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Equivalent Plastic-Strain Analysis of Copper Stretchable Electronic Circuit Using Finite Element Analysis

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ABSTRACT

Nowadays, demand for the stretchable electronic circuit (SEC) innovative technology is promising in various industries such as biology, advanced robotics, and defense due to their ability to endure enormous amounts of energy and have a wide range of tensile capabilities. However, reliable data regarding mechanical characteristics are still sparse due to the percolation nature of the material, which requires its fillers to be connected to one another at all times in order to conduct electricity. To address these issues, the present work opted a finite element analysis (FEA) model that will depict the behaviour of plastic strain on a variety of stretchy conductive ink designs. SEC ink models were created using CAD modeling software and loaded into ANSYS software for finite element analysis (FEA). Behaviors of six different SEC patterns under various longitudinal and lateral stretching conditions were analyzed using the equivalent plastic strain level possessed. Another perspective of the study was to evaluate the impact of expanding the width and thickness of the ink pattern toward the development of the equivalent plastic strain. The result shows that the U-shape SEC pattern had the lowest equivalent plastic strain, with ε_p= 0.033611 for the longitudinal load and ε_p= 0.014648 for the lateral load.

1. Introduction

Stretchable Electronic Circuit (SEC) technology is a substitute for rigid electronic circuit technology that has been enhanced to be bendable, twistable, and stretchable for a variety of applications. It implements Stretchable Conductive Ink (SCI) which is an ink that provides electrical conduction [1]. Today, demand for this novel technology of stretchy electronics has been steadily increasing in fields such as biology, sophisticated robotics, wearable electronics, and the military [2].

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Wearable electronic systems are currently having a favorable effect on several elements of daily life, contributing to economic activity and the rapid expansion of stretchable electronic devices and related manufacturing applications [3].

The most challenging problem is that the entire electronic structure must be bendable and stretchable. This motivates researchers to develop stretchable electronic circuits that meet both mechanical stretchability and electrical conductivity standards in order to assist others. As a result, the combination of numerous variants of insulating elastomers such as natural rubber, styrene-butadiene rubber, ethylene-propylene-diene monomer, polyurethane, thermoplastic polyurethane (TPU), and predominant polydimethylsiloxane (PDMS) as two circuits such as Ag, Cu, and Ag-PDMS was tested in order to create the optimize SEC.

To further improve the stretchability of the SEC, different approaches, including as wavy structure configuration, island-interconnect configuration, mesh structure, fractal design strategy, origami, and kirigami structural configurations, are applied to produce structure design strategies [4]. Another challenge in constructing stretchable electronic devices is patterning flexible conductors, which is particularly challenging when direct printing is used. Stretchable conductors have been proven in recent investigations, culminating in the development of more complex and sophisticated stretchable electronic devices [5].

The stretchability of the substrate and conductor is governed by two parameters: stretchable material and stretchable structure, according to the earlier study. TPU, which is one of the flexible and stretchable substrates, is widely used in tribological applications such as conveyor belts [6], tires [7], pulleys, and bushings as a result of its superior wear resistance and mechanical properties resulting from the physical cross-linking provided by the hard crystalline parts. Due to their rubber-like elasticity, superior tear strength, high elasticity [8], high transparency, and resistance to oil and grease, TPUs display promising performance in a range of applications. Shoe soles, cables [9], artificial tissues and organs [10], biofuels, non-flammable items, packaging films [11], and shape memory materials are some of the uses for TPU elastomer [12]. The stretchability of the SEC based on the build-up of plastic strain was confirmed by adjusting the breadth and thickness of conductive ink and by varying the ink pattern. The horseshoe form was identified as one of several patterns investigated to minimize plastic strain [6]. Additionally, substrate configurations were evaluated, and a sandwich system of substrate material covering the whole conductor was proposed to increase the conductor's failure limits.

