.51</td>
</tr>
<tr>
<td>(x) (deg)</td>
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<td>105</td>
<td>97.5</td>
<td>60</td>
<td>42.5</td>
<td>37.5</td>
<td>50</td>
<td>37.5</td>
<td>30</td>
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</table>
the elastic and plastic deformations of the constraint resin layer. They are \( \alpha = K/\sqrt{L^2 h/d^3} \) and \( \alpha = K'' / L L/h \). In order to design hinges based on given folding angles, a set of experiments are performed to determine the values of \( K \) and \( K'' \) and to verify the models between bending angle \( \alpha \) and hinge design parameters (\( L, d \)). In our study, the thickness of the polystyrene film \( h \) is fixed \((h = 0.29 \text{ mm})\).

A set of experiments with different parameter values (\( L, d \)) are designed based on the origami sheet as shown in Fig. 6. The origami sheets are then fabricated based on the fabrication process as discussed in Sec. 5. Some of the built hinge samples are shown in Fig. 12(a). The samples are then put in a preheated oven with a controlled temperature \((120 \degree \text{ C})\) for a certain time period \((15 \text{ s})\). After the folding completes, the bending angle of each sample is measured. The measured data are shown in Table 1.

Since the polymer used in self-folding origami structures has certain elastic deformation range. When the folding angle is small, the deformation will fall in the elastic deformation range; while for a larger folding angle, the deformation tends to be out of the elastic deformation range and the cured layer will deform plastically. Accordingly, the elastic model will be used for small bending angles while the plastic model will be used for large bending angles.

A few trials have been made to identify a folding angle threshold that can divide the two types of models to fit the measurement data. An empirical value \( \alpha = 80 \degree \) is selected as the threshold between the elastic and plastic deformations. Accordingly, the regression of the experimental data has two segments. Since the terms of the models on the \( X \) axis are different, two separate graphs that present the final data fitting results are shown in Figs. 13(a) and 13(b), respectively.

In Fig. 13(a), the elastic model is used to fit the data with small folding angles. The fitting result is \( \alpha = 3.23 \sqrt{L^2 h/d^3} + 26.16 \degree \). To design a bending angle that is smaller than \( \alpha_0 \) \((26.16 \degree)\), further tests on such small folding angles need to be performed in our future study. Similarly, in Fig. 13(b), the plastic model is used to fit the data with large folding angles. The fitting result is \( \alpha = 0.98 \times hL/d^2 + 75.7 \degree \). Note for different constraint materials (e.g., another type of photocurable resins), the aforementioned calibration process needs to be repeated. Accordingly, an appropriate self-folding origami sheet can be designed based on the fitted models.

**6.2 Verification Experiments.** Figure 14 shows two test cases for verifying the fitted elastic model for small folding angles.
(\(\alpha < 80\,^\circ\)). Both cases are designed using the first folding angle model \(\alpha = 3.23 \sqrt{L^2 h/d^4} + 26.16\,^\circ\). Figure 14(a) shows a rolled tube case, which is a unidirectional folding example. The desired bending angle for the rolled tube case is 51.4\,^\circ. The selected hinge parameter values are \(L = 1.6\,\text{mm}, d = 0.23\,\text{mm}\). Figure 14(b) shows a “Z” shape case, which is a bidirectional folding example. The desired bending angle for the “Z” shape case is \(\pm 64\,^\circ\). Table 2 shows the parameter values of both cases that are based on the measurement of the fabricated samples. As shown in the table, some variations exist in the designed \(L\) and \(d\) due to the fabrication errors. Accordingly, the row three in the table is the computed \(\alpha\) values using the fitted model based on the measured \((L, d)\) values. The row four in the table is the measured \(\alpha\) values after the folding experiments. The error of the two \(\alpha\) values is \(-8\%\) in average.

Figure 15 shows a test case for verifying the fitted plastic model for large folding angles (\(\alpha \geq 80\,^\circ\)). A lotus design with some extra features (“USC” characters) is used in the test. A folded lotus is also shown in Fig. 15. Note that the fabrication inaccuracy brings some deviations to the designed parameter values \((L, d)\). The measured parameter values based on the fabricated samples are shown in Table 3. The computed \(\alpha\) values based on the second folding angle model \((\alpha = 0.98 \times hL/d^2 + 75.7\,^\circ)\) are shown in the third row of the table. The measured \(\alpha\) values after the folding experiments are also shown in the table. The error of the two \(\alpha\) values is \(-4.2\%\) in average.

