Self-Folding of Origami Inspired Sacrificial-Hinges to be used in Compliant Mechanisms

Group PME-2018-B1: Mansour Khaleqi (4383648), Joris Kortekaas (4315871),
Elske van Leeuwen (4484460), Bram Westbroek (4388615)

***Abstract*— Implementing Origami inspired self-folding of sacrificial hinges into the design of compliant mechanisms can overcome challenges of fabricating at nano-scale. A literature survey has been done to find the most promising self-folding technique. A thermally stimulated shape memory polymer has been chosen to activate folding lines in a structural layer of spring steel. To understand the folding of a sacrificial hinge, first single folds are examined. An analytical model has been made to calculate the required moment to bend these folding lines and experiments are done to find the shrinking moment of the actuation layer. A formula for the required moment over the stiffness of the flexure is found and a self-folding sacrificial hinge is produced.**

***Keywords*—; origami; self-folding; sacrificial hinges; shape memory polymer; flexures; folds; thermal**

I. INTRODUCTION

Origami can, besides beautiful art, lead to ingenious engineering applications. The last decade origami has become of increasing interest to engineers for applications reaching from nano- to macroscale [1]. The main advantage of origami-inspired design is the relatively easy fabrication in two-dimensions to create a three-dimensional structure. Other benefits are increased strength to weight ratios, less material usage and it has the ability to create complex geometries [2]. Conventional three-dimensional production techniques are currently not able to create small scale objects, while two dimensional techniques are able to create objects at nanoscale. Origami inspired design provides a solution to this problem since it transforms a planar material into a three-dimensional structure. Towards microscale it becomes increasingly difficult to fold objects by hand, which demands the use of self-folding techniques [3].

In previous literature different methods for self-folding are discussed, most of which make use of an external stimulation energy to initiate the activation of the folding process. Examples of self-folding techniques are a magnetic field that can create cubes when it is applied on particles embedded in the material [4], preprogrammed multilayer composites which will fold when placed in an oven [5] and ink-patterned plastic sheets that will start folding when exposed to UV light [6]. Table 1 shows different combinations of stimuli and activations. Some combinations have a lot of examples, others have no promising examples. This is reflected in the number of dots. These blanks could still be filled in by new research.

Most existing self-folding techniques create simple structures such as single folds or cubes, but they lack research into self-folding of more complex objects. A next challenge is to fabricate compliant mechanisms using self-folding technology.

TABLE I. OVERVIEW OF KNOWN COMBINATIONS OF STIMULI AND ACTUATIONS.

		Stimulus (Energy)					
		Thermal	*Electric*	*Magnetic*	*Chemical*	*Light*	*Pneumatic*
Actuation (Force)	*Mechanical*	●●●●●●●●●●●		●	●●●●●●●●●●●	●●●	●●
	Capillary	●●					
	Electrostatic		●●				
	Magnetic			●●●●			

Compliant mechanisms transfer or transform motions or displacements at one point into displacement at another point through elastic body deformation [7], e.g. a compliant universal joint or a four-bar mechanism. To create compliant mechanisms by folding planar sheets, sacrificial hinges can be used to get the desired three-dimensional orientations. Combining roll, pitch and yaw rotational hinges will make every orientation possible. An example of a sacrificial pitch hinge is shown in Fig. 1.

The folding of sacrificial hinges requires sharp folds with a small radius. Literature has shown that thermally stimulated self-folding methods are capable of this [8], and thus this stimulus is chosen for further research. Most thermal stimulated self-folding techniques include multiple structural layers and one or more actuation layers [5][9], which consist of shape memory polymers (SMP). Lowering the number of layers will most likely simplify the fabrication process. In this research we will try to create structures with only one structural layer and one SMP actuation layer. Predefined folding lines in the structural layer have to contain flexures to keep the different sections together to ease the fabrication process. However, this brings forth a new challenge since the actuation layer should be able to bend this flexure. The aim of this research is to examine the relation between the required moment to bend a flexure in

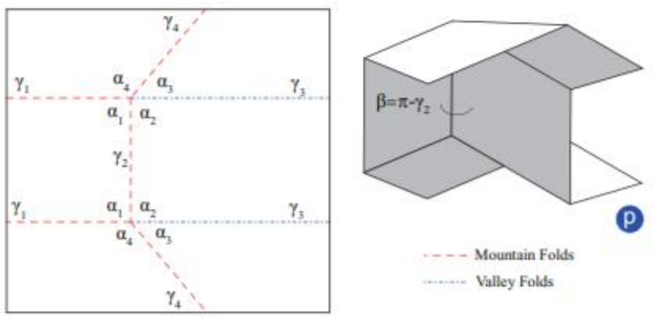

Fig. 1. A pitch sacrificial hinge in the unfolded form (left) and the folded form (right). Provided by D. Farhadi Machekposhti (not published).

the structural layer and the amount of SMP used as actuation layer. An analytical model will be derived to estimate the required bending moment and will be compared with experimental measurements. Experiments on the structural layer are conducted to obtain more knowledge of the used SMP.

