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Finite Element Analysis of Novel Hexagonal Honeycomb Sandwich Beam Performance under a Three-Point Bending Effect

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Keywords： Three-point bending, Sandwich beam, Honeycomb, New hexagonal honeycomb core.

ABSTRACT

Sandwich structures have significant potential for application in the aerospace, automotive, shipping, and engineering industries due to their lightweight, high specific strength, and high specific stiffness. This study examines the bending characteristics of a hexagonal honeycomb sandwich beam made of aluminum alloy (6061-T6) material. In this work, we create some circular elements into the hexagonal honeycomb corners. We used the finite element method to conduct three-point bending test. The dimensions of the cell are as follows: length (l = 5 mm), thickness (t = 0.4 mm), and the diameter of the circle hexagonal (Ø CH) has four variations: 1 mm, 2 mm, 3 mm, and 4 mm. The numerical simulation includes a three-point bending test based on the ASTM C-393 standard. The results showed that the increase in compression displacement contributes to increased interaction among honeycomb cores, therefore increasing the bending deformation of sandwich beams. CH 1 demonstrates a significant 64% enhancement in reaction force when compared to the traditional honeycomb. The results of this study indicate that CH 1 is a highly effective option for applying the novel honeycomb sandwich beam. The traditional honeycomb structure demonstrates more dissipation of deformation energy compared to CH 1.

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INTRODUCTION

Sandwich structures have significant potential for application in the aerospace (Guo et al., 2023), railway vehicles (Tsai et al., 2023), automotive, shipping, and engineering industries due to their lightweight, high specific strength, and high specific stiffness (Xue et al., 2022). Sandwich structures commonly consist of two high-strength plates and are composed by inserting a core between two thin but rigid skins (Tan et al., 2020). Sandwich structures show excellent characteristics compared to traditional monolithic structures because they have high specific strength, impact resistance, and good energy absorption performance (H. Wang et al., 2023). Furthermore, sandwich structures are significant bending-resistant and energy-absorbing elements widely used in engineering (W. Zhang et al., 2021).

The application of skin-core structures in sandwich materials has generated significant interest (Rizzo et al., 2023). Sandwich structures can endure higher bending loads than conventional plates at the identical mass (Patel et al., 2023). Generally, sandwich structures comprise various skin material types, including fiber-reinforced composites, steel, and aluminum. The core model is created in several structural and material configurations, including lattices, honeycombs, and foam cores (Kueh et al., 2023). The mechanical properties of a sandwich structure are significantly influenced by the core properties (M. Zhao et al., 2022).

Numerous researchers have proposed and developed various forms of honeycomb cores to enhance the impact resistance performance of sandwich structures (Zeng et al., 2022). The honeycomb structure is the most commonly used and researched among several sandwich core structures (Song et al., 2023). Furthermore, honeycomb is a significant option due to its designability and excellent load-carrying. The advantages of honeycomb structures are their lightweight, good impact properties, and high specific strength and stiffness (J. Zhang et al., 2022). The honeycomb sandwich structure design is formed from 2 thin-facing layers attached to both core sides (Naufal et al., 2023). The honeycomb sandwich is a standard sandwich structure that offers numerous advantages compared to traditional structures (Wowk et al., 2020). The geometry of cells in honeycomb structures varies greatly, and the typical cell is hexagonal, square and columnar (Xia et al., 2022).

In recent years, several experimental, analytical, and numerical studies have been carried out on sandwich panels or beams. The bending test is a commonly studied aspect of sandwich structures, owing to increasing studies examining three-point bending or four-point bending from sandwich performance (Pyrzowski et al., 2023). The investigation into the bending performance of sandwich beams has attracted the interest of numerous researchers. Specifically, the examination of failure modes and bending responses in sandwich structures containing cores of various types. Wei et al. (2020) examined the bending characteristics of composite materials from hexagonal honeycomb sandwich beams. The sandwich beams were analyzed with a three-dimensional failure mechanism map and verified using three-point bending testing.

Hang et al. (2023) examined the damage sensitivity of composite hexagonal lattice honeycomb sandwich structures in four-point bending and in-plane compression by experiment and numerical simulation. Hou et al. (2022) studied the mechanical properties of the honeycomb curved sandwich structure on carbon fiber and its application in the engine hood, and analyzed it by the three-point bending test. X. G. Zhang et al. (2023) evaluated 3D re-entrant and hexagonal honeycomb core metamaterials on three-point bending test performance experimentally and numerically. Guo et al. (2023) analyzed the mechanical behaviour and damage model of a novel lightweight honeycomb sandwich structure at many scales. Furthermore, the Strategy of the honeycomb sandwich structure uses several design parameters. The analysis showed that the optimal size of the hexagonal honeycomb core to withstand high loads is L = 5 mm–7.5 mm and t = 0.3 mm–0.4 mm.

