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Mechanical Properties of Gerbera Stem Inspired Dodecagonal Structures

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Abstract
In recent years, bio-inspired graded structures have demonstrated remarkable potential in enhancing mechanical properties across different engineering applications. While unidirectional gradient architectures have been widely studied, the potential of dual-gradient designs in geometrical configurations beyond hexagonal or tetrakaidecahedron topologies remains unexplored. To address this gap, this research investigates the mechanical behavior of dodecagonal structures inspired by the dual-gradient architecture which is found in the stem of the Gerbera plant. The dodecagonal lattice structures were designed in both uniform and dual gradient configurations. The designed structures were manufactured from PLA+ material using FDM (fused deposition modeling) based 3d printing technology. Quasi-static compression tests were performed on the manufactured specimens to evaluate their elastic, plastic and energy absorption behaviors. The deformation responses were also analyzed to investigate the effects of the topology of the structures on their mechanical properties. The results indicate that the uniform structure exhibits better stiffness and strength compared to dual-gradient structure. However, it shows low energy absorption performance due to its unstable stress-strain response. In contrast, the dual gradient structure exhibits a more stable stress-strain behavior and hence shows improved energy absorption performance. Further analysis reveals that, the topology of the structures governs their collapse process and consequently drives the structures to exhibit a specific set of mechanical properties. The results from this research emphasize the potential of uniform structures in load bearing and dual-gradient structures in energy absorption applications.

Keywords: Gerbera Stem, Biomimetic design, Additive manufacturing, Quasi-static compression, Deformation mechanisms.

1. Introduction
Biomimicry is the practice of getting inspiration from designs, processes or methods existed in nature for developing more efficient and innovative man-made structures [1]. One significant area of interest within this field is the development of nature-inspired mechanical metamaterials. Mechanical metamaterials exhibit superior combination of mechanical properties which make them appealing in numerous sophisticated applications including automotive, aerospace, sports, civil construction, and biomedical equipment [2, 3]. However, manufacturing of these structures was very difficult due to their complex topologies. Fortunately, the recent advancements in additive manufacturing technology have expanded the range of materials and methodologies for manufacturing complex structures [4].

Several studies have explored the mechanical properties of bio-inspired graded structures. For instance, Hamzehei et al. [5] introduced DNA-inspired graded lattices and found that structure with varying cell wall thickness exhibits a 33% higher energy absorption capacity compared to those with constant wall thickness. Similarly, Wei and Xu [6] reported enhanced energy absorption in a graded brick-mud structure. They attributed this improvement to a more uniform stress distribution by the graded design. Zhang et al. [7] developed a nature-inspired graded re-entrant anti-trichiral structure, which exhibited superior stiffness and energy absorption performance. Specifically, they found a 25% increase in energy absorption efficiency of graded structure than its uniform counterpart. Thus, these findings highlight the promising role of bio-inspired gradient structures in improving mechanical performance. However, most of these researches focused on investigating effect of the unidirectional gradients on mechanical properties. In natural structures, gradients are often multidirectional. For instance, Xu et al. [8] observed a dual gradient in the topology of sunflower pith. The gradient is observed in the cell wall thickness and pore size of sunflower pith. Based on this concept, they designed dual gradient hexagonal and elongated

tetrakaidecahedron lattices. These structures exhibit auxetic behavior and enhancement in mechanical properties. Despite these promising results, there remains a gap in the literature regarding the exploration of dual-gradient structures in other geometrical configurations.

In this study, we turn our attention to the Gerbera plant stem which belongs to the same family as the sunflower and exhibits a dual-gradient architecture [9]. We aim to investigate the effects of dual gradient architecture inspired by Gerbera plant stem on the mechanical performance of dodecagonal lattices utilizing structure-property relationship. To achieve this, we have designed and manufactured the uniform and bio-inspired dual gradient dodecagonal structures. Quasi-static compression tests were conducted using a universal testing machine to explore the potentiality of the studied bio-inspired structure. Finally, the mechanical properties included strength, stiffness, and energy absorption performance of the structures have been analyzed to discover their correlations with the topological architecture of the designed structure.