This research has been conducted as part of the Bachelor End Project for Mechanical Engineering students at the TU Delft in the third year of their Bachelor studies.

II. METHODOLOGY

The bilayer composite that will be investigated in this paper consists of one structural layer, which is made from spring steel 1.4310 and one actuation layer, which is made from an SMP. The SMP used is an ordinary shrink plastic of which is known that it will actuate at 130°C and has a shrinking ratio of 2.5. In order to understand the more complex folds of a sacrificial hinge, single folding lines were examined experimentally and theoretically.

A sample of a folding line with flexures is shown in Fig. 2. An SMP layer is attached to both ends of the sample using a combination of 50µm double sided 3M ATG904 tape and Bison Super Glue Control. This has been found to be the best combination to withstand the high temperature without losing adherence. During uniform heating in a preheated oven the SMP layer contracts which applies a force on the structural layer that causes a bending moment on the fold line resulting in a rotation of the structure Fig. 2c.

In order to calculate the required moment to fold the structural layer an analytical model was derived. Assuming the material shows elastic-ideal-plastic behavior during bending, two stress distributions can be discerned. A linear stress-distribution arises when only elastic deformation occurs, and the hypothesis of Bernoulli can be applied. When the outermost fiber in the flexure reaches the yield strength the hypothesis of Bernoulli still holds but the material will yield with a constant outer fiber stress. When the yield stress is reached in the outermost fiber the curvature is:

$$k_e = \frac{2Y}{tE} \tag{1}$$

Taking that only the flexure sees the stresses and deformations, the moment that is required to bend it is:

$$M = EIk \qquad \text{for } k < k_e \tag{2}$$

with $I = \frac{1}{12}bt^3$ and $k = \frac{\theta}{l}$

$$M = M_p\left(1 - \frac{1}{3}\left(\frac{k_e}{k}\right)^2\right) \qquad \text{for } k > k_e \tag{3}$$

with $M_p = \frac{1}{4}bt^2Y$ and $k = \frac{\theta}{l}$

As it is unlikely that ideal elastic-plastic behavior arises, a hardenings factor is added in the plastic region:

$$H = \frac{T-Y}{\frac{\varepsilon}{100} - \varepsilon_{yield}} \tag{4}$$

with $\varepsilon_{yield} = \frac{Y}{E}$

here, T is the ultimate strength and ε is the elongation at ultimate strength.

Thus, the moment in the elastic-plastic region becomes:

$$M = M_p\left(1 - \frac{1}{3}\left(\frac{k_e}{k}\right)^2\right) + HIk \quad \text{for } k > k_e \tag{5}$$

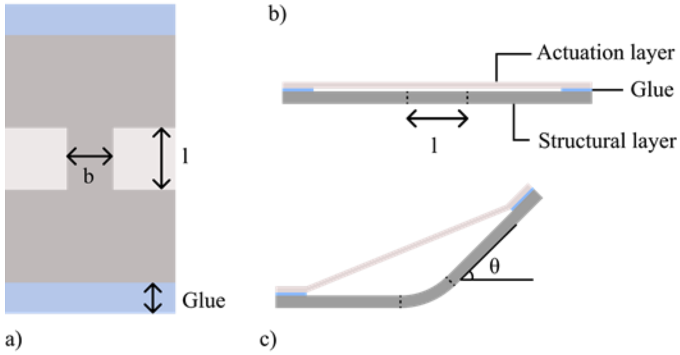

Fig. 2. Top view of a folding line with a flexure. (a) Side view in unactuated and actuated form. (b and c)

The material properties of spring steel used for the calculations can be found in table 2.

