

Low-Velocity Impact Behaviour of Biomimetic Cornstalk-Inspired Lightweight Structures [†]

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Abstract: This study investigates the dynamic response and damage characteristics of cornstalk-inspired lightweight structures. Specimens were fabricated via 3D printing using Acrylonitrile Butadiene Styrene (ABS) as the chosen thermoplastic due to its toughness and resistance to impact. Low-velocity impact tests were conducted at varying incident energies, with subsequent damage analyses performed using X-ray CT scans. The effect of geometrical variations in the constituents on energy-absorbing capability was also investigated. The results demonstrate a ~14% increase in specific energy absorption (SEA) compared to quasi-static measurements. This research is built upon the authors' previous work on the quasi-static response of the cornstalk-inspired design.

Keywords: bio-inspired design; dynamic response; collapse mechanism; lightweight structure; energy absorption

1. Introduction

Bio-inspired structures have garnered considerable attention due to their enhanced strength-to-weight ratio and ability to absorb impact energy effectively [1–3]. These bio-inspired structures have a unique blend of mechanical properties, making them useful for engineering applications [4]. Implementing lightweight structures for impact-resistant applications necessitates thoroughly examining their deformation characteristics and energy absorption capabilities across various loading rates. The deformation pattern and mechanical response of porous structures depend on the structure's constituent elements. Among the prevalent occurrences, low-velocity collisions are likely to be experienced by porous structures.

Biomimicry is an approach to taking structural inspiration from instances from nature with the desired impact-resistant characteristics. All the authors tend to mimic structural features based on any one of the three scales (macro, meso, or micro) when designing. The ability of porous biological materials to absorb mechanical energy has been studied over the past few years. Some examples of sources of inspiration for studying porous biomimetic structures are the luffa [5], pomelo [6], lotus root [7], turtle [8], and bone [9].

Cornstalks are thick and strong structures [10]. They can endure mechanical stresses. The stress can be caused by human activity using agricultural machinery and other tools used in agricultural processes, such as pruning, transplanting, or thinning. The other form of stress is provoked by adverse weather conditions, such as withstanding impacts from the stones of a hailstorm. These activities and occurrences are a few prime examples of how cornstalks and other plants can endure drastic external forces [11–13].



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Siddique et al. [14] have shown that cornstalk-inspired designs have the potential to serve as efficient energy absorbers, as they can significantly deform under axial compression while maintaining a nearly constant force. In their previous work, the authors extensively analysed the literature, applications, and mechanical properties of the base material and the deformation characteristics of cornstalk-inspired structures that observed quasi-static compression loading [14].

While quasi-static compression analyses offer valuable insights into the deformation pattern of structures, they do not explicitly dictate if the response would be the same during an impact [15]. Numerous authors have studied the collapse behaviour (under impact) of porous structures [16–18]. It was claimed that the mechanical response and deformation pattern under an impact significantly affect porous structures' response. The cornstalk-inspired design, resembling a sandwich structure, is commonly susceptible to impact loads, leading to severe structural damage, a reduced load-bearing capacity, and shortened service life. Therefore, it is crucial to investigate the dynamic collapse mechanisms of the cornstalk-inspired structure to comprehensively understand its mechanical behaviour under dynamic loading conditions.

This paper presents the first investigation of a novel cornstalk-inspired structure that has been mimicked at the mesoscale and subjected to dynamic compression. We conducted low-velocity impact experiments using a drop-weight impact facility administering impact energies at 200 J, 350 J, and 500 J to investigate the dynamic response of lightweight cornstalk-inspired structures compared to their quasi-static response. The contact force–displacement response and the corresponding energy absorption were measured. In addition, we studied the influence of changes in geometry (under dynamic conditions) on the ability of bio-inspired designs to absorb energy by adjusting the thickness of the tube reinforcement and the distance between the outer surfaces of neighbouring tubes. After the impact tests, the failure characteristics of the specimens were analysed by X-ray CT scans to understand the deformation behaviour during an impact.

2. Biomimetic Designs and Materials

The cornstalk-inspired design was mimicked at a mesoscale by replicating the building blocks, i.e., vascular bundles and medullary core, of the stem that are visible under a microscope. During the design phase, simpler models of a stem-like structure were created, with the reinforcement represented by cylinders embedded inside a porous matrix, as shown in Figure 1. The authors have obtained the copyright permissions from the publishers, via the Copyright Clearance Center, to reuse images in this paper.

