Study on the compressive behavior of Miura origami column structure

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Abstract. Miura-origami pattern has taken interest of many engineers and mathematicians due to its unique foldability and wide range of engineering applications. However, its mechanical behavior is yet to be fully explored, especially when it is made by additive manufacturing (3D printing) method. In this paper, the compressive behavior of 3D printed column structure using the Miura-origami pattern is investigated. Polylactic Acid (PLA) material was used to make the specimen with various printing parameters, i.e. infill pattern and density. Moreover, six kind of origami patterns with different folding angle and wall thicknesses were tested. Finally, the elastic and plastic deformation behavior under compressive load is examined. The result is useful to develop a finite element model which can be utilized to comprehensively explore the mechanical behavior under complicated loading condition. In addition, this study is expected to give impact on developing an innovative engineering design by the use of Miura-Ori pattern, for example is on designing an energy absorption device such as prosthetic leg and automotive crash box.

1. Introduction
Origami is an ancient Japanese art associated with paper folding patterns that can be designed into a variety of shapes. In recent years, many types of origami folding patterns have been developed, and there has been a surging amount of research about its potential for the engineering applications. One of the most interesting types of origami patterns is Miura origami (Miura-Ori) pattern. It consists of repeating parallelograms panels arranged along the mountain and valley creases. Due to its unique folding pattern, Miura-Ori pattern can give an interesting mechanical properties and behaviors to the structure [1].

In recent years, the engineers and researchers have utilized Miura-Ori fold in some engineering applications such as in the 1996 Space Flyer Unit- solar arrays panel [2], artificial muscles [3], and modular robots [4]. Moreover, the application of origami structure as an energy absorption device for e.g. automotive crash box has been studied in some literatures [5, 6]. Yet, the mechanical behavior of Miura-Ori structure under compressive load is not fully understood yet.

To address this issue, this research provides an investigation on the mechanical properties of a Miura-Ori column structure, in which the specimen is made of Polylactic Acid (PLA) material and manufactured using 3D printing method. The folding angle and wall thickness are the two parameter variations that were applied in the design. Finally, the effect of the angle and thickness variation on the
energy absorption capacity of the structure were investigated. The result can be useful for the development of Finite Element Model (FEM) in order to predict the behavior of Miura-Ori column structure with various condition and determine whether it is feasible to be used as an energy absorption device [7]. In addition, it can also be utilized as a tool for engineering education [8].

2. Research methodology

2.1. Origami column structure
The Miura-Ori pattern is constructed with four repeating parallelograms panels which are arranged along the alternating mountain and valley folds as shown in figure 1. The size of each parallelogram for all specimens were kept constant where \( b = 11 \text{ mm} \) and \( c = 8.66 \text{ mm} \). In this study, the Miura origami column was designed with three folding angle variation (\( \theta = 70^\circ, 90^\circ, 110^\circ \)) and two thickness variation (\( t = 1 \text{ mm} \) and \( 2 \text{ mm} \)). Figures 2a and 2b show the Miura-Ori column model.

![Figure 1. The unit cell of Miura-Ori pattern.](image1)

![Figure 2. Front (a) and isometric (b) view of Miura-Ori column structure.](image2)

The column structure specimens consist of 3 layers, and the height \( h \) depend on the angle variation \( \theta \), the width \( w \) depends on the thickness \( t \) of each parallelogram, while the lid thickness \( d \) was kept constant at 0.8 mm. The specimen dimension parameters are tabulated in table 1.

2.2. Compression test
Compression test was done in order to record the load and displacement curve using a Test Resource 313 Universal Testing Machine with a speed of 1.3 mm/min referring to ASTM D695. The specimens were greased in order to avoid shear stress between the specimen’s surface with the top and bottom compression platens.
Table 1. Specimen dimension.

| Angle (θ) | Thickness (t) | Width (w) | Height (h) | Cross Sectional Area | Specimen Code |
|-----------|---------------|-----------|------------|----------------------|---------------|
| 70°       | 1 mm          | 43.15 mm  | 31.42 mm   | 336.8 mm²            | M701          |
|           | 2 mm          | 47.22 mm  |            | 694.9 mm²            | M702          |
| 90°       | 1 mm          | 48.8 mm   | 38.35 mm   | 270.8 mm²            | M901          |
|           | 2 mm          | 51.06 mm  |            | 545.2 mm²            | M902          |
| 110°      | 1 mm          | 61.85 mm  | 41.17 mm   | 237.8 mm²            | M1101         |
|           | 2 mm          | 64.99 mm  |            | 480.24 mm²           | M1102         |

For the control settings, the local overload was set differently depending on the structure’s thickness. Local overload is determined as the maximum compressive load that can be applied by the machine, which means that the compression test will immediately stop whenever the local overload is attained. The schematic picture of the compression test is shown in figure 3. The load and displacement data from the testing machine are sent in a form of electrical signal into the DAQ system and then recorded in a computer. The control parameters are shown in Table 2. The corresponding stress was calculated by dividing the load with the initial cross-sectional area of the specimens, while the strain can be calculated by dividing the displacement with the initial height (h) of the specimen.