C. Zhang et al. (2023) examined the three-point bending behaviour when analyzing and designing a sandwich beam model made of a hollow-core rod lattice. The study revealed that the optimized sandwich beam significantly enhanced the final specific carrying capacity in comparison to the conventional sandwich beam. Xiao et al. (2019) analyzed the structure response experimentally and the finite element of sandwich beams—the analysis model of auxetic reentrant hexagonal honeycomb cores Aluminum material under impact load. The overall analysis of the sandwich beams with different honeycomb cores and cell thicknesses can exhibit failure in different modes.

Geramizadeh et al. (2022) studied the comparison of face sheet thickness on sandwich beams of 3D printed technology with hexagonal and re-entrant honeycomb sandwich beam models. In addition, they performed a three-point bending test and conducted experimental and finite element analysis. The study revealed that augmenting the face sheet thickness by 1 mm in the H2 to H3 and R2 to R3 variants resulted in a corresponding increase of around 11% and 19.8% in the energy absorption capacity of the beams. J. Zhang et al. (2023) examined the failure behaviour of sandwich beams in numerical simulation. Epoxy/aluminium laminate face sheets and aluminium honeycomb cores were tested in three-point bending experiments. In general, it was discovered that the load-carrying capacity and energy absorption of the sandwich beams could be enhanced under various conditions. The ratio of core height to span length and the material effect or reduction of the honeycomb beams' side length occurs when the thickness of the face sheets and cores is increased.

Li et al. (2023) finished a study on a novel variant of auxetic honeycomb core in sandwich beams using a three-point bending test. Their findings revealed that increasing the size of the new honeycomb cells enhances the bending resistance. X. Zhao et al. (2021) published a study on sandwich beams' energy absorption and bending response using novel-type honeycomb cores with auxetic cell. The cell structural characteristics substantially influence the bending test performance.

Bending testing is a commonly used scientific experiment to assess the performance of beam structures under quasi-static uniaxial pressure (Geramizadeh et al., 2022). Currently, specimens of different configurations are applied to examine fracture characteristics and crack propagation under various load methods. An example of such an object is the three-point bending from the beam (J. Zhang, Dong, et al., 2023). The bending process can induce the test specimen's concurrent tensile, compressive, and shear stress states (Paramatmuni & Dunne, 2023). Three-point bending is typically performed in testing due to the uncomplicated setup of the sample device and procedure and specific data analysis (Han et al., 2023; C. Wang & Sun, 2022).

Sandwich beams with excellent mechanical performance have an essential role in engineering applications. This study examines the bending characteristics of a hexagonal honeycomb sandwich beam made of aluminum alloy (6061-T6) material. Sandwich structures, including an aluminum core, are widely used in aircraft and railway vehicle engineering to produce lightweight components (Tsai et al ., 2022) . The difference between the literature and the contribution of this study is the creation of circular elements into the hexagonal honeycomb corners. The aim is to achieve a more efficient configuration through the use of this novel hexagonal design with a circular component. In this research, the study investigates the effect of original hexagonal and novel hexagonal with a circle on the bending performance of sandwich beams. The deformation pattern and energy absorption process of hexagonal honeycomb cores with different circle variations in a novel hexagonal configuration are studied using a numerical simulation. This research is expected to offer further reference data for scholars and researchers to enhance the optimization of the hexagonal core structure.

MATERIAL AND METHODS

Finite Element Model and Materials

This study used the finite element method to conduct three-point bending testing using the ABAQUS/Explicit software. The study used aluminum alloy (6061-T6) material in a hexagonal honeycomb core beam structure, which was analyzed using the three-point bending test method. The mechanical property parameters of the 6061-T6 material are described in Table 1. The study by Guo et al. demonstrated the most effective hexagonal design for honeycomb sandwich structures. Therefore, these dimensions were adopted as the basis for the original design in this investigation (Guo et al., 2023). Fig. 1 shows the geometric pattern of a hexagonal core and a new pattern circle hexagonal core. The dimensions of the cell are as follows: length (l = 5 mm), thickness (t = 0.4 mm), and the diameter of the circle hexagonal (Ø CH) has four variations: 1 mm, 2 mm, 3 mm, and 4 mm. Fig. 2 illustrates the geometric configuration of the sandwich beam with L = 200 mm, B = 40 mm and H = 33.181 mm for CH variations and H = 34.890 mm for traditional honeycomb. The variable diameter of the circle with different codes shown in Table 2.