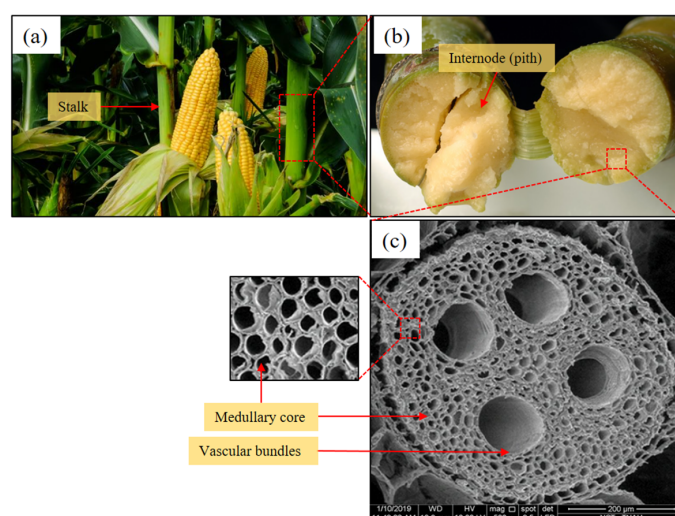


Figure 1. Diagram illustrating the structural hierarchy of a cornstalk [19]: (a) cornstalk, (b) stem cross-section, (c) SEM image of the internal architecture.

The sample dimensions in this study adhere to the guidelines outlined in ASTM C365 [14] and are detailed in Tables 1 and 2. Moreover, Figure 2 visually presents the CAD models of the specimens created using Autodesk Inventor. It is essential to highlight that the study primarily considers two varying parameters, namely the wall thickness (t_w) and spacing (s), as outlined in Table 2. In contrast, the inner diameter (d_i) of the tubes and the pore diameter (p_d) remains constant throughout the study.

Table 1. Geometrical parameters of the sandwich structures (units: mm).

	Length (l)	Width (w)	Core Thickness (t_c)	Facesheet Thickness (t_f)	Total Thickness (t)
Dimensions	30	30	20	1.5	23

Table 2. Specifications of the biomimetic structures (units: mm and g).

Specimen	Wall Thickness (t_w)	Outer Diameter (d_o)	Inner Diameter (d_i)	Spacing (s)	Pore Diameter (p_d)	Mass	Relative Density ρ
Specimen A	2.5	15	10	1	3	16.21 (± 0.15)	0.65
Specimen B	2	14	10	2	3	15.13 (± 0.08)	0.62
Specimen C	1.5	13	10	3	3	14.82 (± 0.11)	0.58

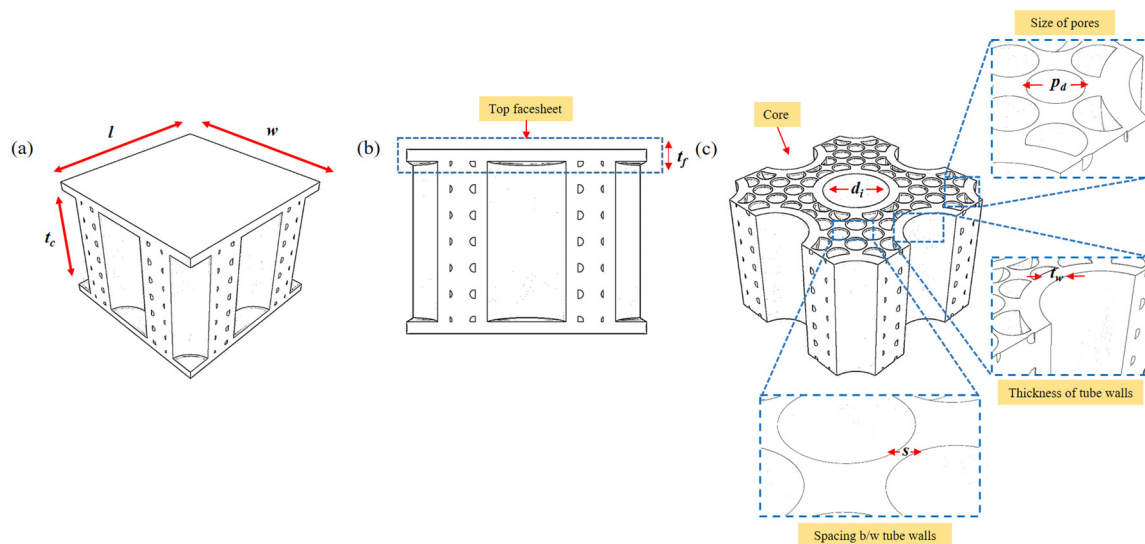


Figure 2. CAD model and geometric configuration of the biomimetic porous sandwich structure: (a) 3D view (sandwich structure), (b) front view (sandwich view), and (c) core (3D view).