2. Biomimetic design

Spricigo et al. [10] investigated the microstructure of the Gerbera plant stem using a scanning electron microscope (SEM), as illustrated in Fig. 1. It can be observed that the stem is significantly porous. The pore size decreases and wall thickness becomes thinner when moving from the outer to the inner region of the stem, revealing a dual gradient architecture. Inspired by this natural architecture, we have designed both uniform and dual gradient dodecagonal structures using SolidWorks 2024. Table 1 presents the physical and geometrical properties of the designed dodecagonal structures. Figures 2(a-b) and 3(a-b) illustrate the CAD model of the uniform dodecagon and the dual-gradient (DG) dodecagon structures, respectively.

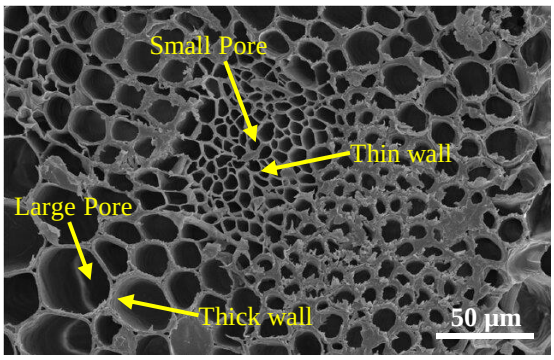


Fig. 1 SEM image of Gerbera plant stem. The variation of pore size and cell wall thickness in the image illustrates the dual gradient architecture of the stem [10].

Table 1. Physical and geometrical properties of the uniform and dual-gradient dodecagonal structures.

Property	Uniform Dodecagon	Dual-Gradient (DG) Dodecagon
Dimensions of CAD models (mm)	60 × 20 × 60	60 × 20 × 60
Diameter of cell (mm)	7.73	Min: 8.00, Max: 9.20
Minimum wall thickness (mm)	1.50	0.90
Mass (grams)	31.41	23.64
Volume of the CAD models (mm^3)	25947.11	21634.85
Surface Area of the CAD models (mm^2)	28602.77	24232.02

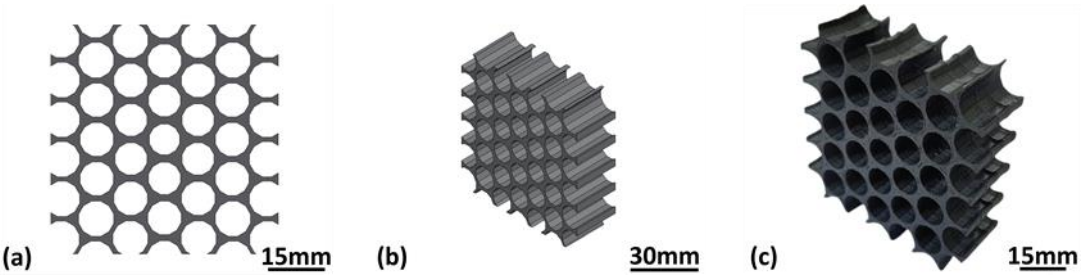


Fig. 2 Dual-gradient (DG) dodecagon (a) Front View (b) Isometric View (c) 3D printed structure.

3. Methodology

Additive Manufacturing

The designed structures were manufactured using a TT-BLUER PLUS, V6 FDM (fused deposition modeling) 3D printer with PLA+ material. The density and Young's modulus of the used PLA+ are 1.24 g/cm³ and 2.6 GPa,

respectively. The settings for additive manufacturing comprised a layer height of 0.1 mm, line infill, and a fill density of 100%. The 3D-printed uniform dodecagon and dual-gradient Dodecagon structures are shown in Figure 2(c) and 3(c), respectively.

