Improvement of serpentine networks in crack resistance

CERI program

Final report

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Introduction

Flexible electronic brings the innovations to the electronic technology field. It is the newest and the most potential of large-area electronics. Nowadays, electronics are mostly made of silicon wafers, which are stiff and not elastic. However, recent advance in silicon-based polymers film provides new routes to build circuits, which offers the searchability of electrical properties. Rigid electrical components standing on flexible substrates (mostly silicon-based polymers) with serpentine or wavy connection is the most widely used structure for flexible electronics. In most cases, the mechanical property of substrates is control by the selection of polymers, mixing ratio and structure design. However, selection of polymers is often limited by availability, and mixing ratio for most silicon-based polymers is fixed. Structure design of substrates, such as introducing pillows into substrates, is able to control the local mechanical property, which is often used to protect rigid electronic components. However, it is very expensive and time-consuming to get molds for the molding process, especially for complex microscopic patterns, so we want to find an easy and price effective solution.

It has been proposed that mechanical property of substrates can be tuned over very a large range by embed serpentine networks into them. Both the mechanical property of materials and structure of networks affect the stiffness of composite substrates. By employing this idea, flexible substrates can be made to accommodate the mechanical property of different parts of human body. A question arises regarding this technique: can we change to local mechanical stiffness of the composite substrates? An intuitive idea to this question is to break the lines of networks. An intuitive question regarding this technique arise: can we modify the mechanical property of composite substrates by breaking some lines in the networks? It is believed lines with different orientation have different influence on the stiffness of composite substrates. We will check the validity of this idea and hope to apply them to flexible electronics, especially microfluidic devices.

The goal of this research is to study the influence of breaking lines in networks on the mechanical stiffness of composite substrates and discuss the crack resistance on each pattern. Our research provides a simple solution to tailor the mechanical stiffness of composite substrates, which can reduce the discomfort of wearable electronics when attached to human bodies. We will design our own structure to achieve the high crack resistance and the low Young's modulus, which could provide us a solution in the design of wearable and flexible electronics in human health monitoring.

Literature Review

Electronics are mostly made of silicon wafers, which are stiff and not elastic. Recent advance in silicon-based polymers film provides new routes to build circuits with stretchability. Engineering the mechanical properties of polymer substrates (including stiffness and crack-resistance) according to practical applications has been an important issue in wearable and flexible electronics.

Flexible substrates (mostly silicon-based polymer) offer a new property of extendable to advanced electronic devices by having phases with non-mineralized biological materials and making them as a suitable platform for other electrical applications. When integrating circuits on flexible substrates, special design patterns are needed. (1) There are two key structure properties – toughness and strength in material design. (2) Strength refers to a large elastic range, and toughness is the amount to absorb energy and plastically deform before the crack propagation. Hence, these two properties are often mutually exclusive. Material with high strength will have low toughness, so engineers attempt to design structural materials that are both strong and tough. Here is where they get inspiration for new idea from natural organisms, such as muscles and brain tissue. There are several important advances in recent years which researcher got inspired from the natural world. (3) They created an artificial skin construct with photolithographically defined polyamide, which has highly elastic, ultra soft and vapour permeable characteristics. (4) (5) This structure design could be called serpentine networks.

Serpentine-shaped structure offers great flexibility in turning their stiffness through changing the characteristic unit. Due to its high stretchability, serpentines structure has been widely used in industry field, such as the airplane buckle, which minimized the stiffness of the inorganic materials, percutaneous coronary intervention, which improved the expandable of intrinsically stiff materials, and health monitor system sensor, which made the sensor be easier to cover on the surface. (6) Serpentine-shaped structure is like the horizontal “S”, which could see in the Figure 1 below.

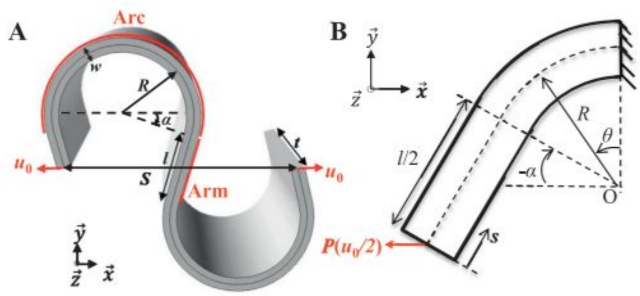

Figure 1. Schematic of serpentine network. (6)

There are four geometric parameters which will influence the structure: the width w, the arc radius R, the arc angle a, and the length l. These factors will determine the strain of the serpentine unit, and change the property of whole structure. By applying the expression below in Figure 2, we are able to comprehend the effective strain of each shape in Table 1. According to the literature, if we have smaller ratio of W/R., the bigger angle a, and the larger ratio l/R, the value of the effective stiffness will become lower. In other words, the lower effective stiffness means higher effective elastic.(6)

$$S = 4\left(R\cos\alpha - \frac{l}{2}\sin\alpha\right)$$

$$\varepsilon_{app} = \frac{2u_0}{S}$$

Figure 2. the expression of strain effective. (6)