The specimens were fabricated using an in-house 3D printer called Ultimaker™ S5 (Ultimaker, Zaltbommel, the Netherlands). Acrylonitrile Butadiene Styrene (ABS) filaments from Ultimaker™ were selected as the printing material to manufacture them, and the mechanical properties are listed in Table 3 [20].

Table 3. Mechanical properties of Acrylonitrile Butadiene Styrene (ABS).

Properties	ABS
Density (g/cm^3)	1068
Young's modulus (Gpa)	1.85
Yield strength (Mpa)	36
Ultimate strength (Mpa)	40
Poisson's ratio	0.35
Failure strain at break	0.047
Hardness (shore D)	76
Cowper–Symonds, $\text{C} (\text{s}^{-1})$	678.7
Cowper–Symonds, p	3.23

3. Methodology

3.1. Drop-Weight Impact Tests

Using the drop tower setup, an Instron CEAST 9350 (Instron, Norwood, MA, USA) was used to carry out the low-velocity impact experiments at 200 J, 350 J, and 500 J of incident energy, corresponding to 4.32 m/s, 5.63 m/s, and 6.78 m/s. The drop tower consists of many components that create a free-falling carriage mechanism. The impactor, a flat round-shaped object, was connected to the instrumented 90 kN load cell. A data acquisition system (DAS) with a sampling rate of 1000 kHz was set. All the specimens were tested at room temperature for consistency, with a constant mass impactor unit weighing 5.482 kg and additional weight blocks (15 kg), resulting in a total mass of 20.482 kg.

The force histories of all the low-velocity experiments were extracted from the DAS. The data were processed to obtain the displacement histories based on the following equation [21]:

$$S = \int \int \frac{F(t) - Mg}{M} dt^2 \quad (1)$$

where S is the displacement along the impact axis, $F(t)$ is the force obtained from the experiment, t is the time, g is the acceleration of the gravity taken as 9.8 m/s^2 , and M is the total dropping mass.

To calculate the stress–strain diagram from the force–displacement curve, the following equations were followed:

$$\sigma = \frac{F}{A} \quad (2)$$

where σ is the stress calculated by dividing the applied force (F) by the cross-sectional area (A) of the specimen.

$$\epsilon = \frac{S}{S_0} \quad (3)$$

where ϵ is the strain calculated by dividing the displacement (S) by the original length S_0 of the specimen.

Nine specimens were subjected to impact testing in each group specific to incident energy, as outlined in Table 4. To simplify the labelling, a sample named C200A signifies that specimen A was impacted with 200 J of incident kinetic energy during compression.

Table 4. Dynamic compression test conditions.

S/N	Sample Label	Specimen	Impact Energy (J)	Number of Samples
1	C200A	Specimen A	200	3
2	C200B	Specimen B		3
3	C200C	Specimen C		3
4	C350A	Specimen A	350	3
5	C350B	Specimen B		3
6	C350C	Specimen C		3
7	C500A	Specimen A	500	3
8	C500B	Specimen B		3
9	C500C	Specimen C		3

3.2. Damage Examination

An X-ray micro-computed tomography (CT) imaging system was incorporated to comprehend the extent of the damage characteristics and the impact resilience of the cornstalk-inspired structures after dynamic compression with a flat impactor, as shown in Figure 3. The specimens were scanned at the Microscopy Laboratory based at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) using a Zeiss Xradia 515 (ZEISS Group, Oberkochen, Germany) equipped with a tungsten on diamond

window X-ray source (40 kv, 2 W), an LED source filter, and a flat panel detector to obtain MicroCT images with a reported pixel size of 19.4 μm .

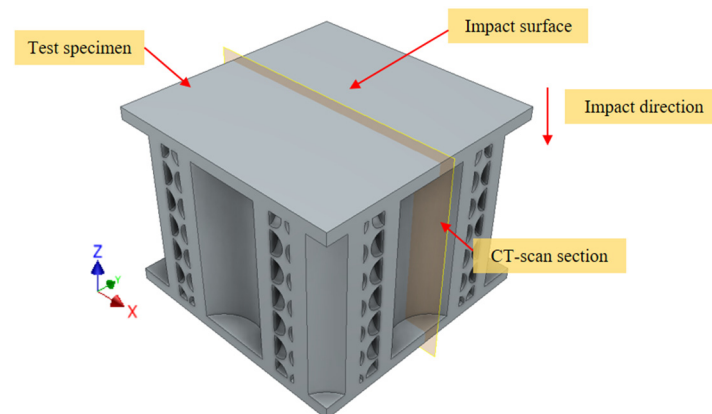


Figure 3. Schematic showing the X-ray CT scan section of the impacted specimens.