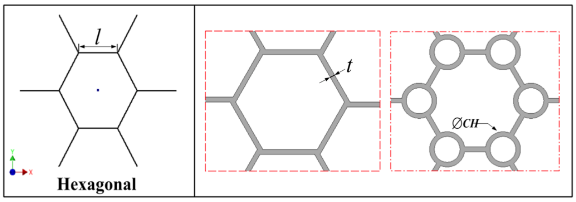

Fig. 1. The geometric pattern of sandwich beams on a circle hexagonal core structure.

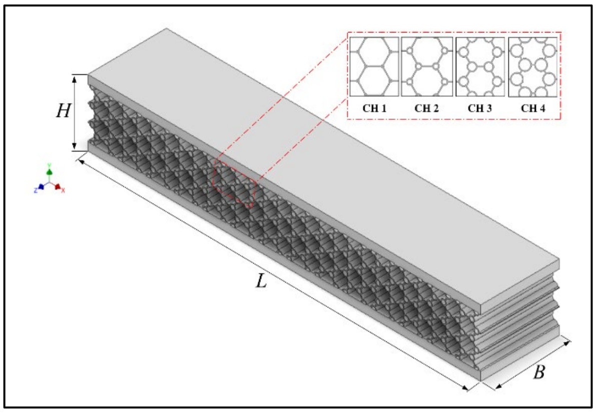

Fig. 2. The geometric configuration of the sandwich beams with circle hexagonal core.

Table 1. Material properties of aluminum alloy (6061-T6) (Li et al., 2023; X. Zhao et al., 2021)

6061-T6	
Density	2.7
Young Modulus (MPa)	68140
Yield Stress (MPa)	308.03
Poisson's Ratio	0.317

Table 2. Variations in code beams

Code Beam	Diameter of a Circle (mm)
CH 1	1
CH 2	2
CH 3	3
CH 4	4

Fig. 3 illustrates the finite element analysis of sandwich beam configuration under three-point bending. The numerical simulation includes a three-point bending test based on the ASTM C-393 standard. The test specimen is positioned on two rigid support left and right, and the rigid indenter applies a uniaxial compressive force to the symmetrical center of the speciment (See Fig. 3). The friction coefficient value for the general contact between the Indenter or support rods with the face sheet is 0.2 (H. Wang et al., 2023; Xia et al., 2022; X. Zhao et al., 2021).

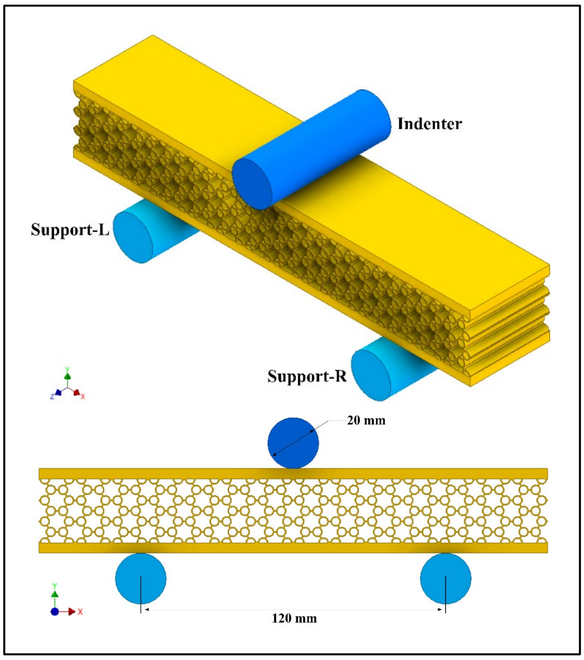

Fig. 3. Three-point bending finite element analysis model illustration.

The honeycomb core is meshed by four-node shell elements (S4R). C3D6 elements model the honeycomb sandwich beam, while the Indenter and Support [Left and Right] are modeled by R3D4 elements. The number of elements in the numerical model of the CH1 variation hexagonal sandwich beam is 59441. To specifically examine the mode of deformation of the honeycomb sandwich beam, the final loading displacement set to 25 mm.