TABLE II. MATERIAL PROPERTIES OF SPRING STEEL

Youngs modulus	E	185 GPa
Yield stress	Y	1500 MPa
Tensile strength	T	1700 MPa
Maximum elongation	ε	25%

To test the validity of the analytical model for our structural layer the force required to bend a single fold was measured with a load cell calibrated for 250 grams (Futek FSH02665). Strips of metal with width *b* were used to represent the flexures. These were fixed at one side and clamped by a movable 3D-printed quarter circle on the other side leaving a gap height *l* between the two fixtures, as shown in Fig. 3(a and b). A 0.5 mm nylon wire was connected between the load cell and the quarter circle and rolled of the arc of the circle during bending. This ensures the force is always applied perpendicular to the sample and the force vector as seen by the load cell does not change. A linear motion stage (PI M-505.4DG) was used to pull the load cell backwards and move the quarter circle with the sample to a ninety-degree rotation angle. The displacement of the load-cell correlates with the angle of rotation of the sample. Samples with different widths as well as different thicknesses of the spring steel (0.05, 0.1 and 0.2 mm) were measured to verify scalability of the concept.

In order to examine the actuation layer, we carried out two sets of experiments. First an invariable amount of SMP was placed on top of a structural layer containing folding lines with different stiffnesses. In 50 μm steel plates of 15 by 30 mm, flexures were cut with widths of approximately 1 to 12 mm, with increments of 1mm, and a gap of 2 mm. 5 mm of the ends

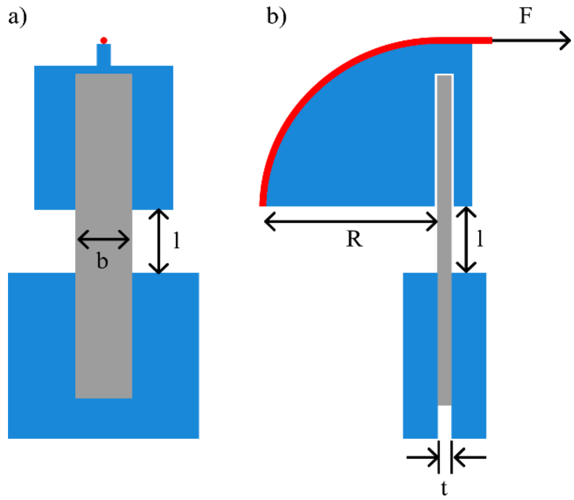

Fig. 3. Schematic front view of the test set up. (a) Schematic side view of the test set up. (b)

of the SMP layer were glued on the structural layer as can be seen in Fig. 2a. After simultaneously heating the actuation layer of the samples in a preheated oven of 130℃ the rotation angles of the samples were measured by applying image analysis on a picture of the sample. The maximum rotation angle that can be reached when the SMP shrinks to its minimum size is:

$$\alpha = 180 - 2\sin\left(\frac{1}{c}\right)\frac{180}{\pi} \qquad (6)$$

here, c is the shrinking ratio

A sample was classified as a success if the shrinking paper could fold to angle alfa with a margin of 5 percent. When a sample with a certain stiffness did not reach that desired angle, because either the shrinking paper yielded itself or the glue came loose, the amount of SMP was classified as insufficient for that stiffness and the sample was classified as failed.

To determine the influence of the size and pattern of the SMP layer a second experiment was done. Flexures with the same width were cut into 30 by 50 mm steel plates of 50 μm thick. Two different surface areas of SMPs were glued on the samples with three different length to width ratios and one alteration in pattern; two strokes of SMPs were used instead of one.

III. Results

We measured the forces that are required to bend flexures of 100 μm thick spring steel with a width of 3.0, 6.6 and 9.2 mm, which all contained a 2 mm gap. Fig. 4 (a) shows these measured forces together with the theoretically modeled forces. Furthermore, the forces were measured while bending 100 and 200 μm thick folding lines with gaps of 3.8 and 4.2 mm and flexure widths of 2.8 and 2 mm respectively plotted in fig 4b. In the same graph the analytical model is plotted for the 200 μm thick folding line and a scaled version of the measured 100 μm thick folding line with a factor calculated with our model.