4. Results and Discussions

Dynamic compression experiments were conducted at three incident administered energies on the biomimetic structures, with three variations in their geometry, to study the mechanical response of the lightweight porous structure.

4.1. Effect of Varying Impact Energy

Figure 4 represents the mechanical responses caused by the varying impact energy on the cornstalk-inspired design. At the early loading stage, the bio-inspired structures exhibit a pronounced elastic response until the specimen is compressed to a 0.07 strain. This vivid elastic behaviour can be attributed to the structural design that mimics the natural stiffness and flexibility of cornstalks [22].

The cornstalk-inspired design features a hierarchical structure with well-defined cellular configurations that provide a high initial resistance to deformation. This resistance results from the alignment and interaction of these cellular components, which efficiently distribute the applied load and resist compression in the elastic region, as seen in Figure 4a. As the load increases, the structure initially deforms elastically, reflecting the ability of the design to absorb and distribute impact forces effectively [23].

The transition from the elastic to the plastic region occurs as the applied load exceeds the elastic limit, leading to non-linear deformation as the specimen compresses further. This behaviour is consistent with the mechanical properties expected from the bio-inspired design, which is optimised for a balance between stiffness and flexibility.

Based on the data in Table 5, it can be inferred that the energy absorbed correlated directly with the strain experienced by the test specimen, until the impactor rebounded and the specimen reached its final strain. Throughout the experiment, it was noted that all the specimens continued to withstand higher energy loads without failing or completely disintegrating, while absorbing a significant portion of the impact energy involved. This phenomenon can possibly be attributed to the inherent design and mechanical properties of the bio-inspired structures, as stated below.

- The bio-inspired structures are designed with a hierarchical arrangement that mimics the natural design of cornstalks. This hierarchical structure includes a network of cells or hollow tubes that efficiently absorb and dissipate energy. The multiple levels of structural organisation allow for progressive deformation, which distributes the impact energy more evenly across the specimen and prevents localised failure [24];

- The energy absorption mechanism of the bio-inspired design relies on both elastic and plastic deformation. At lower energy levels, the structures primarily absorb energy through elastic deformation, which allows them to return to their original shape upon unloading. At higher energy levels, the structures undergo plastic deformation, which further absorbs and dissipates energy through internal deformation mechanisms, such as fibre breakage or cellular collapse, without complete disintegration [25];
- The materials used in the bio-inspired structures are selected for their ability to withstand significant impact forces while maintaining structural integrity. These materials exhibit a combination of high strength and toughness, which contributes to the ability of the specimen to absorb large amounts of energy without failing [26];
- The geometry of the bio-inspired design used in this study and the material composition ensure that impact forces are distributed across a larger area, reducing the likelihood of catastrophic failure. This distribution helps the specimens to withstand higher energy loads more effectively, leading to enhanced energy absorption capabilities.