Evaluation criteria of crashworthiness

Four different criteria are presented to qualitatively investigate the crashworthiness of sandwich structures, based on the reference from X. Zhao et al. (2021). These criteria include energy absorption (EA), specific energy absorption (SEA), mean crushing force (MCF), and peak crushing force (PCF). The EA value, which can be found by integrating the load-displacement curve, shows the total energy the sandwich beam took in during the specific compression displacement phase. Therefore, the following Equation 1 can be used to describe EA:

$$\boldsymbol{EA} = \int_{0}^{d} \boldsymbol{F(x)dx} \quad (1)$$

where F(x) represents the instantaneous force, while d represents the amount of compression displacement.

$$\boldsymbol{MCF} = \frac{\boldsymbol{EA}}{\boldsymbol{d}} = \frac{\int_0^d \boldsymbol{F(x)dx}}{\boldsymbol{d}} \quad (2)$$

The crushing force efficiency (CFE) is a significant measure commonly defined as the ratio of the MCF to the global peak crushing force (GPCF), as shown at Equation 3:

$$CFE = \frac{MCF}{GPCF} \quad (3)$$

where the GPCF refers to the global peak crushing during the complete compression process.

The sandwich beams unit energy absorption efficiency, denoted as SEA, can be expressed as Equation 4:

$$SEA = \frac{EA}{m} = \frac{\int_0^d F(x)dx}{m} \quad (4)$$

where m is the mass of the sandwich beams.

RESULTS AND DISCUSSIONS

Deformation patterns

Fig. 4 illustrates the deformation process in the three-point bending analysis, given a displacement of 25 mm. This investigation includes hexagonal sandwich beams, specifically the traditional honeycomb and CH variations. Similar deformation patterns are found between all CH variations and the traditional honeycomb at a depth of 5 mm. However, the deformation changes to specific areas during the bending displacement process without changing the original geometry of the remaining honeycomb cores. The honeycomb core shows bending deformation as the compression displacement increases, especially on the face sheet. At a depth of 10 mm, the traditional honeycomb has minimal bending deformation, while the CH 2 variation has a more significant bending deformation. The results show a progressive increase in the deformation area category at the sandwich core as the compression displacement increases.

Furthermore, it was found that there was no bending of the honeycomb core around the two areas of the support left and right during the entire period of deformation. There is significant deformation at a compression displacement of 15 mm depth. Specifically, CH 2 and CH 3 variations have more significant bending deformation than CH 4, CH 1, and Traditional Honeycomb. As the compression displacement increases, the interaction among the core also increases, resulting in an enhancement in the loading performance of the sandwich beams. The sandwich beam showed bending deformation through the whole structure at a depth of 20 mm, with the most severe deformation observed in CH 2. The damaged area had a significant core collapse at the final loading displacement of 25 mm. Compared to different variations, CH 1 showed stronger deformation resistance.

The comparison results indicate a significant difference in the deformation patterns between traditional honeycomb and CH variation. The traditional honeycomb demonstrates overall deformation, but the CH variant displays local deformation. There is no deformation of the honeycomb structure around the two ends of support left and right, and the face sheet beams consistently have tensile bending. The stress is focused on the indenter and the specific area of the honeycomb in direct contact with the indenter.

Reaction Force

The results of the traditional honeycomb and CH variations demonstrate significant differences in the values of reaction force and performance of the beams. Fig. 5 illustrates the graph of reaction force results between specimens subjected to three-point bending. Traditional honeycomb showed the highest reaction force of 19100 N. Additionally, the CH variations produced lower values, with CH 1 reaching 6945 N, CH 2 8750 N, CH 3 10800 N, and CH 4 15140 N.

Comparing the value of the reaction force makes a result that variations of CH are ideal compared to traditional honeycomb because they show reduced and lower reaction force values. CH 1 shows the most significant increase in variation, amounting to 64% when compared to the reaction force values on a traditional honeycomb. CH 2 is 54%, CH 3 is 43%, and CH 4 has a 21% improvement.

The results indicate CH variations have potentially improved three-point bending performance, as demonstrated by the reaction force value graph. The study found that CH 1 was the most efficient design structure among the honeycomb sandwich beams, displaying a remarkable 64% enhancement over the traditional honeycomb design, which showed the lowest reaction force value. CH 1 has improved structural performance compared to traditional honeycomb and other variations of CH. In the results, CH 4 has the highest reaction force value compared to the other CH. However, CH 4 outperforms traditional honeycombs regarding reaction force value, resulting in a more efficient structure.