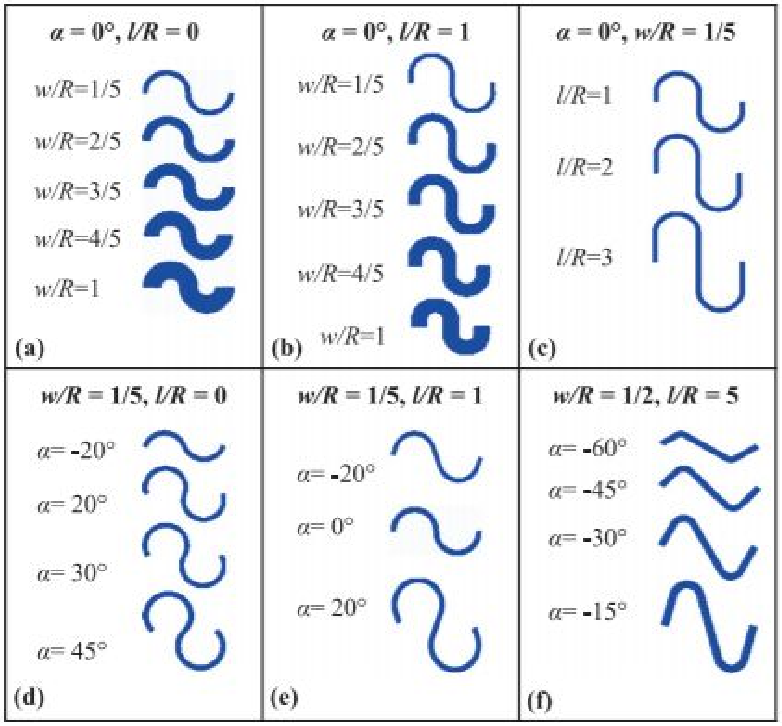

Table 1. Different situation of serpentine structure. (6)

Methodology

Having already presented the basis of the knowledge of this project, we would need to collect the evidence to support our hypothesis. The purpose of this research is to provide a simple solution to improve the elasticity of the patterns and try to explore other situation to discuss the crack resistance of the patterns. Although there are vary technique to test the stress-strain response, it is important to standardize the method utilized in the experiment for us to easier reproducibility in analysis and in practice.

In this hex pattern design, we get inspired from the bio-inspired soft and thin film composites, which presents in figure that shows the pattern of an artificial skin. (3) We use AutoCAD software to sketch a similar pattern but with several holes, which presents in figure below. The purpose of our design is to tailor the mechanical stiffness of composite substrates, but in the meanwhile we still want to keep the toughness of the pattern. Therefore, we keep the completed unit between intervals. After designing, we need to use 3D printer, B9Creator (v1.2) to print out the model. The material of ink is a kind of photopolymer resin, which changes its properties when exposed to light. Hence, we use the printer with built-in projector to print out our design pattern. The model could be very accurate because the photopolymer are immediately manifested structurally when exposing to light.

In the next step, we will need to have an equipment for us to measure the stress-strain response to test the Young's modulus. We set up with several acrylic plates with load cell monitor, which could be used to measure the force, and we also have the motion stage to be the power to stretch the pattern stably. In the Figure below, it is our homemade mechanical stretching system, which is mainly composed of a load cell and motor-controlled motion stage.

The final step is used the Arduino software to run the test in order to get time and force. There are two code to control the load cell and motion controller. One is the program to control the load cell calibration, and another code is decide how many cycle we want to turn per minute. The code will show in Appendix A. The last, the measure force with time will be output to a computer for a real time analysis, and we would apply formula on our data to calculate the Young's modulus.

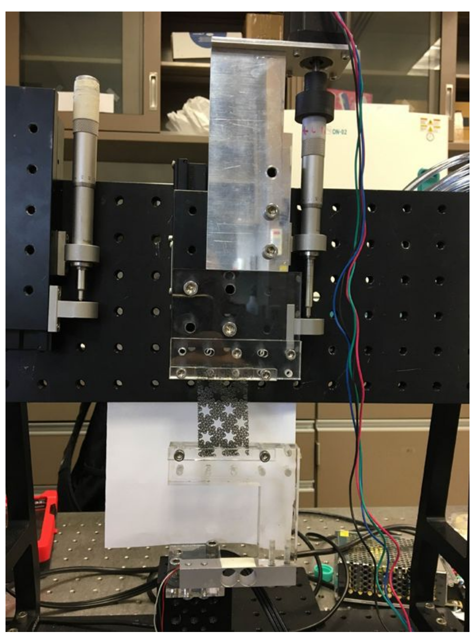

Figure 3. The equipment of mechanical stretching system

Testing Progress & Results

The design serpentine structure were in the following Figure 4 and 5. As we knew that different line orientation would influence different stiffness on the pattern (7), so we decided to make one of the structure with holes, and the other one without holes. In the Figure, we could comprehend that there was one completed unit between two holes. We wanted our circuit to be in simple geometric form, so we could easily to analyze and adjust.