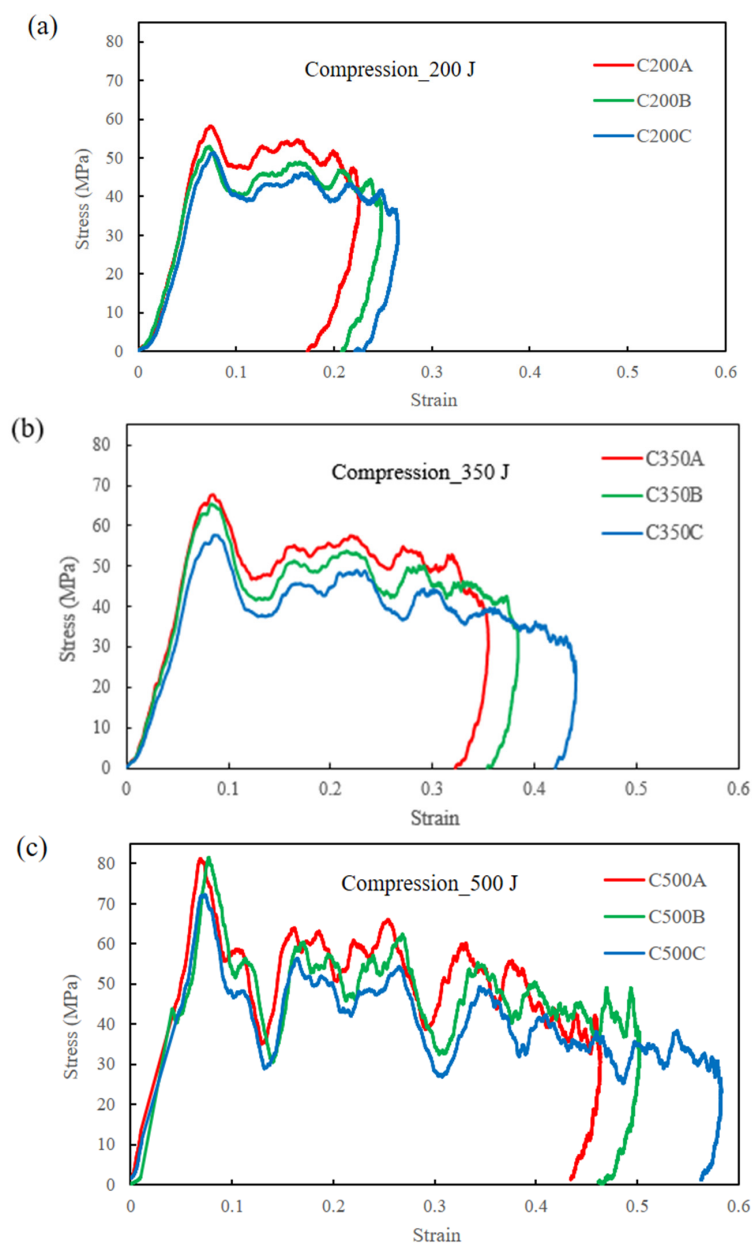


Figure 4. Drop-weight impact test results (compression): (a) 200 J, (b) 350 J, and (c) 500 J.

Table 5. Characteristics of cornstalk-inspired specimens.

Impact Energy (J)	Sample Label	Maximum Stress (MPa)	Strain	Energy (J)	SEA (kJ/kg)/(mm)
200	C200A	58.12 (± 0.008)	0.17 (± 0.002)	185.79 (± 0.05)	2.9 (± 0.4)
	C200B	52.99 (± 0.011)	0.20 (± 0.009)	189.85 (± 0.07)	2.7 (± 0.2)
	C200C	51.38 (± 0.004)	0.22 (± 0.001)	191.82 (± 0.07)	2.5 (± 0.1)
350	C350A	67.72 (± 0.009)	0.32 (± 0.012)	343.79 (± 0.08)	2.9 (± 0.4)
	C350B	64.15 (± 0.012)	0.36 (± 0.011)	344.53 (± 0.15)	2.7 (± 0.3)
	C350C	56.84 (± 0.011)	0.42 (± 0.007)	347.19 (± 0.11)	2.4 (± 0.1)
500	C500A	81.53 (± 0.003)	0.43 (± 0.009)	471.32 (± 0.02)	3.2 (± 0.3)
	C500B	81.21 (± 0.001)	0.46 (± 0.002)	478.89 (± 0.05)	3.0 (± 0.2)
	C500C	72.43 (± 0.004)	0.56 (± 0.005)	483.11 (± 0.07)	2.5 (± 0.5)

At an incident energy level of 200 J, it was observed that the test specimens could absorb approximately 95.9% of the kinetic energy, exemplified by specimen C200C, which absorbed 191.82 (± 0.07) J (as indicated in Table 5). This energy absorption capacity increased gradually when the same specimen was subjected to a 350 J incident energy impact. For instance, specimen C350C absorbed around 99.1% of the incident energy, measuring at 347.19 (± 0.11) J, without failing under the impact. However, when the same specimen experienced a 500 J impact, its energy absorption capability slightly decreased. For example, specimen C500C could absorb approximately 96.6% of the impact energy, measuring at 483.11 (± 0.07) J, before rebounding the flat impactor and the decompression of the specimen without disintegration. This outcome highlights the effectiveness of bio-inspired structures' mechanical performance within the range of 200 J to 500 J of incident energy. Further insights into the efficiency of bio-inspired structures are provided in subsequent sections.

4.2. Effect of Geometry Variations

The variation of the relative density of the test specimens was carried out by tuning the thickness of the tubes and the spacing between the adjacent tubes [27], as summarised in Table 2. Specimen A incorporates structures having thicker tube walls and a lower spacing between adjacent tubes, whereas the constituents of specimen C incorporate thinner tube walls and a higher spacing between the adjacent tubes.