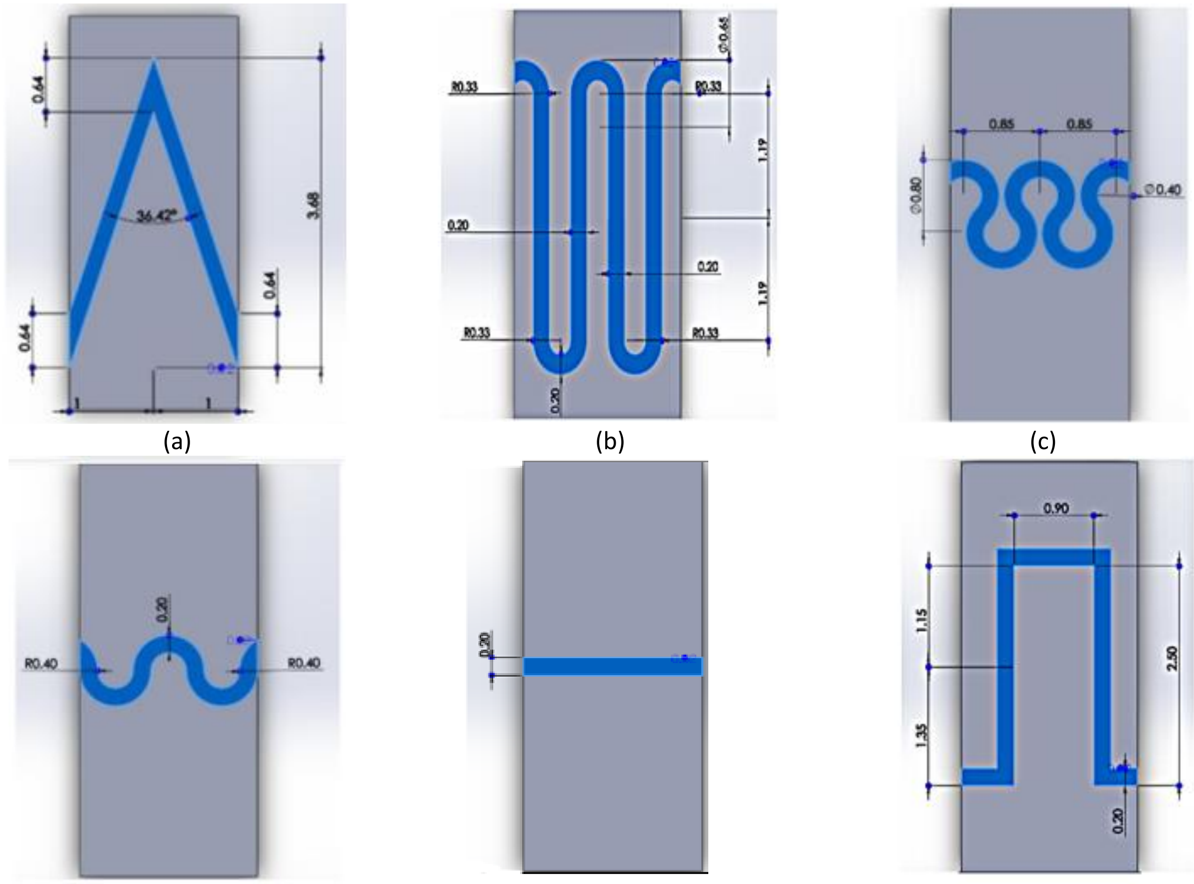
The examination of SEC dependability was difficult due to its stretchability and connectivity's long-term performance. For example, sensor heartbeat monitoring needs up to 3% stretch on an arm or leg hundreds of times every day. The sensor's lifetime must be extended to benefit the user's consumption when using the SEC gadget [7,8]. Wearability is likely to be influenced by stretching cycles, depending on the use. Thus, in this paper, the main objective was to evaluate the stretchability of different ink patterns when subjected to longitudinal and lateral loading. This was done based on the evaluation of the amount of equivalent plastic strain of each design. Another aim was to evaluate the effect of varying width and thickness of the patterns on their respective stretchability.