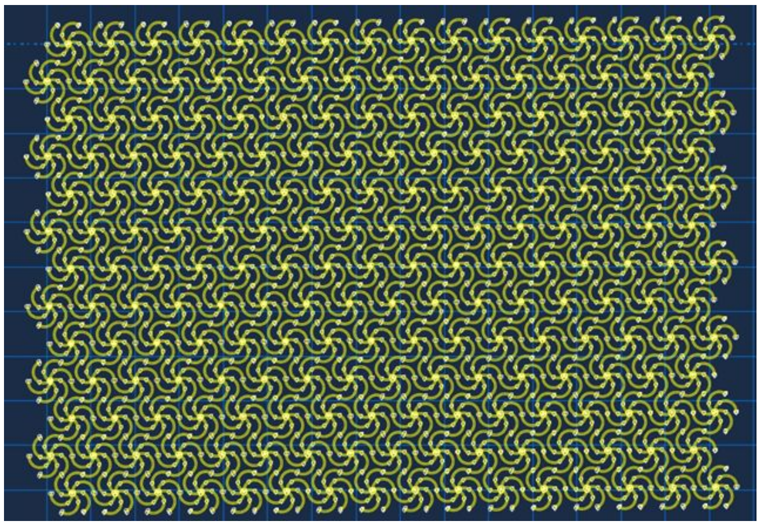

Figure 4. Serpentine networks.

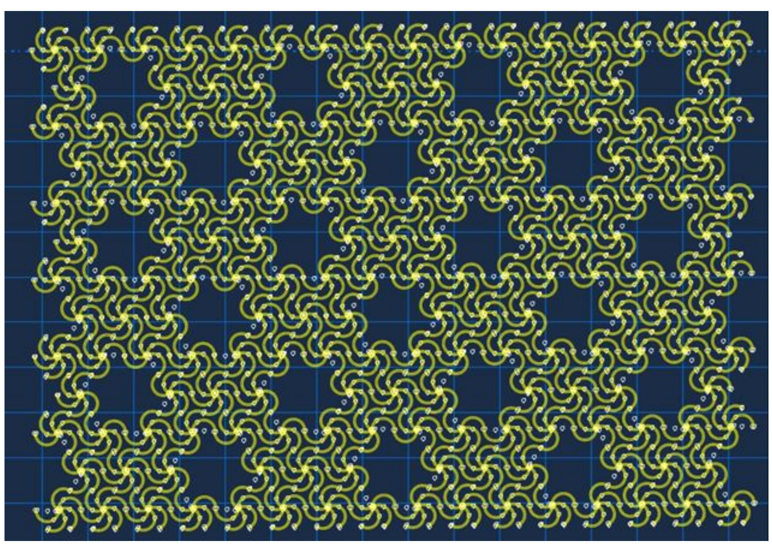

Figure 5. Serpentine networks with holes.

In the experiment process, we had used our homemade mechanical stretching system to test the stress-strain response on our design structure in order to determine the Young's modulus of each pattern. Young's modulus was a measurement of stiffness of solid material, which was able to analyze the elastic of the material. Testing the stress-strain response could also observe the elastic deformation to understand whether the material could return to its original shape after the load is removed. By approaching the precise data to support our hypothesis, we controlled several factor for the comparison between two design networks, such as maximum displacement, number of cycle, and same size of module. In addition, to security consider the accurate experiment, we needed to calibrate the load cell sensor. We put two weights with 1000 grams and 500 grams respectively on the load cell, and run the program to adjust the float calibration code, which could see in Appendix A.

In our experiment, we set up two acrylic plate with PDMS (Polydimethylsiloxane) to fix the design pattern. The PDMS was used to protect the design from frictional damage. When we started operating the motion controller, the pattern was slowly expanding until the number of cycle reached the value we had set. After the pattern stopped stretching, we sent the command to reverse the cycle in order to make the pattern back to the origin point, so we could repeat our experiment to get an average results. We had tried the thickness in 0.1 mm and 0.2 mm of both structure, and we set the number cycle to be 5, which meant the displacement was 2.5mm in total.

