Experimental Comparison of Additively Manufactured PLA Honeycomb Cores with Aluminium and Nomex® for Crashworthy Sandwich Structures

M. P. Falaschetti[1,2,*], F. Semprucci[1], and G. Palardy[3]

[1]Department of Industrial Engineering, University of Bologna, 40136 Bologna, Italy

[2]CIRI Aero Interdepartmental Centre for Industrial Research on Aerospace, University of Bologna, 40136 Bologna, Italy

[3]Department of Mechanical and Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, USA

* Corresponding author (*mariapi.falaschetti2@unibo.it*)

Keywords: *Honeycomb cores; Crashworthiness; Additive manufacturing; PLA; Sandwich structures*

1. Abstract

Honeycomb sandwich structures are extensively used in aerospace and automotive engineering due to their ability to combine low weight with efficient energy absorption. Conventional aluminium and Nomex® honeycomb cores provide reliable mechanical performance; however, they are constrained by manufacturing limitations and exhibit variability in collapse behaviour. Additive manufacturing offers new opportunities to tailor internal geometries and control deformation mechanisms, although the crashworthiness of such structures relative to established materials remains unclear.

This study experimentally evaluates the quasi-static compressive behaviour of additively manufactured polylactic acid (PLA) honeycomb cores and compares their performance with commercially available aluminium and Nomex® cores. Four PLA configurations were investigated, including uniform and bio-inspired graded geometries. The results indicate that, although traditional cores exhibit high Specific Energy Absorption (SEA), their deformation is characterised by mixed collapse modes and significant scatter. In contrast, graded PLA designs promote stable, progressive folding, in which geometric variation governs the collapse sequence. This leads to a marked reduction in variability and demonstrates that appropriately designed additively manufactured cores can achieve consistent, reliable energy absorption comparable to that of conventional solutions.

2. Introduction

Crashworthiness is a fundamental requirement in the design of structures subjected to impact or compressive loading, particularly in aerospace and automotive applications [1,2]. The ability to dissipate kinetic energy in a controlled and predictable manner is essential to protect critical components, cargo, and occupants. For this reason, lightweight energy-absorbing structures have been extensively studied over the past decades [3].

Sandwich structures are among the most effective solutions in this context. Comprising thin, stiff face sheets bonded to a lightweight core, they achieve high bending stiffness at low areal mass [4]. Among the various core topologies, honeycomb architectures are widely adopted due to their efficient load distribution and favourable energy-absorption characteristics [5]. Their cellular geometry promotes progressive collapse under compressive loading, a behaviour particularly desirable in crashworthiness applications [1,3].

Conventional honeycomb cores are typically manufactured from aluminium or aramid-based materials such as Nomex®, both of which exhibit well-established mechanical properties and broad industrial adoption [6]. However, their crushing behaviour is governed by complex, interacting failure mechanisms, including local buckling, fracture, and interfacial debonding, which often proceed non-uniformly, resulting in unstable collapse modes and variability in energy absorption performance [7].

Recent advances in Additive Manufacturing (AM) have significantly expanded the design space for cellular structures. Fused Filament Fabrication (FFF), in particular, enables the production of complex geometries with high degrees of freedom, allowing the tailoring of internal architectures for targeted mechanical responses. This capability has spurred growing interest in bio-inspired design strategies, wherein graded configurations, analogous to those observed in natural load-bearing systems [8,9] are introduced to guide deformation and enhance damage tolerance [10,11]. By incorporating geometric gradients, such as progressive variations in wall thickness or cell size, it becomes possible to steer the collapse front and promote stable, sequential failure [12].

Despite these prospects, the mechanical behaviour of additively manufactured polymeric honeycombs remains considerably less characterised than that of their conventional counterparts [8]. In particular, their crashworthiness performance and deformation repeatability under quasi-static compressive loading warrant systematic investigation.