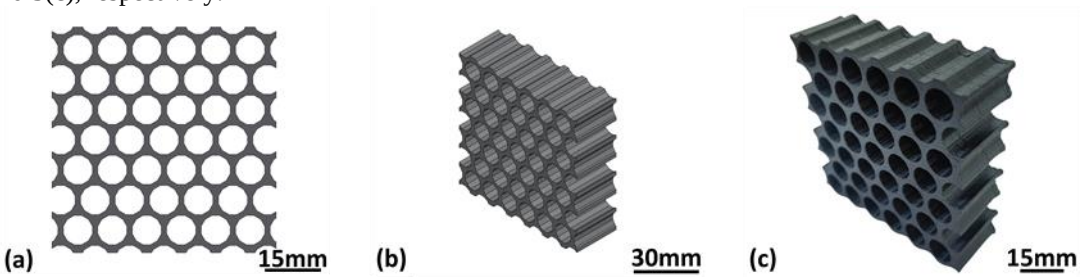


Fig. 3 Uniform dodecagon (a) front view (b) isometric view (c) 3D printed structure.

Mechanical Experiment

Quasi-static compression tests were performed on the manufactured structures using a 1000 kN Shenzhen WANCE Universal Testing Machine to investigate their elastic and plastic and energy absorption properties. The experimental setup is shown in Figure 4. The specimens were placed between loading platens, and the contact surfaces between the samples and the platens were lubricated to reduce the frictional effects. A steady uniaxial compression was applied at a strain rate of 0.001 s^{-1} at ambient temperature. The compression process of the samples was captured using a digital camera to analyze their deformation mechanisms.

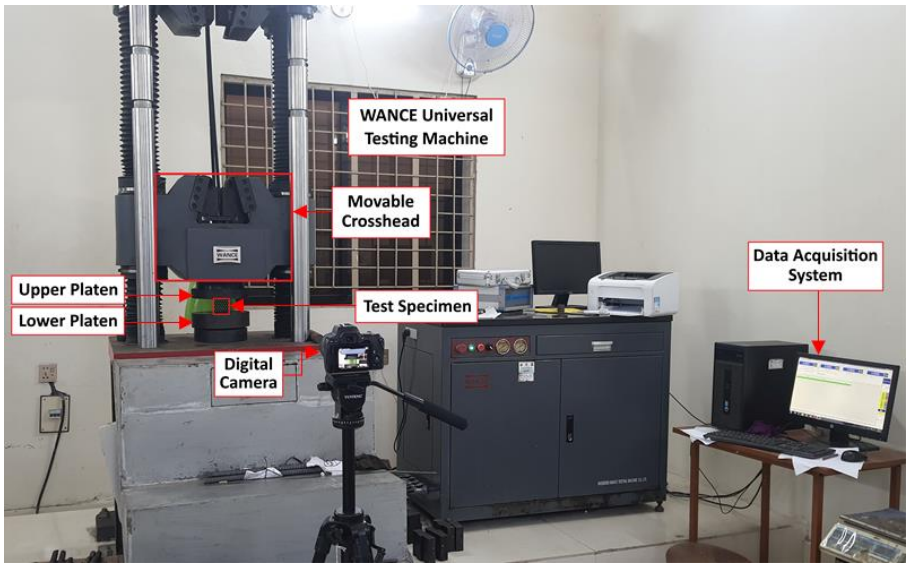


Fig. 4 Experimental setup of quasi static compression test (Shenzhen WANCE Universal Testing Machine, Capacity: 1000 kN).

Evaluation of Energy Absorption Parameters

The energy absorption performance of a structure depends on its deformation response in both elastic and plastic regions. Energy absorption performance depends on some key factors including the initiation of plastic region, nature of stress-strain response in plastic region, and peak stress experienced by the structure before densification [11]. Based upon this factors, two parameters have been considered in this study to evaluate energy absorption performance of the structures:

(i) Specific energy absorption (SEA): The energy absorption capacity, W_{ε_d}, is measured from the area under the individual stress-strain curves up to densification strain, illustrated in Equation 3 [12].

$$W(\varepsilon_d) = \int_0^{\varepsilon_d} \sigma(\varepsilon)\, d\varepsilon \qquad (1)$$

where, ε_d is the densification strain and σ is the corresponding stress value.