![Figure 3. Schematic diagram of compression test.](image)

Table 2. XY software control settings.

| Thickness | Control Rate | Local Overload | Logging Rate |
|-----------|--------------|----------------|--------------|
| 1 mm      | 1.3 mm/min   | 10 kN          | 10/second    |
| 2 mm      | 1.3 mm/min   | 20 kN          | 10/second    |
3. Result and discussion

3.1. Strain stress curve
The load vs. displacement data from 3 set of experiments are plotted in figure 4. The determination of mechanical properties such as the yield (peak) strength, compressive modulus, and energy absorptivity were analyzed. The yield strength was obtained by projecting a tangent line with the same slope as the linear region from the stress-strain curve at 0.2% offset strain [9]. The yield point is determined at the intersection point between this linear line and the original curve. Meanwhile, the compressive modulus was obtained by taking the slope at the elastic region from 0.004 strain to 0.006 strain [10]. Finally, the energy absorption capacity was measured by calculating the area under the stress-strain curve.

![Figure 4. Stress-strain curves of Miura-Ori column with 2 mm thickness.](image)

From the stress and strain curves, we can evaluate the effect of angle variation briefly on the mechanical properties. The M1102 specimen has the highest peak stress which is about 23.6 MPa while the M702 has the lowest peak which is about 10.8 MPa. The peak stress is increasing as the angle variation increased. The study by Yang [1] stated that the initial peak force is useful to determine the maximum support force of the tube without failure deformations. Thus, it can be implied that by increasing the folding angle of Miura-Ori pattern, the column structure will be able to withstand more compressive force without failure to occur.

In order to calculate the area under the curve, the length of plateau stress must be determined. Plateau stress is defined as the average value of compression stresses from 0.2 - 0.3 compression strain [11]. From figure 4, it shows that the M1102 has the lowest plateau stress compared to M702 and M902. It can be analyzed that wider folding angle gives lower plateau stress behavior on the structure.

The determination of the plateau stress is important since it is closely related to the energy absorptivity of the structures. According to Ma and Yao [5], an ideal energy absorption must have a low peak force in order that no excessive force is transmitted to the main structure. Besides, it also needs to have high mean crushing force or high plateau stress in order to dissipate as much energy as possible.

3.2. Angle variation vs. mechanical properties
The average values and the standard deviation of yield strength (peak stress) and compressive modulus are plotted in figure 5. M1102 has the highest mechanical properties among the other angle variation, in which the yield strength of M1102 is about 23.6 MPa and the compressive modulus is about 944.7 MPa. As the folding angle variation decreased, the yield strength and the compressive modulus tend to
decrease. In addition, the structure with \( t = 2 \) mm exhibits higher mechanical properties compared to \( t = 1 \) mm. For example, the yield strength of M1102 is about 23 MPa, while the by M1101 is only about 12 MPa, and this is approximately half the yield strength of M1102. Therefore, we can imply as \( t \) and \( \theta \) are increased, the Miura-ori column structure exhibits higher yield strength and compressive modulus.

**Figure 5.** Yield strength (a) and compressive modulus (b) vs. angle variation.

3.3. *Angle variation and energy absorptivity*

The energy absorptivity was determined by calculating the area under the stress-strain curve of Miura-Ori column structure with 2 mm thickness. Figure 6 shows that the M702 has the highest energy absorption capacity 8000 J/m\(^3\), followed by M902 with 7800 J/m\(^3\), and M1102 which only exhibits 4000 J/m\(^3\). It can be implied that the energy absorption capacity of the Miura column structure is decreasing as the angle variation increased. It happened due to the geometry constrain of \( \theta = 110^\circ \) design, where it performs unstable deformation and then suddenly shattered as the compressive load was continuously applied. The previous study by Ma and Yao [5] notified the difficulty in the use of origami patterns as an energy absorption devices lies at the post-buckling stage which is highly non-linear and thus cannot be effectively manipulated by conventional structural design approaches such as variation of cross section profiles [5].

**Figure 6.** Energy absorptivity vs. angle variation.

4. **Conclusion**

In this paper, the mechanical behavior of Miura-origami pattern for 3D printed column structure was investigated under compressive load. As a result, higher mechanical properties, i.e. yield strength and compressive modulus, were obtained with increasing the folding angle of the Miura-Ori pattern. However, due to its geometric constraint, the result showed that the wider folding angle could reduce
the energy absorption capacity of the structure. Finally, the structure with 2 mm wall thickness exhibits higher yield stress, compressive modulus, and energy absorption capacity compared to the 1 mm structure. As a future work, the development of finite element model (FEM) to understand comprehensively the behavior of Miura-Ori column structure will be done.

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