The angle of rotation in degrees as a function of the stiffness of the heat activated samples are shown in Fig 5. These samples

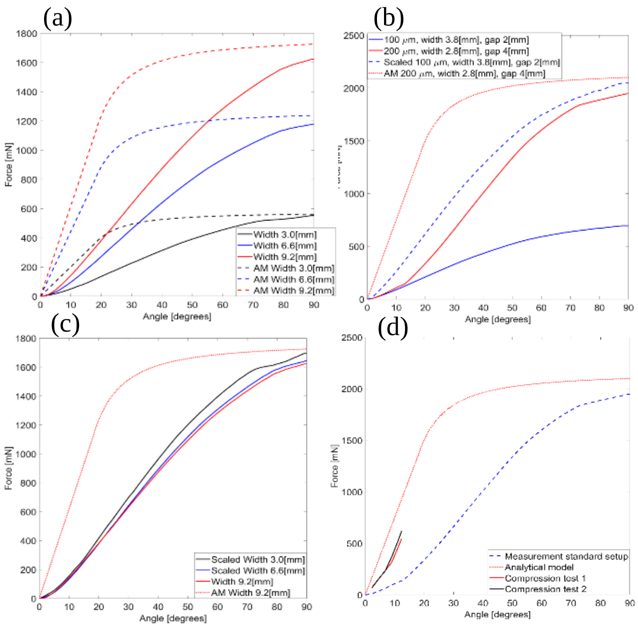

Fig. 4. The measured and analytical modeled (AM) forces in millinewton of the structural layer during bending till 90 degrees of samples with varying widths (a). The measured forces of different plate thicknesses (b). The measurements of Fig. 4a scaled to the same width (c). A 200µm thick sample tested only on elastic behavior (d).

had the same amount of SMP layer. The blue and orange dots represent the samples where the SMP bended the samples with success or failure respectively. Table 2 shows the angle of rotations for heat activated samples with different size configurations of the SMP layer. The stiffness of the flexures is kept constant.

TABLE III. Rotation angels of samples with varying SMP surface layer

Area 1		**Area 2**	
size [mm]	***angle of rotation [deg.]***	***size [mm]***	***angle of rotation [deg.]***
10x40	110.8	15x50	124.1
15x30	112.8	20x40	122.4
20x22	116.7	28x28	128.0
(2x7.5)x30	110.9	(2x10)x20	122.1

IV. Discussion

The results of the structural layer experiments show a difference between the analytical model and the measurements. However, the data do show that the measured forces scale the same as the analytical model. According to our analytical model the measured force scales linearly with the width of the flexure. When the samples in Fig. 4a are scaled to the same width, the measurements should scale to the same force as well. In Fig. 4c the scaled measurements are shown and indeed the forces are nearly identical. The data in Fig. 4b imply that the thickness scales according the analytical model. Equation (2) was used to calculate a factor to scale the results from the 100 μm sample to the 200 μm sample. Again, the scaled measurements are close to each other. Despite the similarities of the end values between the analytical model and the measurements, and the prove of scalability of the measurements, there are significant differences between the data and the model. This could be explained by the use of a wire in the setup, which stretches when a force is applied. The wire which connects the samples to the load cell was changed from nylon to copper, but this had very little influence on the measurements. The elongation of the copper and nylon wire was calculated using Hooke's law [11]. Both elongations are very small and so indeed resulted in very small deviations in the angle of rotation. The cable elongation is not a good explanation for the large difference between the analytical model and the test results.

To verify if the analytical model is correct another experimental setup was designed to test only the elastic behavior of the material. Since only small angles of rotation are measured, this setup did not require the quarter circle and wire.

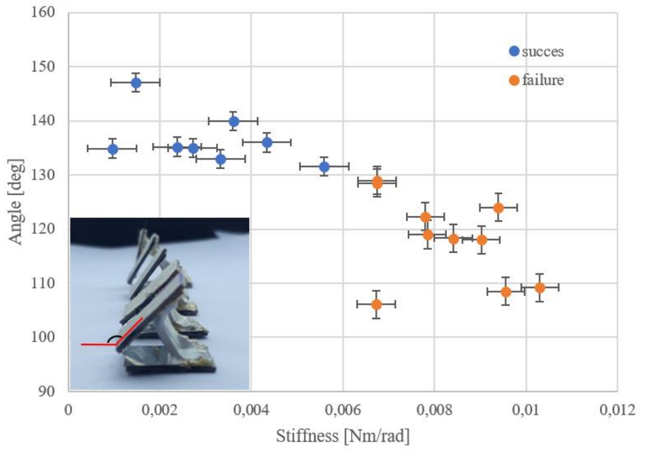

Fig. 5. Rotation angles in degrees of samples with different stiffnesses actuated with a constant SMP surface layer.

small deformations. The results from this experiment on 200 μm thick samples, shown in Fig. 4d, are closer to the analytical model, which tells us that the model is likely to be correct for the elastic part of the deformation. We assume that the error in the first setup is generated by the knots in the cable that stretch and compress during the measurement. This however was not validated.