The specific energy absorption is the energy absorption capacity normalized by the density of the structures.

$$SEA = \frac{W(\varepsilon_d)}{\rho} \qquad (2)$$

Where, ρ is the density of the structure.

(ii) Energy absorption efficiency (η): It is the ratio of the energy absorption capacity (W_{ε_d}) and the maximum compressive stress before densification (σ_m). This can be calculated from the Equation 5 [12].

$$\eta(\varepsilon_d) = \frac{1}{\sigma_m}\int_0^{\varepsilon_d} \sigma(\varepsilon)\, d\varepsilon \tag{3}$$

5. Result and discussion

Stress-Strain responses

The stress-strain responses of both uniform and dual gradient dodecagon structures are presented in Figure 5. It is observed that the stress-strain responses of both the structures demonstrate a linear elastic region, followed by a long plastic region and eventually transition to the densification. A drop in stress after initial yield can be observed for both the structures, which indicates the initiation of plastic deformation and permanent damage. The uniform dodecagon structure exhibits significant stress fluctuations throughout the plastic region which is possibly due to the formation of multiple shear bands during the collapse process [13]. However, the dual gradient dodecagon structure shows minor stress oscillations initially but maintains a more stable plastic plateau throughout the plastic region. The underlying causes of this discrepancy in stress-strain responses are further analyzed in the following deformation mechanisms section.

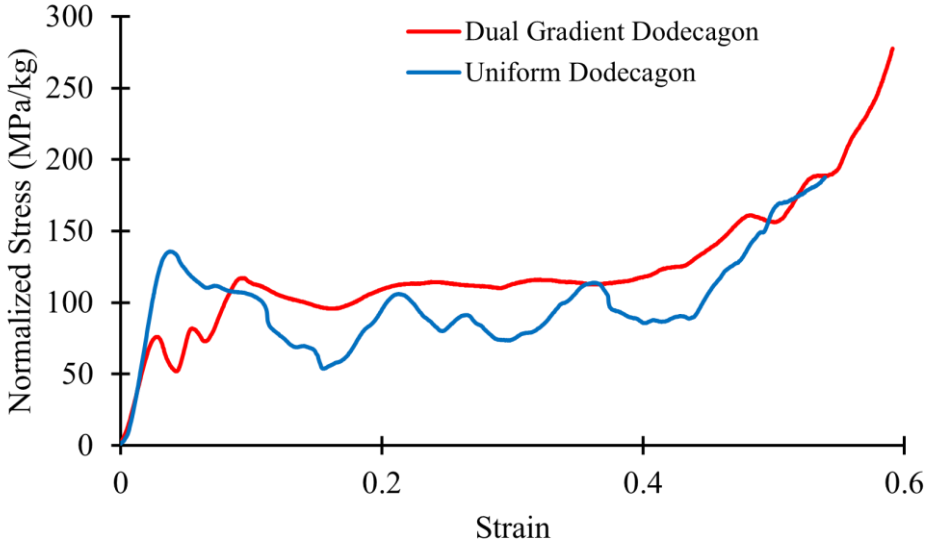


Fig. 5 Stress-strain responses for uniform dodecagon and dual gradient dodecagon structures.

Elastic Behavior

Yield strength and Young's modulus are the two principal parameters which determine the elastic behavior of any materials [11]. Figure 6(a) illustrates a comparison of the Young's modulus and yield strength between uniform and dual gradient dodecagon structures. The uniform dodecagon exhibits a 51.24% higher yield strength and a 79.26% greater Young's modulus compared to the dual gradient structure. This disparity arises from the non-uniform density distribution in the dual-gradient structure, which limits its overall strength and stiffness. Specifically, the presence of thinner walls in the dual-gradient configuration reduces its load-bearing capacity and makes it less effective during elastic deformation [14]. Therefore, the uniform dodecagon is a more suitable choice than the dual gradient structure for structural applications because of its higher strength and stiffness.