After stretching the structures, we sent the output into Excel to analyze the data. The data we had collected was time and force, but we needed to adjust the data for correct result because the data was collected when we clicked the button, but it did not start expand. Besides, the load cell sensor had its own error collaboration for every testing, so we would have to subtract the value and multiply the factor to get the stress value. The formula of stress and strain was showing in Table 2. We got the correct value of force, and divided it with the area of the serpentine pattern, which was width times thickness (32.4 mm * 0.1 mm), to get the stress value. On the other hand, we would use the time to calculate the strain. Although we had fixed the displacement, but as we had mentioned earlier, there were small human error by clicking the button to operate the system. Therefore, we used time times the length per second to obtain the specific length of stretch, and divided with the original length, which was the distance between two acrylic plates. We had to plot the stress versus strain to modify the Young's modulus to support our assumption.

$$\text{Stress} = \frac{\boldsymbol{Force\ (or\ load)}}{\boldsymbol{Area}} \quad \boldsymbol{\sigma} = \frac{\boldsymbol{F}}{\boldsymbol{A}}$$

$$\text{Strain} = \frac{\boldsymbol{Length\ of\ Stretch}}{\boldsymbol{Original\ Length}} \quad \boldsymbol{\varepsilon} = \frac{\boldsymbol{\Delta L}}{\boldsymbol{L}}$$

$$\textit{Young's modulus} = \textit{slope} = \frac{\boldsymbol{Stress}}{\boldsymbol{Strain}}$$

Table 2. Formula of Stress, Strain, and Young's modulus.

The experiment result of thickness of 0.1 mm was showing below. Figure 6 and Figure 7 represented the data we had collected in three time testing, we observed that first time of stretching the structure had higher line than other two because we noticed that there were some connection between each units of serpentine networks. The reason was when photopolymer resin ink overfilled and exposed to the projector light, it would fill up the gap between each units. Hence, we decide not to use first result, and took the average of the rest two data. In the Figure 8 and 9, we realized the slope of the serpentine networks with holes was much lower than the one without holes, which did meet our expectation due to the theory.

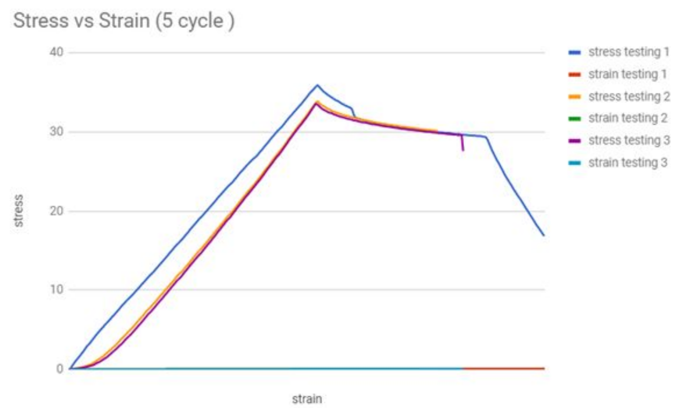

Figure 6. Three time testing data of Serpentine networks with holes.(0.1 thickness)

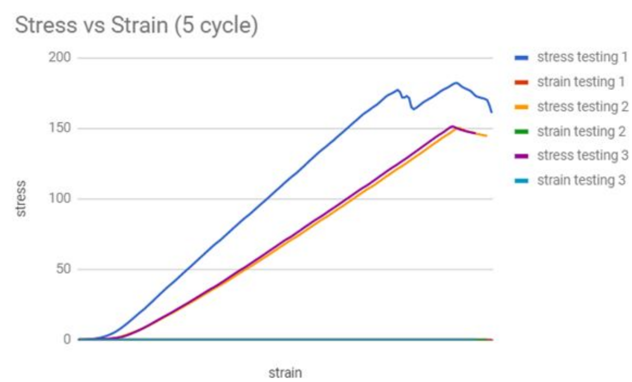

Figure 7. Three time testing data of Serpentine networks without holes.(0.1 thickness)

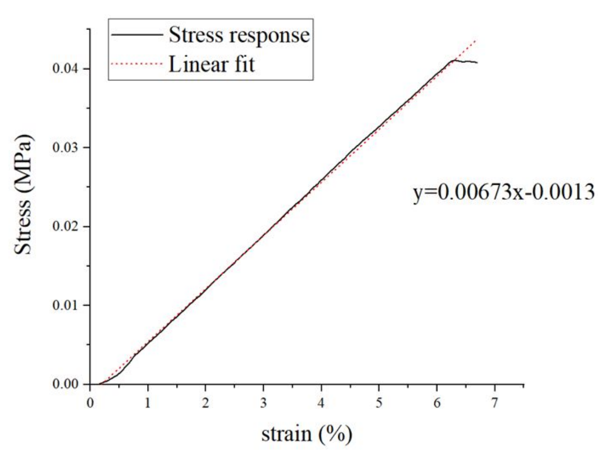

Figure 8. The average data of Serpentine networks with holes.(0.1 thickness)