2. Methodology

This section discussed the methods that were employed to complete this project. The plastic strain behavior of different ink patterns was simulated and calculated using finite element analysis. This job was carried out using ANSYS software, and the findings were compared to those received from the reviewed article. The application of the software in simulating engineering problems was extensively done by Basri *et al.,* [13] and Zakaria *et al.,* [14]. SOLIDWORKS software will be used to create a 3D model of the SEC and several conductive ink patterns.

2.1 Dimension of the Different SEC Patterns

In this subsection, six different models of SEC were modeled based on an article reviewed by Aziz *et al*., [2] and Norhidayah *et al.,* [15]. The construction of the SEC models comprised of both conductive copper ink and TPU substrate was designed by utilizing SOLIDWORKS. All the details of the geometry for the six different SEC models are shown in Figure 1. The unit for the geometry construction of each model was adjusted to be in millimeters (mm). The designed models from SOLIDWORKS were further imported into ANSYS software for the finite element analysis.



(a) (b) (c)

(d) (e) (f)

Fig. 1. Design and dimension of modelled conductive ink pattern of (a) zigzag (b) U-shape (c) horseshoe 45° (d) horseshoe 0° (e) straight (d) rectangular

2.2 Material Properties

Outputs of the simulation from the finite element analysis method heavily rely on the input parameters. One of the input parameters is the material properties of the implemented materials. Among the materials used as conductive ink in SEC applications are graphene [16], silver [17], and copper [18,19]. Both thermoplastic-urethane (TPU) substrate and copper conductive ink utilized within this research is adapted from Kim *et al.,* [20]. The material properties are tabulated in Table 1. Although copper possesses a high oxidation rate at high-temperature elevation, it remains the top selection when it comes to circuitry interconnection due to its relatively lower cost, higher mechanical stability, and exceptional electrical and thermal conductivity over the likes of Gold (Au); Nickel (Ni) and Aluminium (Al) [21]. The materials' elastic and plastic mechanical properties were tabulated as per Table 1. The copper material's yield strength and tangent hardening modulus were 100 MPa and 1.12 GPa, respectively. The high stretchability property of the TPU makes it suitable to be adapted as the substrate for stretchable applications [17]. The simulation model was evaluated as isotropic material with a bilinear hardening.

Table 1
Material properties of TPU and copper used in simulation

Material Properties	Materials	
	TPU	Copper
Density (kgm^{-3})	1.11×10^3	8.93×10^3
Young's Modulus (Pa)	8.5×10^6	1.17×10^6
Poisson's Ratio	0.46	0.343
Bulk Modulus	35.58×10^6	1.242×10^{11}
Shear Modulus	2.9247×10^6	4.3559×10^6
Yield Strength (Pa)	-	100×10^6
Tangent Modulus (Pa)	-	1.12×10^9

2.3 Boundary Conditions of the Model

For longitudinal load, one of the ends of the zigzag copper SEC was designated as fixed support, while remote displacement was applied at the other lateral end. The region of the applied fixed support was represented by the "A" mark, while the region of the applied remote displacement was denoted by the "B" mark, as shown in Figure 2.