Energy Absorption Performance

The energy absorption performance of the uniform and dual gradient dodecagon structure is presented in Figure 6(b). It is observed that the dual gradient structure outperforms the uniform structure in terms of specific energy absorption (SEA) and energy absorption efficiency. The dual gradient structure exhibits a 23.26% higher SEA and a 58.14% higher energy absorption efficiency compared to the uniform structure. The lower energy absorption performance of the uniform structure can be attributed to its unstable stress-strain response (Figure 5) which leads to a lower mean plateau stress during energy absorption process. The lower plateau stress results in a lower SEA. In addition, the unstable response results to a large discrepancy between the peak stress and plateau stress, which limits its energy absorption efficiency. In contrast, the dual gradient structure exhibits a more stable plastic stress (Figure 5). This leads to a higher mean plateau stress and less difference between peak stress and mean stress, resulting in better SEA and efficiency.

The underlying reasons for such energy absorption characteristics of these structures are explained in detail with the aid of deformation mechanism in the subsequent section.

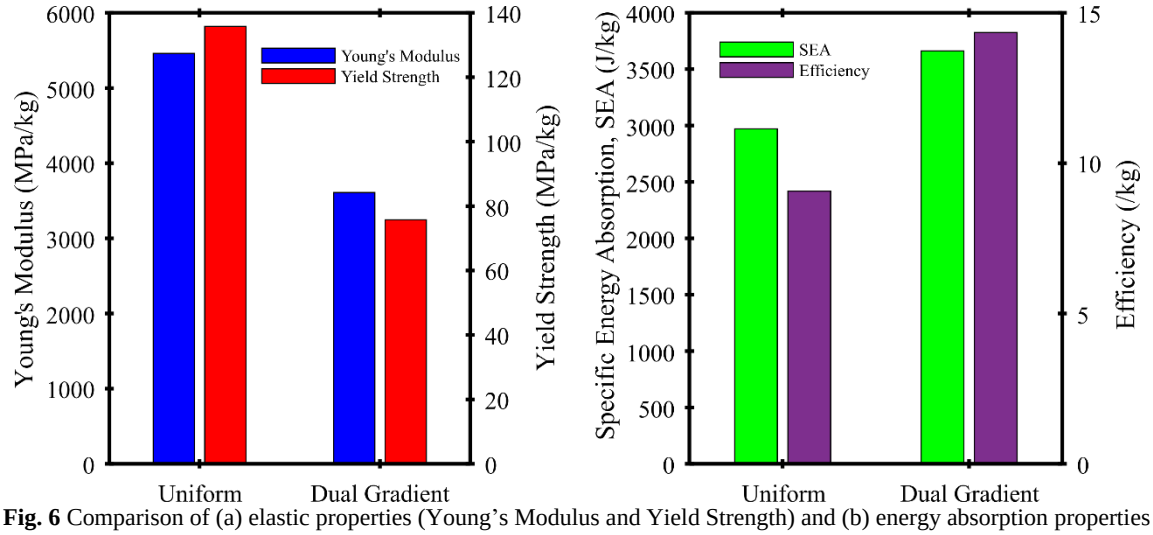


Fig. 6 Comparison of (a) elastic properties (Young's Modulus and Yield Strength) and (b) energy absorption properties (Specific Energy Absorption (SEA) and Efficiency) between uniform dodecagon and dual gradient dodecagon structures.

Deformation Mechanisms

The deformation responses of the studied structures are analyzed using the recorded videos of the quasi-static experiments. The deformed structures from six different states of strain are presented in Figure 7.