Therefore, this study evaluates the compressive behaviour of PLA honeycomb cores produced via FFF and benchmarks their performance against aluminium and Nomex® equivalents. The analysis centres on Specific Energy Absorption (SEA), deformation stability, and inter-specimen variability, with the aim of elucidating the influence of geometric design parameters on crash performance.

3. Materials and Methods

3.1 Core Design and Manufacturing

Three core materials were considered: aluminium, Nomex®, and polylactic acid (PLA). The aluminium and Nomex® cores were commercially sourced, whereas the PLA cores were specifically designed for this study. Their general dimensions of all cores were 62 mm (width) x

42 mm (height) x 10 mm (thickness), with an additional bevel of 20º to act as a trigger during compression tests.

Four different PLA geometries were investigated. Two configurations featured uniform wall thickness and served as baseline designs: one with a thick wall measuring 2.16 mm (Figure 1-a) and another with a thinner wall measuring 0.41 mm (Figure 1-b). The latter was selected based on the minimum thickness that could consistently be 3D printed with high quality. The remaining two configurations incorporated a gradual variation in wall thickness inspired by natural cellular systems. One featured a through-thickness gradient (Figure 1-c) while the other employed a through-height gradient (Figure 1-d). In both cases, the minimum and maximum wall thicknesses varied from 0.41 mm to 2.16 mm. The graded geometries were designed to introduce controlled variations in stiffness throughout the structure. This approach aimed to influence the initiation and propagation of deformation during compression.

The specimens were labelled according to their cores, so the coupons with Nomex® core were designed a CN, those with aluminium core as CA, and those with PLA cores as CI, CII, CIII, and CIV, corresponding to geometries in Figure 1-a to Figure 1-d, respectively.

The PLA cores were manufactured using FFF. The printing parameters were selected to ensure adequate dimensional accuracy and interlayer bonding. Key parameters included a printing velocity of 60 mm/s, a layer height of 0.20 mm, a hot end extruder temperature of 200°C, and a bed temperature of 55°C. The selected PLA filament (Sunlu) diameter was 1.75 mm.

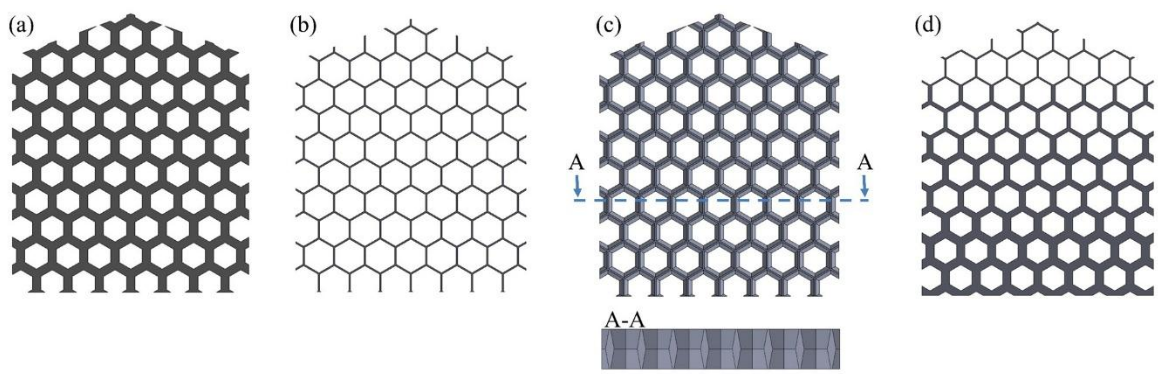

Figure 1. Geometry of the investigated PLA honeycomb cores: a) uniform thick wall (CI), b) uniform thin wall (CII), c) through-thickness gradient (CIII), and d) through-height gradient (CIV).

3.2 Sandwich Panel Manufacturing

All cores were integrated into sandwich structures using carbon fibre (CF)/epoxy face sheets manufactured from T700S-150-DT120 prepreg via a hand lay-up process. The laminates were produced with a $[0/90]_{2s}$ stacking sequence and subsequently cured in an autoclave for 90 minutes at 135°C and 6 bar. The face sheets were then cut by waterjet and bonded to the cores using an epoxy resin at 50°C for 12 hours in an oven.