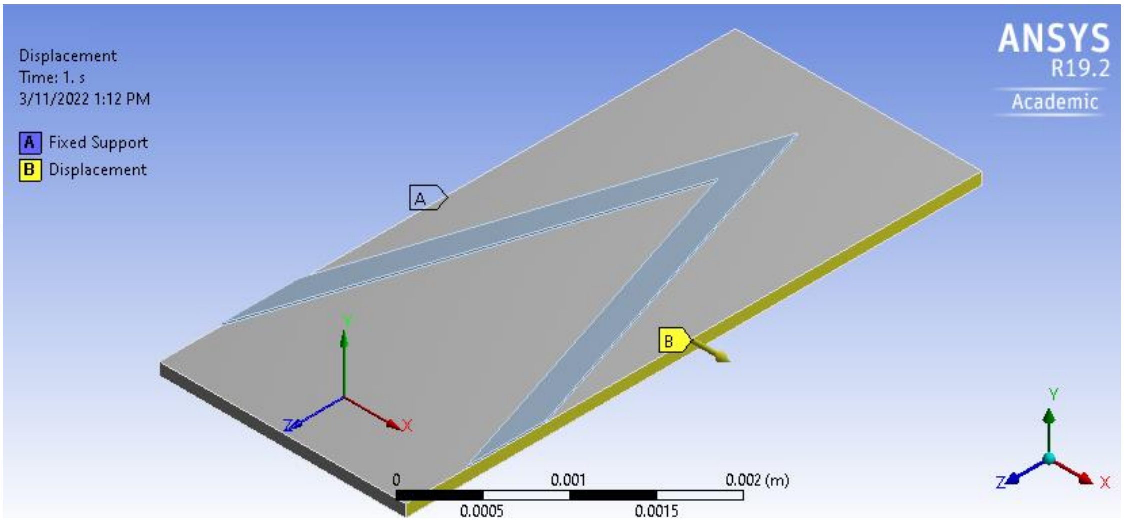


Fig. 2. The setup of the boundary condition for the SEC

The displacement of 10% from the length of the model was applied to investigate the effect of the applied displacement towards the development of equivalent plastic strain on the zigzag model. For lateral loading of the model, a similar setting for displacement was used based on the longitudinal loading, with small changes implemented where the boundary conditions for the applied loading were relocated. In this case, the fixed support denoted as the "A" mark, was pinpointed on the top side of the model, while the applied loading, represented as the “B” mark, was located at the bottom side of the model.

2.4 Simulation of Equivalent Plastic Strain of the SEC

A simulation of the SEC based on the applied remote displacement was conducted based on the input parameters inserted from the material properties section. In the case of this study, the desired output parameter from the simulation of the models was their equivalent plastic strain values. This is because the strain value is crucial for fatigue life prediction [22,23]. Predicting the fatigue life during mechanical loadings is essential to determine the stretchability of the SEC. All the models of different patterns were subjected to an elongation of 10% in both x- and y-axes. Apart from analyzing the effect of the varying shape of patterns, the width and thickness of the optimum conductive ink pattern were increased to study further the effect of the varying parameters towards the development of plastic strain within the pattern.

On the other hand, detecting the crack propagation of the ink pattern under applied load is necessary since more cracks will distort the capability of the ink to conduct electrical charges. Hypothetically, the SEC pattern exhibiting the lowest equivalent plastic strain is assumed to be the best pattern in terms of stretchability when subjected to the same load.

3. Results and Discussion

In this section, all six different patterns of SEC were simulated to obtain their respective maximum equivalent plastic strain developed within the ink. All the simulation processes were conducted by running them utilizing ANSYS software. It was found that different SEC patterns exhibited a different plastic strain values. Both radius of curvature and the width of the SEC ink patterns were varied to study the reaction of the pattern toward the load applied.

3.1 FEA Results of Equivalent Plastic Strain on Different Ink Pattern

The FEA results of the elastic-plastic strain simulation for all different patterns generated were tabulated within Figure 3. This indicates the stretchability of numerous SEC patterns of stretchable copper conductive ink bonded on top of the TPU substrate.