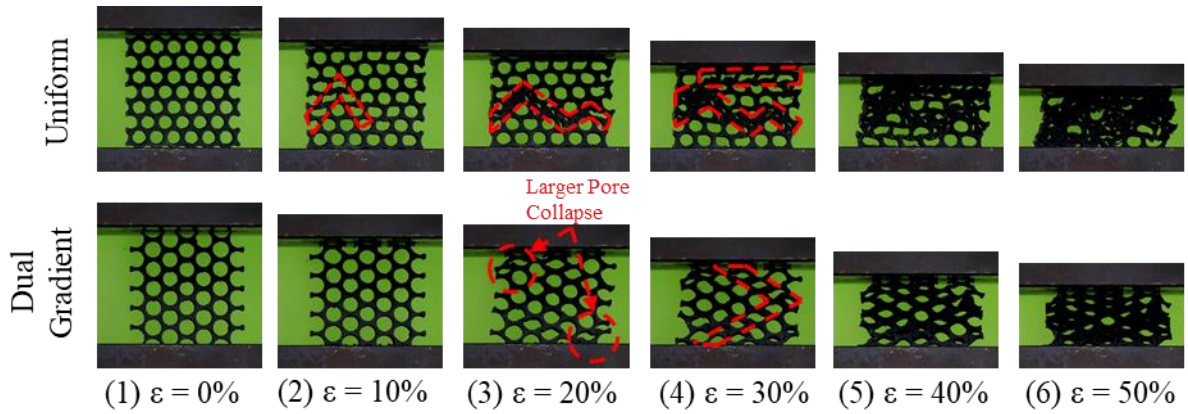


Fig. 7 Deformation response of the uniform and dual Gradient Dodecagonal structures at various strains.

It is observed that at 10% strain, some cell walls of the uniform structure start to buckle at the middle and form an upside down 'V' shape shear band. At 20% strain, more pronounced buckling of the cell walls can be seen, and eventually they start to collapse. At 30% strain, cell walls start to collapse at the upper part of the structure leading to the formation of a second shear band. Local densification of the cell walls is observed around the bands at 40% strain. The majority of the cell walls are collapsed at around 50% strain which initiates the densification stage. The formation of shear bands leads to intermittent rise and drop in stress [13]. Consequently, an unstable stress-strain response can be observed (Figure 5) and energy absorption performance of the structure degrades (Figure 6(b)).

The dual-gradient structure, however, exhibits significantly different deformation behavior. Unlike uniform structure, almost no localized shear bands are observed at 10% strain in dual gradient structure. Instead, the structure expands laterally under axial compression which indicates an even distribution of stress throughout the structure. At 20% strain, the larger pores near the edges start to collapse. When the structure reaches 30% strain, buckling of the cell walls leads to the gradual collapse of larger pores (as indicated by two bands in Figure 7), while the smaller pores remain largely unaffected. With increasing strain, the collapse progresses from the larger pores toward the smaller ones and the previously collapsed pores starts to densify. Finally, the entire structure starts to densify. The progressive collapse of the pores and the more even distribution of stress in the dual-gradient

structure, compared to the localized deformation in the uniform structure, results in a more stable stress-strain response (Figure 5) and superior energy absorption performance (Figure 6(b)).

6. Conclusions

The elastic and plastic responses of the uniform and dual gradient dodecagonal structure were analyzed under quasi-static compression loading to investigate their potentiality for various applications. Several key parameters such as yield strength, Young's modulus, energy absorption capacity and energy absorption efficiency were investigated for both of the designed structures. Deformation mechanisms were analyzed to correlate the deformation modes with mechanical properties. The following specific conclusions can be drawn from this study:

1. The uniform dodecagonal structure exhibits 51.24% higher yield strength and 79.26% higher Young's modulus compared to the dual gradient structure. The presence of thinner walls in the architecture of the dual-gradient structure limits its elastic properties. Therefore, the uniform structure is more suitable for the applications that require higher strength and rigidity.
2. The dual-gradient structure offers 23.26% higher specific energy absorption capacity (SEA) and 58.14% higher energy absorption efficiency compared to the uniform structure. The lower energy absorption capacity of uniform structure is due to its unstable stress-strain response, caused by multiple shear bands formation during collapse process. In contrast, the dual-gradient structure distributes stress evenly, with a progressive collapse from larger to smaller pores. Such deformation response lowers greatly improves its energy absorption performance. Thus, the bio-inspired dual gradient structure shows promising potential to be used in various energy absorption applications.

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8. References

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