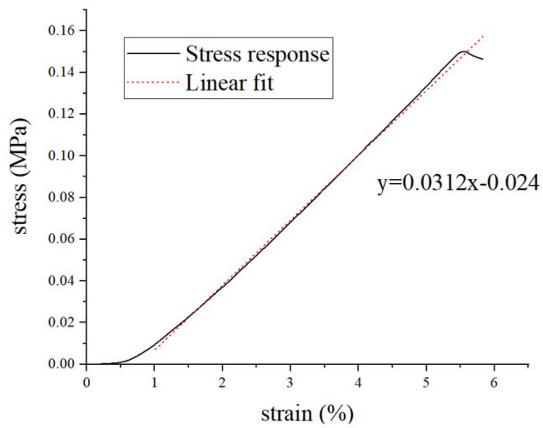

Figure 9. The average data of Serpentine networks without holes.(0.1 thickness)

In addition to the thickness of 0.1 mm, we still did the serpentine structure with 0.2 mm thickness because we wanted to determine whether the thickness would affect the stiffness of our design. We repeated the steps we had done previously and collected the data to investigate the slope value of each sample. The following Figure 10 and Figure 11 were the three time testing data, and we found out that there was same situation that the first experimental data had certain different from the other two results. Therefore, we neglected the data of first testing and calculated the average for the rest two results, which could see the outcome in Figure 12 and Figure 13.

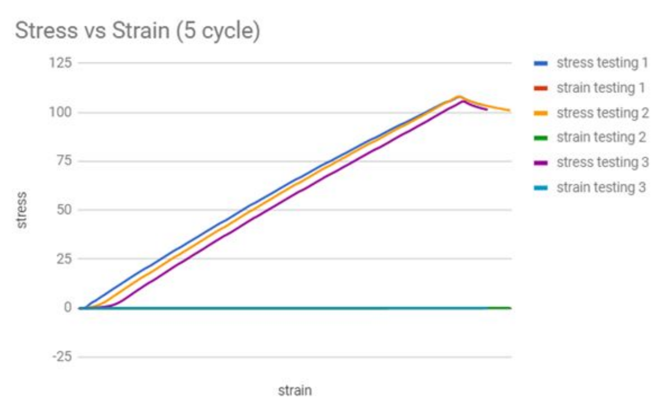

Figure 10. Three time testing data of Serpentine networks with holes.(0.2 thickness)

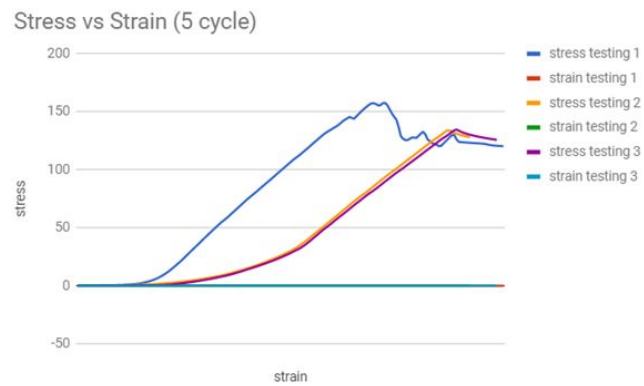

Figure 11. Three time testing data of Serpentine networks without holes.(0.2 thickness)

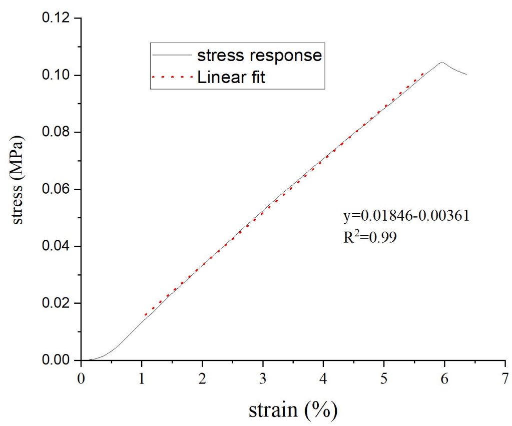

Figure 12. The average data of Serpentine networks with holes.(0.2 thickness)