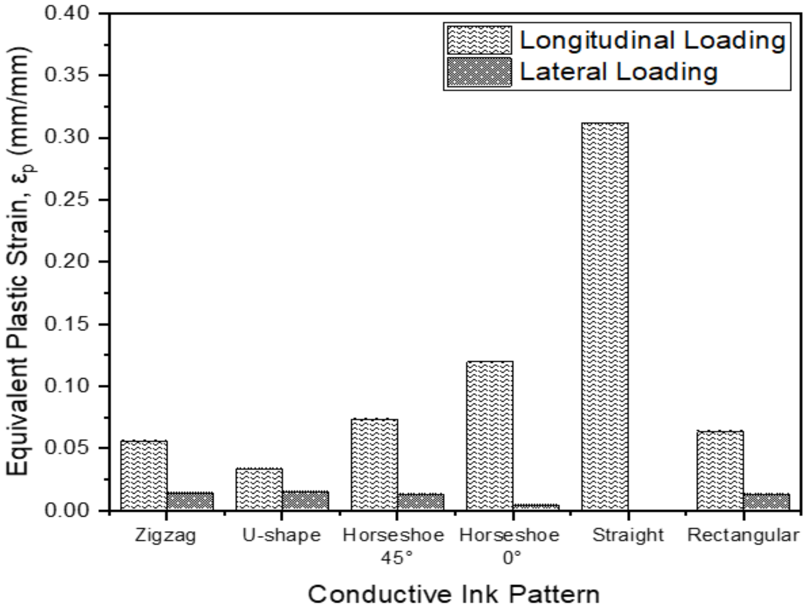


Fig. 3. FEA results of equivalent plastic strain for different patterns subjected to longitudinal and lateral loading

The detail of the visual contours presented in Figure 4 (zigzag pattern), Figure 5 (U-shape pattern), Figure 6 (horseshoe 45° pattern), Figure 7 (horseshoe 0° pattern), Figure 8 (straight pattern) and Figure 9 (rectangular pattern) were generated through static structural analysis. All six different SEC patterns were subjected to longitudinal and lateral loading, and the development of the equivalent plastic strain was observed.

(a) (b)

Fig. 4. Simulation of equivalent plastic strain (mm/mm) for zigzag pattern subjected to (a) longitudinal (ε_p = 0.056022) (b) lateral loading (ε_p = 0.013981)

(a) (b)

Fig. 5. Simulation of equivalent plastic strain (mm/mm) for U-shape pattern subjected to (a) longitudinal (ε_p = 0.033611) (b) lateral loading (ε_p = 0.014648)

(a) (b)

Fig. 6. Simulation of equivalent plastic strain (mm/mm) for horseshoe 45° pattern subjected to (a) longitudinal (ε_p = 0.073432) (b) lateral loading (ε_p = 0.012903)

(a) (b)

Fig. 7. Simulation of equivalent plastic strain (mm/mm) for horseshoe 0° pattern subjected to (a) longitudinal (ε_p = 0.119610) (b) lateral loading (ε_p = 0.0038882)

(a) (b)

Fig. 8. Simulation of equivalent plastic strain (mm/mm) for straight pattern subjected to (a) longitudinal (ε_p = 0.311840) (b) lateral loading (ε_p = 0.000000)

(a) (b)

Fig. 9. Simulation of equivalent plastic strain (mm/mm) for rectangular pattern subjected to (a) longitudinal (ε_p = 0.063310) (b) lateral loading (ε_p = 0.013366)

Based on the tabulated results, for longitudinal loading of the model, the U-shape SEC pattern possessed the lowest equivalent plastic strain at ε_p = 0.033611. On the other hand, the straight pattern exhibited the highest strain value at ε_p = 0.311840. It was observed that the value of the equivalent plastic strain for the highest value recorded increased by approximately 827% compared to the lowest value, which is relatively very high. It can be said that the meandering shape of the SEC pattern is effective in the reduction of the equivalent plastic strain. The U-shape pattern possessed relatively much lower equivalent plastic strain values than the others. In contrast, the straight pattern boasted the highest strain value, with an increment of 160.714%, compared to the pattern of horseshoe 0°, which exhibited the second highest equivalent plastic strain. It can be seen that when subjected to longitudinal load, the reliability of the SEC conductive ink pattern can be ranked as U-shape > Zigzag > Rectangular > Horseshoe 45° > Horseshoe 0° > Straight.

In the case of lateral loading, an opposite scenario was observed. Unlike longitudinal loading, the U-shape pattern showcased the highest equivalent plastic strain under the subjection of the lateral loading with the value of ε_p = 0.014648. The straight SEC pattern remained elastic when subjected to the displacement of 10% at the lateral direction and exhibited no equivalent plastic strain in the designated direction (ε_p = 0). The straight pattern showcased the lowest maximum value of equivalent plastic strain at 0%, while U-shape showed the highest maximum value at 1.4648%, which is opposite to that from longitudinal loading in terms of the reliability of the conductive ink. At 0% equivalent plastic strain, the straight pattern remained elastic under this loading condition and was the only ink pattern to do so. Under 10% deformation resulting from lateral loading, the reliability of the pattern can be ranked as: Straight > Horseshoes 0° > Horseshoes 45° > Rectangular > Zigzag > U-shape.

