Finite element analysis of Miura origami column under uniaxial compressive load

S C Hidajat¹, I G R Permana¹, M Rismalia¹, Herianto² and F Triawan¹,³,*

¹Department of Mechanical Engineering, Faculty of Engineering and Technology, Sampoerna University, Jakarta, Indonesia
²Department of Mechanical and Industrial Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
³School of Environment and Society, Tokyo Institute of Technology, Tokyo, Japan

*farid.triawan@sampoernauniversity.ac.id

Abstract. This paper presents the finite element analysis (FEA) of 3D printed Miura origami column under uniaxial compressive loading condition. The finite element model (FEM) was developed under elastic-perfectly plastic material model. Investigation on the yield strength and compressive modulus with two varied parameters, i.e. angle and thickness of the Miura origami column was conducted. Abaqus 6.14 software was used to conduct the simulation of compression test. The simulation result is then compared with and examined to the referred experimental data. From the simulation, it was revealed that the results from FEA of Miura-ori column with \( \theta = 90^\circ \) and \( t = 2 \text{ mm} \) showed good agreement with the referred experimental data. However, FEA results mostly overestimates the mechanical properties. This discrepancy could be due to the existence of imperfections and anisotropic material of 3D printed structures.

1. Introduction

Origami, a part of ancient Japanese culture has been a form of art favored by all ages. Despite that, currently this art of paper-folding has caught attention of many engineers and mathematicians. Its unique capability to unfold into a flat sheet and fold into a structure is what makes origami interesting. This means that a complex structure can be unfolded into a flat sheet and can be easily transported. It allows users to pack large structures into small volumes as possible.

Several different types of common origami patterns are Miura-ori pattern, Yoshimura pattern, waterbomb base, and diagonal pattern [1]. Engineers have managed to utilize origami shapes for many applications including packaging [2], artificial muscles [3], modular robots [4], drug delivery [5], optics [6], and many more. Manufacturing methods for origami structures includes machining, 3D printing, folding, casting and forming [3].

The Miura-ori pattern is one of the most interesting patterns for engineers since it has unique mechanical and material properties. It consists of parallelograms arranged into mountain and valley folds. This fold pattern has a negative Poisson’s ratio which means that it will expand in lateral direction while being pulled in uniaxial direction and contract in lateral direction while being compressed in uniaxial direction. The idea that Miura-ori pattern gives new mechanical properties may give an important impact in science and engineering, as well as in the field of education [7].
Until now, there are only few studies on origami structures under uniaxial compressive load [8, 9] and the behavior of Miura-ori column manufactured by 3D printer is not fully understood. In this work, FEM of Miura-ori column under uniaxial compressive load was developed. Compression simulation was done using commercial FEA software Abaqus 6.14. The results were then compared and examined with the referred experimental data by Permana et al. [10]. The values of compressive modulus and yield strength were evaluated.

2. Research methodology

2.1. Compression test

Miura-ori columns with two varied parameters, angle (θ) and thickness (t) were compressed using Test Resource 313 Universal Testing Machine with a speed of 1.3 mm/min. Figures 1a and 1b show the Miura-ori unit cell dimensions and the schematic of Miura-ori column structure, respectively [10]. The combinations of varied parameters analysed are shown in table 1. From the compression tests, the stress-strain curves were obtained and the values of yield strength and compressive modulus were recorded as reported by Permana et al. [10].

![Figure 1. Dimensions of Miura-ori unit cell (a), schematic of Miura-ori column structure (b). Figures are adopted from Permana et al. [10].](image)

![Table 1. Combination of varied parameters of the Miura-ori column.](image)

| Model | Angle (θ) | Thickness (t) |
|-------|-----------|---------------|
| 1     | 70°       | 1 mm          |
| 2     | 90°       | 1 mm          |
| 3     | 110°      | 1 mm          |
| 4     | 70°       | 2 mm          |
| 5     | 90°       | 2 mm          |
| 6     | 110°      | 2 mm          |

2.2. Finite element analysis procedures

FEA was done for the Miura-ori columns with similar parameters with that of the experiment reported by Permana et al. [10]. Material properties for 3D printed PLA investigated by Rismalia et al. [11] served as an input of elastic-perfectly plastic model in the FEA software Abaqus. Values of Young’s modulus and yield strength were 3.6 GPa and 48.2 MPa, respectively. Isotropic material property with shell section and middle surface definition was used. A discrete rigid plate was used as platen where the compressive load was applied. Tie constraint was used with the plate as the master surface and the top face of the Miura-ori column as the slave surface.