The data from the first experiment have shown us that there is a linear relation between the width of a flexure and the measured force. Assuming that the analytical model can predict the maximum required bending moment accurately we can derive a relation between this bending moment M_{max} and the stiffness S of the flexure which resulted in the following equation:

$$\frac{M_{max}}{S} = \frac{3Yl}{Et} \tag{7}$$

The experiments done with the SMP layer showed that 15 by 30 mm of SMP can maximally fold a flexure with a stiffness of 0.006 Nm/Rad to its maximum folding angle. From (7) the bending moment can be calculated that the shrinking paper has created which is: 0.0058 Nm The rest of the samples did not reach the maximum folding angle derived with (6), so the SMP layer must have yielded. From the second experiment we can see that the length to width ratio of the SMP layer has influence on the generated moment per area. The 2:1 samples were taken as a base value. The 'longer' samples roughly showed a 10% increase in generated moment, and the 'wider' samples showed an increase of roughly 5% compared to the base value. These values are still hypothetical since not enough tests have been done to completely validate this hypothesis. It is difficult to find a quantifiable relation between the amount of SMP and the moment it can create since it is hard to completely understand the behavior of the SMP.

Sacrificial hinges were folded using the bilayer method. One folding line in the sacrificial hinge contains a stiffness of 0.0617 Nm/rad and using the given relation in (7) a moment of 0.0038 Nm needs to be exerted to bend the flexures. However, not all folding lines can be actuated, so the moment that the SMP layer needs to apply on one fold is higher than the calculated value. The data from the experiment show that an applied SMP layer of 15 by 30 mm should easily be able to fold the actuated folding lines and probably can compensate for the non-actuated folding lines. Fig. 6 confirms that an SMP folded bilayer sacrificial pitch hinge can actually be folded using this method.

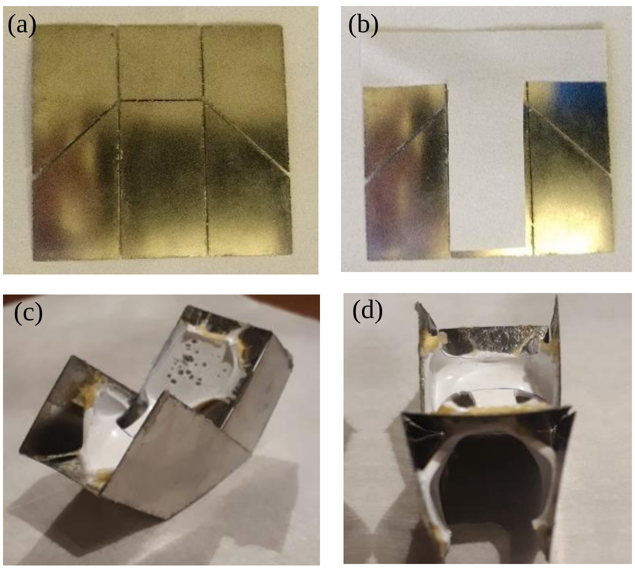

Fig. 6. Laser cut 4-degree pitch sacrificial hinge. (a) Laser cut 4-degree pitch sacrificial hinge with SMP layer attached. (b) Self-folded sacrificial hinge. (c) Front view self-folded sacrificial hinge. (d)

V. Conclusions and Recommendations

This paper shows that a self-folding technique can be applied to create more complex structures such as sacrificial hinges. The studied self-folding technique uses a bilayer configuration consisting of a shape memory polymer (SMP) actuation layer and a structural layer. This structural layer contains predefined folding lines with flexures. A relation between the stiffness of a flexure and the required bending moment to fold this flexure can be approximate by using a simple analytical model. Results of experiments on the actuation layer showed that the way the SMP layer is applied does have influence on the moment it can exert on the structural layer. Different size configurations have been tested which led to the statement that the SMP layer can generate a bigger moment per area when the length to width ratio is increased. Two different patterns of the SMP layer were tested as well and this showed little to no influence on the effectiveness of the actuation. More research can be done to fully understand the contracting behavior of the SMP layer. Following research could be to investigate the effect of having folding lines in different orientations as seen in sacrificial hinges and how these folding lines influence each other if not all the folding lines are actuated.

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