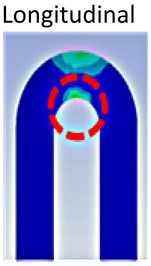
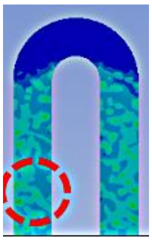
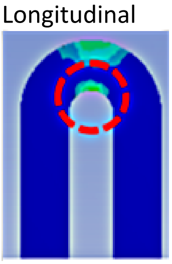
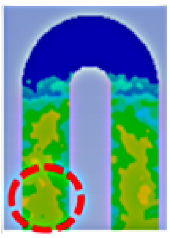
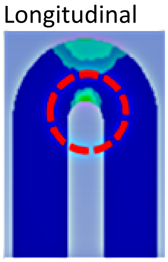
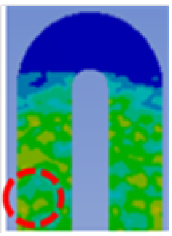
The maximum value of equivalent plastic strain developed within each conductive ink pattern under lateral loading was much lower than that obtained from the longitudinal loading. Due to the relatively much lower equivalent plastic strain exhibited by all patterns under the lateral loading compared to longitudinal loading, the results from lateral loading were assumed to be less significant than those obtained from longitudinal loading.

Based on Lee *et al.,* [18], the lower the value of equivalent plastic strain for a model, the greater the potential for crack propagation and stretch cycle failure of the conductive ink. The results demonstrates that the U-shape yields the significantly lowest equivalent plastic strain for longitudinal loads and is not much different for the lateral load. The U-shaped conductive ink pattern provided the best elongation of 10 percent for stretchable and flexible electrical circuits.

3.2 Effect of Varying Width of Conductive Ink

This subsection evaluated the effect of different widths of conductive ink. The U-shape pattern was chosen for this study as this pattern presented the lowest maximum value of equivalent plastic strain from longitudinal loading. This made the U-shape pattern more reliable in stretchability than the other patterns. The effect of 10% width increment (maximum of 20% increment) on the equivalent plastic strain of the U-shape pattern was evaluated and tabulated in Table 2. Generally, the equivalent plastic strain decreased with the increment of width for lateral loading, while for longitudinal loading, the pattern of the strain value was unclear and random.

Table 2
Effect of different widths of ink on FEA simulation of equivalent plastic strain

Type of design					
U-shape (internal width)		U-shape (10% width increase)		U-shape (20% width increase)	
Equivalent Plastic Strain (mm/mm)					
Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral
					
ε_p = 0.033611	ε_p = 0.014648	ε_p = 0.029670	ε_p = 0.0098245	ε_p = 0.031287	ε_p = 0.0084582

For the benchmark, the 0.2 mm initial width of the conductive ink, which resulted in ε_p = 0.033611 for longitudinal loading and ε_p = 0.0014648 for lateral loading, was used. Figure 10 compares the simulated equivalent plastic strain between longitudinal and lateral loading for different U-shape conductive ink pattern widths. A significant downtrend was observed for the simulated strain from longitudinal to lateral loading. This further cemented the influence of width on the development of the equivalent plastic strain. The increment of the conductive ink's width was reduced by reducing the equivalent plastic strain and consequently prolonged the fatigue life of the stretchable electronic circuit while employing the U-shape pattern as a conductive ink.