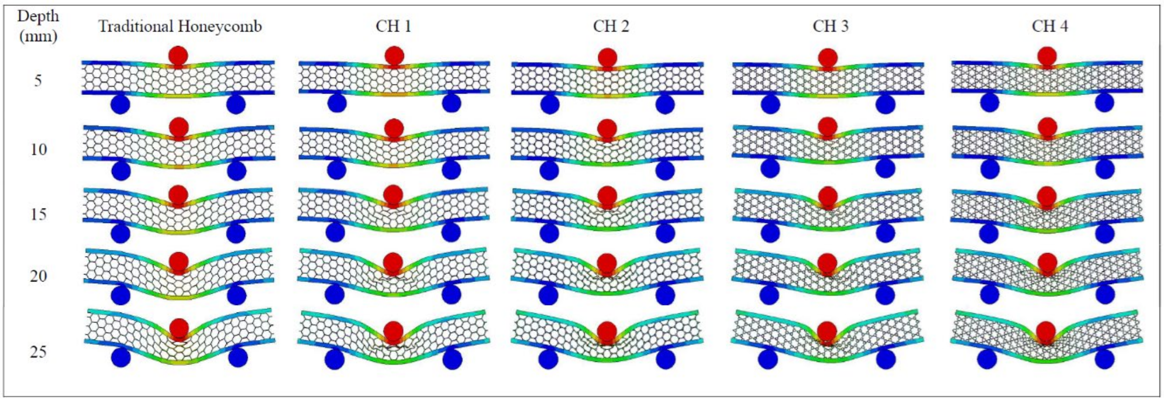

Fig. 4. Deformation mode of sandwich beams with different circle cores

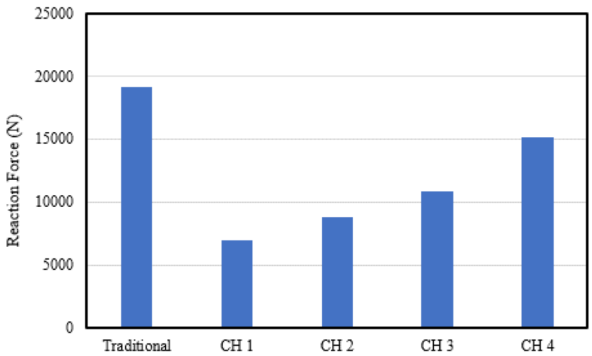

Fig. 5. Reaction force values from traditional honeycomb and CH variations.

Plastic dissipation energy (ELPD)

The distribution of the plastic dissipation energy (ELPD) data for hexagonal sandwich beams under three-point bending show at Fig. 6. Furthermore, the graph presents a comprehensive examination of the energy dissipation in the sandwich beam structure. The diagram illustrates that the energy dissipated is high in the traditional honeycomb variation. In addition, it is found that the energy dissipation in all four variations increases as the size of the circle in the honeycomb core design increases. The minimum amount of energy dissipated is observed in CH 1, with an exact value of 1098 J. The energy dissipated in the traditional honeycomb has the highest value, while CH 1 decreases by 64%. The energy dissipated in traditional honeycomb has the highest value, while in CH 1 it decreases by 64%. In the energy dissipation instance of CH variations between traditional honeycomb, CH 2 saw a 38.3% decrease, CH 3 saw a 27.6% decrease, and CH 4 had a 60.5% decrease. The graph of CH variation shows that the energy dissipation increases with the increase in the size of the circle in the honeycomb core.

Increasing the size of circle each core will enhance the respective energy dissipation capacity of the corresponding sandwich. Furthermore, it has been demonstrated that traditional honeycombs have a higher capacity for dissipated deformation energy compared to CH 1, therefore suggesting that traditional honeycombs undergo higher plastic deformation than CH 1.

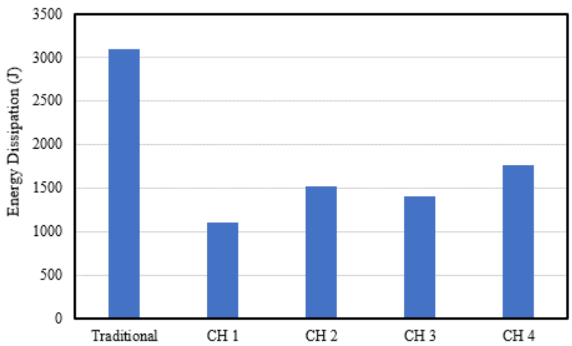

Fig. 6. Plastic dissipation energy (ELPD) values from traditional honeycomb and CH variations.