There are two boundary conditions applied on the model. Displacement-controlled load with a ramp profile was applied on the reference point of the plate. The center node of the lower surface of the
column was fixed in x-, y-, z- directions and rotations, while other nodes were constrained in only z-direction and x-, y-, z- rotations in order to prevent rigid body motion. Figure 2 shows the applied configuration of boundary conditions. Both the top plate and Miura-ori column were assigned shell quad elements with reduced integration (S4R). Mesh verification was done by varying the approximate global mesh size of the Miura-ori column by 1, 0.5, and 0.2. It was decided that the top plate and Miura-ori column were meshed with an approximate global size of 7 and 0.5, respectively since further decrease in mesh size resulted in negligible increase in accuracy. Analyses were conducted using general-static procedure.

![Figure 2](image-url)

**Figure 2.** Displacement-controlled load and lower surface fixed in x-, y- and z- directions expressed by $u_x$, $u_y$ and $u_z$.

### 3. Results and discussion

#### 3.1. Finite element model validation

Compression test simulations for Miura-ori columns with different varied parameters are compared with that of the experiments. The stress was obtained by dividing the reaction force on the plate by the original cross-sectional area of the column. While the strain was defined as the z-direction displacement divided by the initial height of the column. It is seen that the stress-strain curve of the Miura-ori column with $\theta = 90^\circ$ and $t = 2$ mm from FEA exhibited good agreement with the experiment as shown in figure 3. Values of yield strength and compressive modulus for this structure obtained from FEA is comparable enough with that of the experiment.

![Figure 3](image-url)

**Figure 3.** Stress-strain curve of Miura-ori column with $\theta = 90^\circ$ and $t = 2$ mm.
3.2. Discrepancy in yield strength and compressive modulus

Figure 4 shows the values of yield strength and compressive modulus for all angles and thicknesses. For columns with $t = 1$ mm, both the yield strength and compressive modulus recorded in FEA is higher than that of the experiment. Highest discrepancy between mechanical properties from FEA and experiment occurs in the Miura-ori column with $\theta = 90^\circ$. While for columns with $t = 2$ mm, the highest discrepancy of yield strength and compressive modulus occurs in the Miura-ori column with $\theta = 70^\circ$ and $\theta = 110^\circ$, respectively. Generally, mechanical properties recorded in FEA is higher than in the experiment.

The discrepancy occurs because 3D printed structures contain imperfections. 3D printed Miura-ori structures, especially in the region of abrupt angle change will cause imperfections since the extruder deposits the filament with different distance from the adjacent layers, thus causing less reliable adhesion between layers. While in FEA the model was ideally continuous, where the regions of the structure are perfectly connected with each other. Another cause of discrepancy is 3D printed structures’ mechanical properties are affected by its printing orientation [12]. Printing the structure in one direction and in another direction causes an increase/decrease in mechanical properties. On the other hand, FEA model had isotropic material properties where the material properties are independent of direction. Figure 5 shows the stress distribution of Miura-ori column structure obtained from FEA. The red contours show the location of stress concentration, thus the location of failure. As investigated by Zhang et al. [13], it is confirmed that large plastic strains are localized along the junctions between the facets. Further analysis by mathematical and numerical approaches to clarify the relationship between the mechanical properties and structure’s local deformation behavior is needed [14 - 16].

![Figure 4](image-url)

**Figure 4.** Mechanical property values with respect to angle. (a) and (c) are values of yield strength for $t = 1$ mm and $t = 2$ mm, respectively. (b) and (d) are values of compressive modulus for $t = 1$ mm and $t = 2$ mm, respectively.
**Figure 5.** Stress distribution in FEA on front (a), side (b), and back (c) of column.

4. Conclusion
Compressive behaviour of Miura-ori column under uniaxial compressive load was investigated by FEA. The goal is to create a valid model of Miura-ori column manufactured by 3D printing. Based on the results, the mechanical properties, i.e. yield strength and compressive modulus, of Miura-ori columns were mostly overestimated by FEA compared to that of experimental. This seems due to imperfections and printing orientation that influences the mechanical properties of 3D printed structures. Thus, the inclusion of imperfections and anisotropic material properties for FEM is suggested for further study.

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