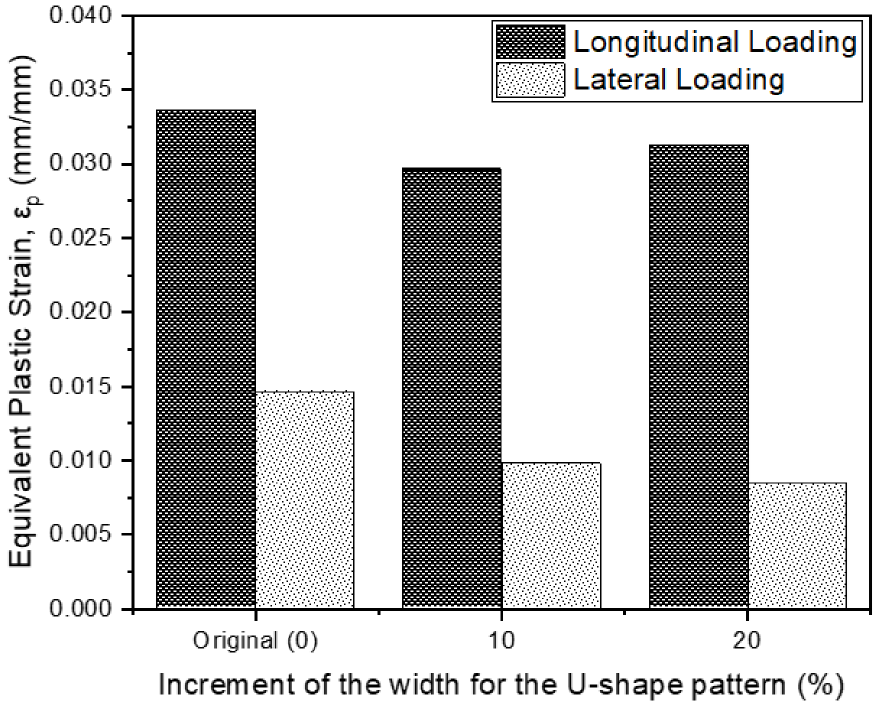
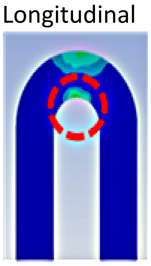
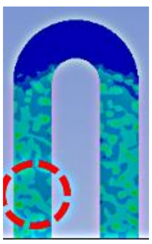
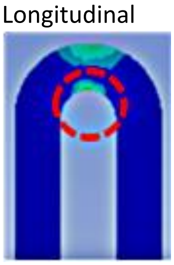
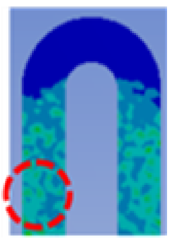
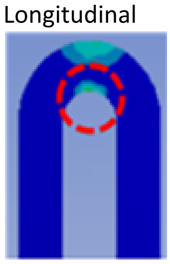
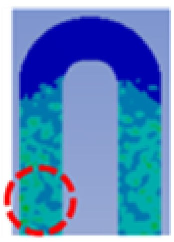


Fig. 10. Comparison of the FEA results of equivalent plastic strain at three different widths of the U-shape ink pattern

3.3 Effect of Varying Thickness of Conductive Ink

Table 3 tabulated the equivalent plastic strain for the U-shape pattern under applied longitudinal and lateral loading. The same procedure from the study for the effect of width was implemented, where three thickness increments of the conductive ink (0%, 10%, and 20%) were varied.

Table 3
Effect of different thicknesses of ink on FEA simulation of equivalent plastic strain

Type of design					
U-shape (internal width)		U-shape (10% thickness increase)		U-shape (20% thickness increase)	
Equivalent Plastic Strain (mm/mm)					
Longitudinal	Lateral	Longitudinal	Lateral	Longitudinal	Lateral
					
ε_p = 0.033611	ε_p = 0.014648	ε_p = 0.033134	ε_p = 0.0121468	ε_p = 0.033845	ε_p = 0.0129470

The results of equivalent plastic strain for the pattern at different thicknesses were evaluated. Figure 11 depicts a graph to aid the comparison of the impact of three different thicknesses during the loadings.