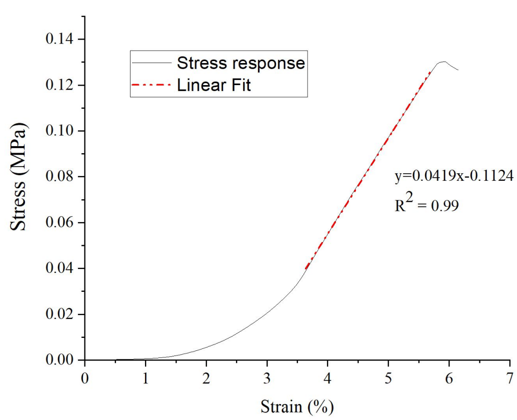

Figure 13. The average data of Serpentine networks without holes.(0.2 thickness)

In order to compare the results easily, we created a table for these four value of Young's modulus, which could be seen in Table 3. We found out that the serpentine networks with holes had higher elastic because it had lower Young's modulus. Moreover, we also realized that the thickness had influence on stiffness due to the value of Young's modulus. It was interesting that thickness had a greater impact on the structure with holes. Therefore, we would want to verify this assumption in the future work.

	Thickness 0.1 mm	Thickness 0.2 mm
Patten with holes	0.00673	0.01846
Patten without holes	0.0312	0.0419

Table 3. Comparison of the four Young's modulus

In order to support our experiment, we used the software called Abaqus to simulate the design. Before the simulation, we also measured the young's modulus of the material of ink because we had to make the system understand what the material it was going to test. The Figure 14 was showing the stress-strain response of the material. After the simulation, we had the simulation motion diagram in Figure 15. In the diagram, under the same load situation, the serpentine networks with hole had average stress on each unit, but we could see that without holes had high intense stress in the middle. Besides, the plot of stress-strain for both structure presented in Figure 16 and Figure 17. We was surprised when we saw the figure because it was a curve line and the slope was comparatively smaller than our experimental data. The reason was that there were connection between our model design, but the one we simulation were not, so the actual unit of the serpentine networks, which would influence the result of simulation. We would put this into discussion and tried to reduce the error between the experimental and simulation results. However, we still believed that the serpentine structure with holes did have higher elasticity than the other because of the value of Young's modulus (0.00035 < 0.00046).

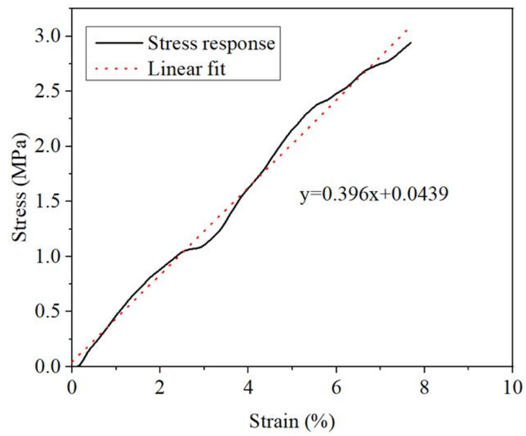

Figure 14. Stress and Strain response of material ink.

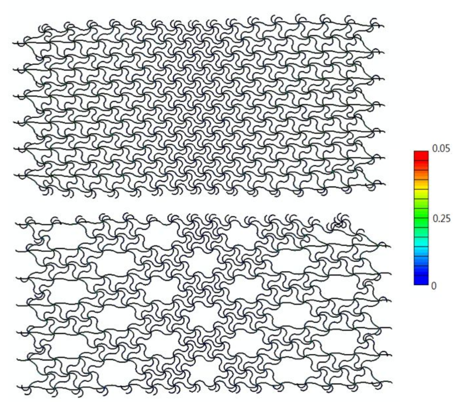

Figure 15. Simulation schematic

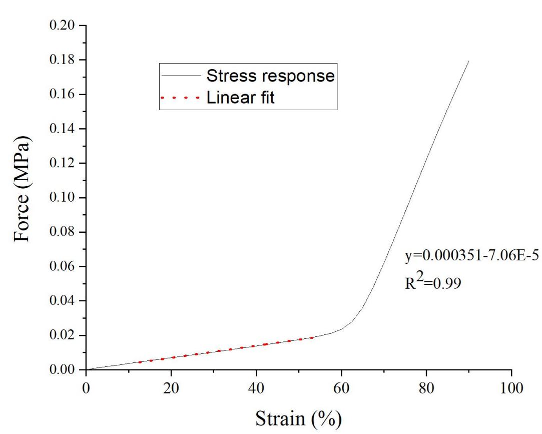

Figure 16. The simulation stress and strain response of structure with holes.