The variation in maximum stresses associated with a change in geometry at different incident energies is illustrated in Figure 5. Maximum stress refers to the amount of force per unit area that the structure can handle before reaching its breaking point or undergoing significant deformation. At 200 J of incident energy, the maximum stress experienced by specimen C200A was 58.12 (± 0.008) MPa. However, as the thickness of the tubes in the structure was decreased and the volumetric fraction was reduced, as represented by specimen C200C, the maximum stress was reduced by 11.6% to 51.38 (± 0.004) (MPa), as stated in Table 5. A similar trend was observed at a higher administered energy (500 J). The result denotes that specimens incorporating thicker tubes in the structure can withstand a greater force before failure or deformation and possess superior strength and resilience under dynamic compression conditions [28,29].

The findings from the geometric variation study are also relevant to crack propagations within the specimens. Thinner tubes are generally more susceptible to crack initiation and propagation due to several factors. Firstly, the reduced material thickness in thinner tubes means there is less material available to absorb and redistribute the stress concentrations that arise during loading. As a result, cracks can initiate more easily when stress exceeds the local strength of the material. Additionally, thinner structures are less able to bridge and arrest cracks once they form. This can lead to more rapid crack propagation under dynamic compression, especially if there are any existing flaws or imperfections in the

material. More explanations of structural deformation during an impact can be found in the subsequent section.

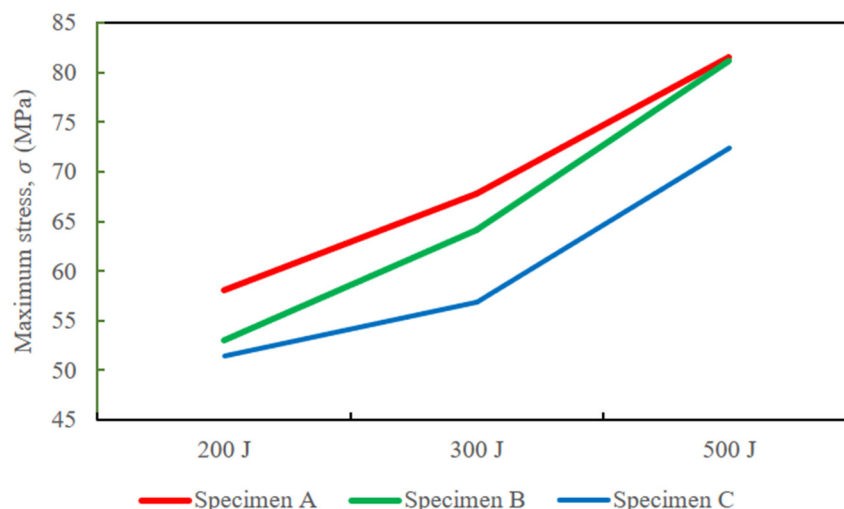


Figure 5. Variation in max stresses with respect to different incident energy levels.

In contrast, thicker tubes provide more material to resist and arrest crack propagation. The increased thickness allows for a more uniform distribution of stresses across the structure and enhances the ability of the material to absorb impact energy without localised failure [30]. Thicker tubes have a greater cross-sectional area, which increases their resistance to crack initiation and slows down the propagation once a crack has formed. This is due to the higher energy required to propagate a crack through a thicker material, making the thicker specimens more resilient to dynamic loading conditions.

The experimental observations and the mechanical behaviour suggest that while thicker tubes improve overall strength and resistance to deformation, they also enhance resistance to crack propagation. This aligns with the general understanding of fracture mechanics [31,32], where increased thickness and material volume contribute to greater toughness and crack resistance.

SEA is a performance indicator that considers the mass of lightweight structures. Energy is expressed mathematically by Equation (4):

$$E = \int_0^{\epsilon} \sigma d\epsilon \quad (4)$$

where E is the amount of energy absorption (J), and σ and ϵ are the compressive stress and strain, respectively. The normalised specific energy absorption (SEA) of all nine test specimens has been tabulated in Table 5 and is presented in Figure 6.

The trend is notable from Figure 6 that the SEA of the bio-inspired structures decreases upon the reduction of its relative density (volumetric fraction), irrespective of the administered incident energy level during dynamic loading. For example, at 200 J incident energy, during the dynamic compression of specimen C200A, the SEA was measured at $2.9 (\pm 0.4)$ (kJ/kg)/(mm). Reducing the relative density of the structure, as exemplified by specimen C200C, led to a notable 13.8% decrease in SEA. Similar observations were made when the specimens were impacted at higher energies.