Stress – Depth

Fig. 7 shows the stress and depth graphs of the simulation sandwich beams. The graph trendline illustrates each sandwich beam's varying increments and decrements of stress. The stress graph indicates that CH 1 has a direct trendline compared to the other sandwich. CH 1 found an improvement in stress without a decrease during the bending process.

During the initial stage of the bending process, specifically at a depth of 5 mm, all sandwich beams demonstrate a uniform stress level of around 350 MPa to 360 MPa. At a depth of 10 mm, the stress values increase for each variation, with the highest stress of 374.1 MPa in the CH 4 variant. However, the stress value in CH 1 is smaller, measuring 361.2 MPa. At a depth of 15 mm, the traditional honeycomb increases at a significant stress of 394.9 MPa, which is higher than the stress observed in various types of CH. However, as the bending process reached a depth of 20 mm, a significant decrease in stress was found in the traditional hexagonal, CH 2, and CH 3 materials. On the other hand, the level of stress continued to escalate in the variations of CH 1 and CH 4. The sandwich beams demonstrated increased stress after reaching their maximum depth; CH 4 recorded the highest value at 420.6 MPa, followed by Traditional Honeycomb at

416.2 MPa.

According to the conclusion of the stress-time graph, the CH 1 variation showed more excellent performance, as indicated by the lowest pressure observed during the bending process.

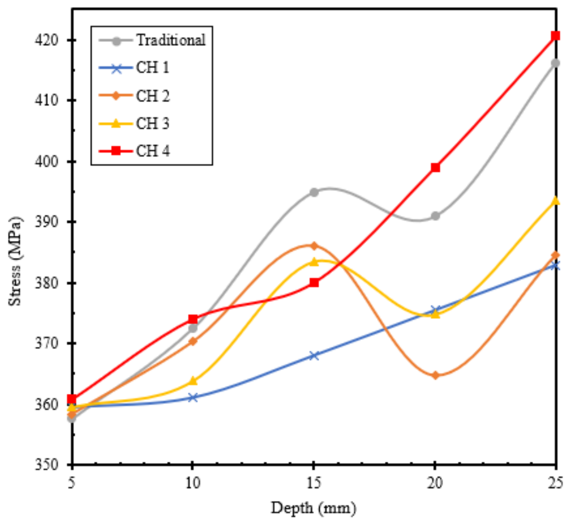

Fig. 7. Stress and depth

CONCLUSIONS

This study conducts a finite element analysis to evaluate the three-point bending performance of a novel hexagonal honeycomb sandwich beam made from aluminum alloy 6061-T6. Abaqus is used to simulate novel-design sandwich beams from traditional hexagonal and added circles between honeycombs. The traditional honeycomb and novel design variations are CH 1, CH 2, CH 3, and CH 4. Then, the sandwich beams under three-point bending are studied through the finite element method. The stress-depth curves, deformation patterns, and energy discuss the mechanical response of the sandwich beams under bending load. The main conclusions are as follows:

1. The deformation patterns show significant differences between traditional honeycomb and CH variations in the three-point bending analysis. The increase in compression displacement contributes to increased interaction among honeycomb cores, therefore increasing the bending deformation of sandwich beams. However, there was no deformation observed in the honeycomb cores near the two ends of the left and right supports throughout the bending procedure. The observed deformation pattern supported the analysis result that CH 1 demonstrated superior resistance to deformation among several CH variations.
2. The results showed significant differences in the Reaction Force between the traditional honeycomb and the CH variation during three-point bending. CH 1 demonstrates a significant 64% enhancement in reaction force when compared to the traditional honeycomb. The results of this study indicate that CH 1 is a highly effective option for applying the novel honeycomb sandwich beam. Interestingly, although CH 4 has the highest reaction force value among the CH variations, it remains more effective than the traditional honeycomb.
3. The traditional honeycomb shows the highest value for the distribution of plastic dissipation energy (ELPD). The traditional honeycomb structure demonstrates more dissipation of deformation energy compared to CH 1, indicating that the traditional honeycomb has more plastic deformation than CH 1.

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