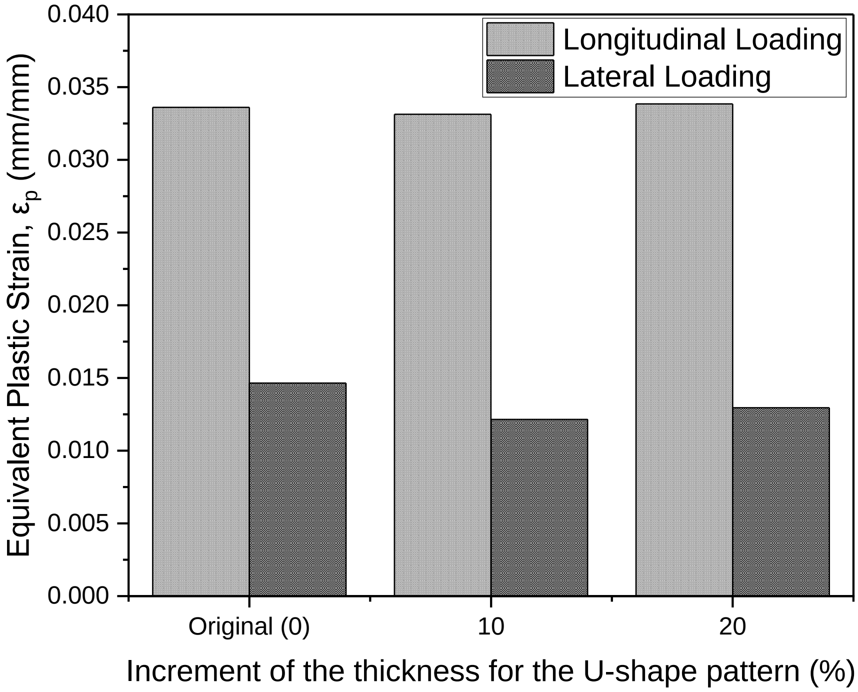


Fig. 11. The impact of increment of the thickness for the U-shape pattern (%) onto the development of the equivalent plastic strain

The development of the equivalent plastic strain through the thickening of the conductive ink was simulated. The original thickness of the U-shape conductive ink was 0.018 mm resulting in a similar equivalent plastic strain at both longitudinal and lateral loading as its initial width design. Under the subjection of both longitudinal and lateral loading, varying thickness does not seem to have a significant, direct impact on the development of equivalent plastic strain, as the maximum strain values seemed to fluctuate for the three different thicknesses. However, for each scrutinized individual thickness, longitudinal loading produced a higher equivalent plastic strain when directly compared to lateral loading by a compelling margin. Thus, in the light of this evidence, it was indecisive whether the variation of thickness contributed to the reduction of the equivalent plastic strain of the pattern. From the results shown, variation of thicknesses does not significantly impact the development of the equivalent plastic strain as no clear increment/decrement trend was observed.

4. Conclusions

In summary, a research study utilizing the FEA method by ANSYS has been done to investigate the stretchability of various design patterns of the ink conductor through the evaluation of the growing equivalent plastic strain within each pattern. Apart from that, the effect of varying the width and thickness of the copper conductor towards the development of equivalent plastic strain was scrutinized. In the study, six different conductive patterns were studied, and the maximum value of the equivalent plastic strain possessed by each pattern subjected to longitudinal and lateral loading was relatively compared. The results obtained through the simulation showed that the lateral loading did not contribute to a large deviation of plastic strain among the different designs of ink patterns compared to when they were subjected to longitudinal loading. As for the longitudinal loading, varying the shape of the ink conductor significantly impacted the development of the plastic strain, where theoretically, the conductor possessing the higher plastic strain exhibited a lower stretchability. From the study, the U-shape conductive ink pattern was chosen as the best design pattern due to its lowest maximum plastic strain value. On the other hand, the straight pattern, which was the standard pattern, suffered the highest maximum equivalent plastic strain. It was also observed that the increment of the width of the conductive pattern visibly contributed to a lower plastic strain, while the variation of thickness had a minimal impact on the build-up of the plastic strain value. Hence, it can be concluded that the reliability of the ink pattern subjected to 10% displacement load can be ranked as U-shape > Zigzag > Rectangular > Horseshoe 45° > Horseshoe 0° > Straight.

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