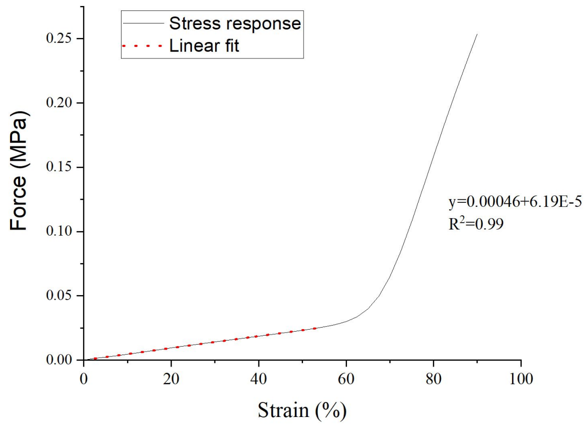

Figure 17. The simulation stress and strain response of structure without holes.

Discussion

From the experiment and simulation, we noticed that serpentine networks with holes had lower Young's modulus, which meant it had high elasticity. The result did make sense to us, but the collected data was not accurate enough because of human error, equipment error, and model error. Our homemade mechanical stretching system was controlled by human with clicking button and read the value, so we decided to borrow a tensile testing machine from other lab in engineering science department. Besides, the 3D model was made of photopolymer. Although it could print the sample with very small dimension, we still needed to think how to solve the connection between each unit. We might change our serpentine into small W/R ratio, so the gap between could become bigger enough for the system verified.

In the future works, we would fix our error and improve the accurate result to support our design and assumption. Moreover, in addition to elasticity, we would still have to modify the crack resistance of our design. We will have Polydimethylsiloxane (PDMS) embed with our design and test it with different crack condition in order to prove that serpentine network with holes could have better adaptability to cracks.(8) It could be like in Figure 18. We looked forward to finish our research and have enough experimental data to support our hypothesis and the theory.

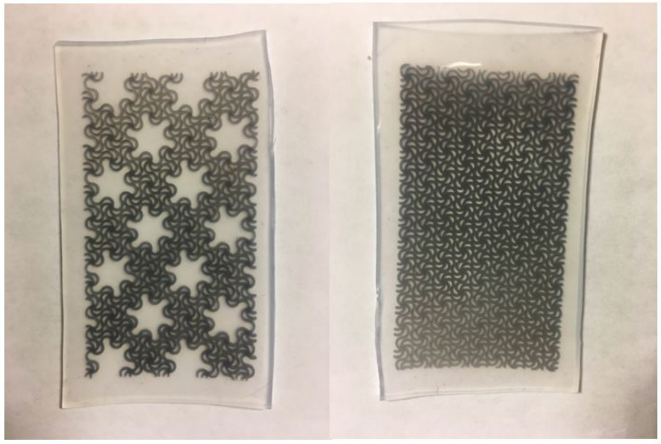

Figure 18 .PDMS with embedded Serpentine networks.

Conclusion

The implementation of our experiment was a success. Although there were some differences between simulation data and experimental data, serpentine network with holes design provided better flexibility. However, we still need to test the crack resistance of our design in our future work, which may promise important applications in wearable and flexible electronics. All in all, we believe that this research result would bring a new idea for the field of mechanical structure. The design could not only be used on flexible electronics, but also other fiber product because our design has the properties of high strengths and flexibility.

Appendices

Appendix A: Arduino code

1. **load cell**

```
#include <HX711.h>
/*include HX711 master fold*/

/*
 Example using the SparkFun HX711 breakout board with a scale
 By: Nathan Seidle
 SparkFun Electronics
 Date: November 19th, 2014
```

License: This code is public domain but you buy me a beer if you use this and we meet someday (Beerware license).

This is the calibration sketch. Use it to determine the calibration_factor that the main example uses. It also
outputs the zero_factor useful for projects that have a permanent mass on the scale in between power cycles.

Setup your scale and start the sketch WITHOUT a weight on the scale
Once readings are displayed place the weight on the scale
Press +/- or a/z to adjust the calibration_factor until the output readings match the known weight
Use this calibration_factor on the example sketch

This example assumes pounds (lbs). If you prefer kilograms, change the Serial.print(" lbs"); line to kg. The
calibration factor will be significantly different but it will be linearly related to lbs (1 lbs = 0.453592 kg).

Your calibration factor may be very positive or very negative. It all depends on the setup of your scale system
and the direction the sensors deflect from zero state
This example code uses bogde's excellent library: https://github.com/bogde/HX711
bogde's library is released under a GNU GENERAL PUBLIC LICENSE
Arduino pin 2 -> HX711 CLK
3 -> DOUT
5V -> VCC
GND -> GND

Most any pin on the Arduino Uno will be compatible with DOUT/CLK.