The consistent observation of the SEA decreasing with the reduction in the volumetric fraction of the bio-inspired structures, even at higher energy levels, can be explained by the inherent properties of the material, the geometry of the structure, and the energy absorption mechanisms of the bio-inspired structures.

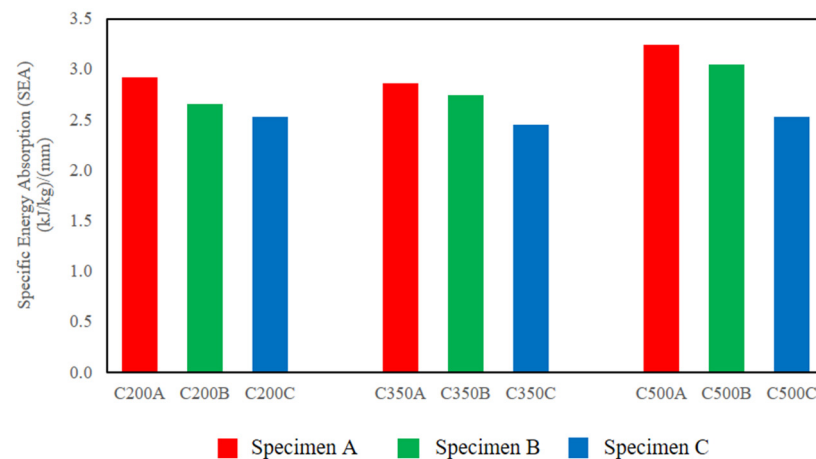


Figure 6. Bar diagrams of the maximum SEA recorded in the impact tests.

The relative density of a structure plays a critical role in determining its energy absorption capacity. Structures with higher relative densities have more material available to absorb and dissipate energy, which leads to higher SEA values. On the other hand, reducing the relative density means less material is present to absorb energy, resulting in a lower SEA. The energy absorption mechanism of the bio-inspired structures is predominantly governed by the same principles, regardless of the incident energy level [33]. When impacted at different energy levels, the structures undergo similar stages of deformation, starting with elastic deformation and followed by plastic deformation and, in some cases, densification.

The decrease in SEA with a reduced relative density is a result of this uniform energy absorption mechanism across all energy levels. Higher energy impacts intensify the stresses experienced by the structures, but the correlation between relative density and SEA remains. As the incident energy increases, both the deformation and energy absorption mechanisms follow a similar pattern, albeit at a higher magnitude [29]. The behaviour is consistent across all the tested energy levels, because the fundamental relationship between material density, structural geometry, and energy absorption capacity does not change.

4.3. Post-Mortem Damage Analysis

To observe the post-deformation behaviour of the cornstalk-inspired lightweight structures after impact, X-ray CT images were taken for visual inspection, as shown in Figure 7.

When the specimens were impacted at an incident energy of 200 J, the motion induced layer fractures in the tube walls and crack initiation at various cell walls throughout the structure. A minor buckling effect was observed only on specimen C after the contact between the impactor and the top surface of the specimen as the impact progressed. Given the lower volumetric fraction of specimen C, there is less material available to resist deformation under load. When the impactor contacts the top surface of specimen C, the thinner tube walls are less capable of withstanding the compressive forces and stresses applied during impact. As a result, the structure is more prone to instability and deformation, such as buckling. Buckling is a common mode of deformation for slender or thin-walled structures under compressive loading [34]. When subjected to dynamic loading, the structural elements of specimen C did not have sufficient rigidity to maintain their original shape, leading to minor buckling.

As the incident energy was increased to 350 J, the damage was initiated on the facesheets, and 3D-printed layer fractures were observed. As the specimen was compressed, it resulted in brittle fractures in the cell walls due to the shear stresses acting on the impacted area. A significant number of vertical cell walls within the pores fractured during compression, followed by some levels of delamination. At 500 J of impact energy, the high

stress concentrations resulted in a shear fracture in the stressed zone of the specimen and initiated layer fractures in the facesheets, thin walls of the tubes, and cell walls of the pores, leading to core disintegration. Layer splitting and debonding were observed on the top facesheets of many specimens due to the continuous pressing action of the impactor.