6.3 Discussion on Folding Angle Control. A critical issue in the origami structure design and fabrication is how to accurately control the self-folding angles. An improved folding angle control method needs to consider the three main processes: the hinge design, the hinge fabrication, and the heating process. Efforts should be put into all the three processes in order to achieve well controlled self-folding performance:

(1) In the hinge design process, an important consideration is how to establish better folding models and how to select appropriate values for the design parameters of an origami sheet. In addition, novel design features may be added in the hinge design for better folding angle control. Figure 16 shows an angle lock design that can be easily added using our 3D-printing-based fabrication process. The designed angle locks can constrain the max bending angle of the related hinge. Consequently, the design of a hinge will be less sensitive to its folding error. For example, suppose a desired bending angle \(\alpha'\) is given for a hinge. The hinge parameters \((L, d)\) could be set for some target angle \(\alpha''\) that is larger than \(\alpha'\). During the folding process, the hinge will autofold to \(\alpha'\) and stop there due to the added angle lock design (refer to Fig. 16). Hence, the folding behavior of the hinge will be less sensitive to the errors in the fabrication and heating processes. For a given angle \(\alpha'\), the thickness of the angle lock layer \(d_1\) could be set based on the geometric relation \((d_1 + d_1 + h) \times \alpha = L\). A test case with the angle lock design is shown in Fig. 19(b).

(2) In the hinge fabrication process, an important consideration is how to fabricate hinges with the designed lengths and thicknesses \((L\) and \(d)\). As shown in Tables 2 and 3, the fabricated hinges have some variations from the designed values. In addition to improving the mask image planning in the MIP-SL process [28,29], the manual operations in the current fabrication process need to be automated.

(3) In the heating process, an important consideration is how to control the heating environment such that the temperature inside the oven can be homogenous with small variations. An oven with multiple thermocouples is built in our study. The temperature distribution inside the oven is measured. Efforts are made to identify the positions inside the oven where the temperature distribution is the most homogeneous. Hence, each hinge of an origami sheet can have the same heating conditions during the self-folding process. Better heating devices with improved temperature sensors and controllers will be considered in our future study.

7 Application Cases

Self-folding origami structures can be used for building complex geometry that may be difficult to be fabricated by other manufacturing processes including 3D printing processes. For example, the test cases as shown in Figs. 18 and 19 all require complex support structures in the MIP-SL process. In comparison, no supports are required in the 2D origami sheet fabrication process since the complex 3D structures can be achieved by the self-folding process. In addition to avoiding support structures, the fabrication process of a 2D origami sheet is much simpler and faster compared to directly printing the related 3D structures [17]. In addition to the polystyrene films, the presented folding mechanism and models can also be applied to other types of materials and microscale objects.
Some more test cases to demonstrate the capability of the developed methods are presented in the Sec. 7. Figure 17 shows a “USC” letter case, which is based on the string-type folding. The designed models of each letter are shown in Fig. 17(a). For each joint of the letters, the values of design parameters \((L, d)\) are selected based on the aforementioned folding angle models and the desired angles in the letters. The fabricated origami strings are shown in Fig. 17(b). After the strings are put in a heated oven, the folded letters are shown in Fig. 17(c).

Figure 18 shows a designed structure with eight folded “legs” (four on each side). The shape of the structure is motivated by a virus structure in the biology. To fabricate such a shape, two origami sheets (refer to Fig. 18(a)) are designed and fabricated based on the processes as described in Secs. 5 and 6. Appropriate hinge parameter values are selected for their desired folding angles in the related legs. Two fabricated origami sheets are glued together by curing a small amount of liquid resin at the center of the structures. The fabricated origami sheet is shown in Fig. 18(b). Accordingly, the folded origami structure is also shown in Fig. 18(b).

Figure 19 shows two more self-folding structures with additional features. A crane test case is shown in Fig. 19(a). Both the front and back sides of the 2D origami sheet are shown in Fig. 19(a)-left. Note some extra features (two “USC” letters) are added in their wings. Such features are hard to be fabricated on the related 3D structure. The self-folded structure after putting the
origami sheet in a heated oven is shown in Fig. 19(a)-right. Figure 19(b) shows a cube test case. Both the 2D origami sheet and the self-folded 3D structure are shown in the figure. Note that the angle lock design as discussed in Sec. 6.3 is added at each hinge (refer to the front side). The test results illustrate that the angle lock design is effective in eliminating any over-folding of the hinges in the 3D origami structure (i.e., the self-folding angle $\alpha$ is ensured to be less than $\alpha'$ related to the angle lock design).

A YouTube video of the presented origami structure design and fabrication method can be found in the link of Ref. [32].

8 Conclusion and Future Work

A bilayer self-folding mechanism that can quickly respond to thermal conditions has been presented. A 3D-printing-based fabrication approach for building related 2D origami sheets has been developed. In addition to constraint layers, the developed fabrication method enables complex features and 3D shapes to be incorporated in related self-folding structures. Heuristic models based on the folding angle analysis have been established for designing parameter values of hinges. Accordingly, a 2D origami sheet can be designed with desired self-folding performance. A novel angle lock design is presented that can be incorporated in a 2D origami sheet to improve its folding angle control. Various experiments have been performed for structures with different complexity. The experimental results verify the effectiveness of the presented design and fabrication method for building self-folding structures with controlled folding behavior.

Some of our future work includes: (1) developing a new testbed to automate some of the manual operations; (2) improving the folding angle models based on more physical experiments; and (3) exploring new applications for the developed self-folding origami structures.

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References