The HX711 board can be powered from 2.7V to 5V so the Arduino 5V power should be fine.

```
*/
#define HIGHFREQUENCY 4
#define DOUT  3
#define CLK  2

HX711 scale(DOUT, CLK);
```

```
float calibration_factor = 2161; //-36 worked for my 0.5N max scale setup
unsigned long time;
void setup() {
  Serial.begin(9600);
  Serial.println("HX711 calibration sketch");
  Serial.println("Remove all weight from scale");
  Serial.println("After readings begin, place known weight on scale");
  Serial.println("Press + or a to increase calibration factor");
  Serial.println("Press - or z to decrease calibration factor");
  pinMode(HIGHFREQUENCY,OUTPUT);
  digitalWrite(HIGHFREQUENCY,HIGH);

  scale.set_scale();
  scale.tare(); //Reset the scale to 0
  long zero_factor = scale.read_average(); //Get a baseline reading
  Serial.print("Zero factor: "); //This can be used to remove the need to tare the scale. Useful in
permanent scale projects.
  Serial.println(zero_factor);
}

void loop() {
digitalWrite(HIGHFREQUENCY,HIGH);
  scale.set_scale(calibration_factor); //Adjust to this calibration factor


 Serial.print(" Time: ");
  time = millis();
  //prints time since program started
  Serial.print(time);
   Serial.print(" ms ");

 Serial.print("Loading: ");
  Serial.print(scale.get_units(), 2);
  Serial.print(" g"); //Change this to kg and re-adjust the calibration factor if you follow SI units
like a sane person

  Serial.print(" calibration_factor: ");
  Serial.print(calibration_factor);
  Serial.println();
```

```
  if (Serial.available())
  {
    char temp = Serial.read();
    if(temp == '+' || temp == 'a')
      calibration_factor += 1;
    else if(temp == '-' || temp == 'z')
      calibration_factor -= 1;
  }
}
```

2. motion controller

```
/*

Stepper Motor Control - one step at a time

This program drives a unipolar or bipolar stepper motor.

The motor is attached to digital pins 8 - 11 of the Arduino.

The motor will step one step at a time, very slowly.  You can use this to test that you've got the four wires of your stepper wired to the correct pins. If wired correctly, all steps should be in the same direction.

Use this also to count the number of steps per revolution of your motor, if you don't know it. Then plug that number into the oneRevolution example to see if you got it right.

Created 30 Nov. 2009

by Tom Igoe

*/
#include <Stepper.h>



const int stepsPerRevolution =400*2*4; //400*2*4; change this to fit the number of steps per revolution,2 comes frm 0.9degree, 4comes from 4 steps as a loop

// initialize the stepper library on pins 8 through 11:
```

```
// pay attention: exchange channel 9 and 10 due to stepper model digital sequence.

Stepper myStepper(stepsPerRevolution, 8, 10, 9, 11);

const int speed=20;

String readString;

void setup() {

  // initialize the serial port:

  myStepper.setSpeed(speed);

  Serial.begin(9600);

  Serial.println("Stepper motor control system");

  Serial.println("Input number of int rotation circles:");

}

void loop() {



         while (Serial.available()) {

              char c = Serial.read();  //gets one byte from serial buffer

              readString += c; //makes the string readString

              delay(20);  //slow looping to allow buffer to fill with next character

            }



          if (readString.length() >0) {
```

```
    Serial.println(readString);  //so you can see the captured string
    int n = readString.toInt();  //convert readString into a number
    int i;
    for (i=abs(n);i>0;i--){
      if(n>0)
    myStepper.step(stepsPerRevolution);
    else if (n<0)
    myStepper.step(-stepsPerRevolution);
    }
    readString=""; //empty for next input
   }
}
```

Appendix B: Table of Actual data

1. Simulation for pattern with/without holes

Strain %	Force MPa without hole	Force MPa Hole
0	0	0
2.5	0.00137	0.0011
5	0.00237	0.00192
7.5	0.00337	0.00274
10	0.00449	0.00365
12.5	0.00573	0.00454
15	0.00701	0.00537
17.5	0.00821	0.0062
20	0.00949	0.00702
22.5	0.0107	0.00783
25	0.01184	0.00864
27.5	0.01298	0.00946
30	0.0141	0.0103
32.5	0.01523	0.01116
35	0.01634	0.01203
37.5	0.01746	0.01292
40	0.01858	0.01382
42.5	0.0197	0.01473
45	0.02083	0.01564
47.5	0.02198	0.01656
50	0.02317	0.01751
52.5	0.02444	0.01852
55	0.02586	0.01968
57.5	0.02757	0.02117
60	0.02992	0.0235
62.5	0.0336	0.02789
65	0.03981	0.03612
67.5	0.04989	0.04813
70	0.0648	0.06199
72.5	0.08455	0.07676
75	0.10805	0.0918
77.5	0.13318	0.10707
80	0.15863	0.1223
82.5	0.18369	0.13723
85	0.20802	0.15175
87.5	0.23144	0.16581
90	0.2539	0.17948

Reference

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