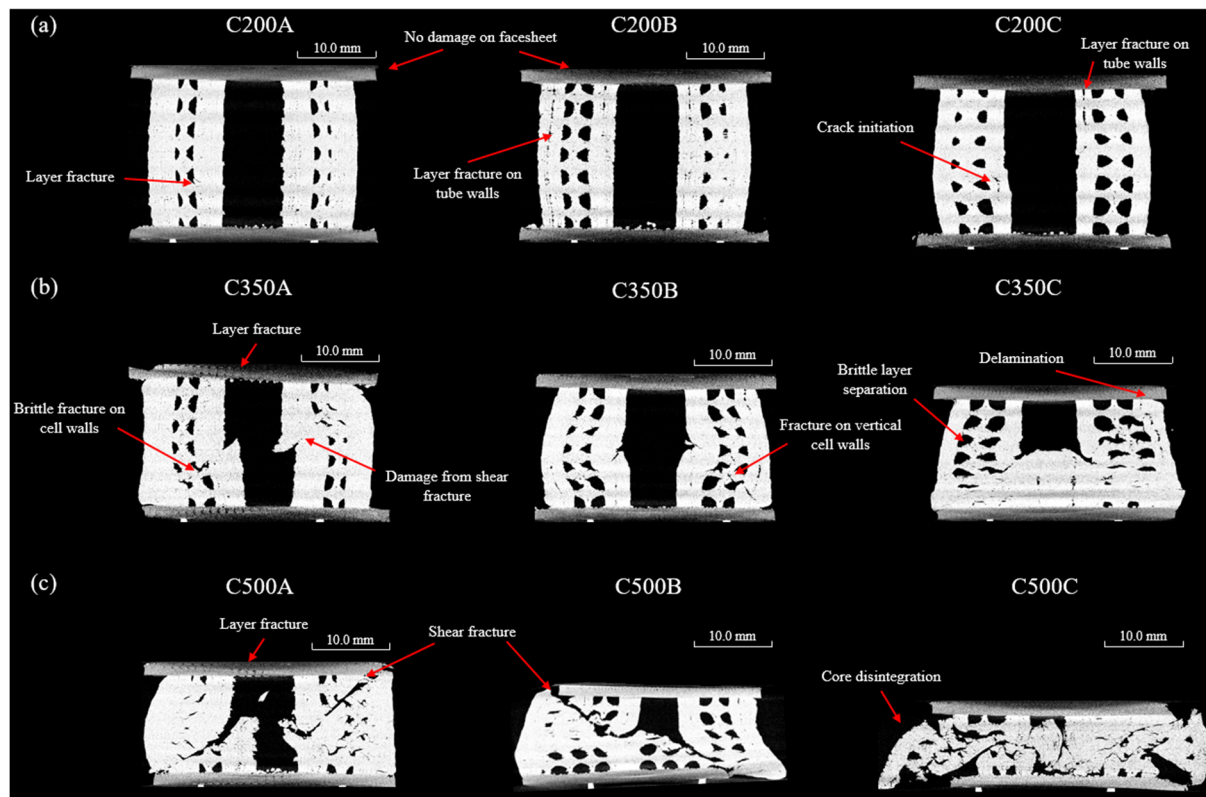


Figure 7. X-ray CT images (voxel: 19.54 μm) of damage characteristics upon impact at (a) 200 J, (b) 350 J, and (c) 500 J.

5. Conclusions

A bio-inspired structure created from the internal architecture of a cornstalk was subjected to impact loading at varying incident energies. The influence of the change in geometry that the specimens undergo on their dynamic response and normalised specific energy absorption was investigated. Lastly, the failure characteristics of the lightweight bio-inspired structures were analysed by X-ray CT scanning to understand the deformation pattern at high impact energies.

Based on the obtained results, several key conclusions can be drawn regarding the mechanical performance of bio-inspired structures. Firstly, these structures demonstrate effective mechanical performance within the range of 200 J to 500 J of incident energy, with the specimens able to withstand impacts without complete failure. Specimens with thicker tubes exhibit superior strength and resilience under dynamic compression across all incident energy levels. Additionally, there is an observed increase in maximum stress (σ_m), stiffness (E), and SEA during the transition from a quasi-static to a dynamic regime. Damage examinations revealed that shear failure of the inner tubes and fracture propagation in the pores contribute to the loss of stiffness during impact, and the collapse sequence of the cell walls varies under different loading conditions.

In addition to exploring the deformation and failure behaviour of bio-inspired structures under impact, this study showed the potential of lightweight porous structures inspired by cornstalks for energy absorption applications in high-speed impact scenarios. The

findings suggest that these structures hold promise for superior performance, nominating them for situations where collisions or other impact events occur at significant velocities.

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