3.3 Mechanical Testing and Energy Absorption Assessment

Quasi-static compression tests were performed using a displacement-controlled testing machine with a loading rate of 12 mm/min. Load and displacement were continuously recorded throughout the tests, while the deformation process was visually monitored, using a camera (Figure 2), to identify the collapse mechanisms. Five specimens were tested for the CI, CII, CIII, and CA groups, four for the CIV group, and six for the CN specimens.

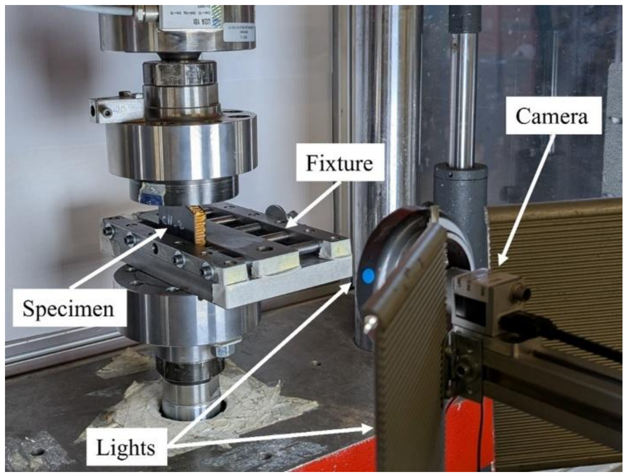

Figure 2. Experimental setup.

The energy absorption assessment was performed by means of the Energy Absorption (*EA*, Eq. 1) and the Specific Energy Absorption (*SEA*, Eq. 2) parameters. The first (Eq. 1) is a measure of the total energy a structure can dissipate during deformation/failure, the latter (Eq. 2) is a normalised measure of that energy that accounts for the mass of the structure. Representing the energy absorbed per unit mass, it is particularly useful when comparing the efficiency of different materials or designs in crashworthy applications.

$$EA(x_c) = \int_{x_0}^{x_c} f(x)dx \tag{1}$$

$$SEA(x_c) = \frac{EA(x_c)}{mx_c/h} = \frac{\int_{x_0}^{x_c} f(x)dx}{m(x_c - x_0)/h} \tag{2}$$

where x_0 and x_c represent the initial and final displacement value for the computation of *EA* and *SEA* parameters, m and h are the mass and height of the tested component, and $f(x)$ is the crushing force. Figure 3 shows a typical Force-Displacement curve during compression tests. In this study, the analysis focused on the plateau region of the response, excluding the initial stabilisation (at $x < x_0$) and final densification phases (at $x > x_c$) of the load.

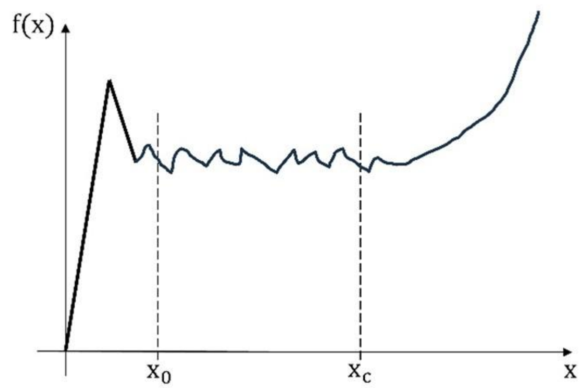

Figure 3. Typical Force-Displacement curve in a crushing compression test.

4. Results and Discussion

As observed in Figure 3, crashworthy components show a compression response with an initial linear stage, followed by a steady-state and a densification phase. However, material properties can cause variations in this behaviour. In this study, notable differences in the stability of the steady-state region were observed across the different coupon groups.

Although all Nomex® core samples (Figure 4-a) exhibited a consistent and repeatable linear elastic phase, the subsequent steady-state region showed considerable variability. The average sustained load was 14.05 kN; however, individual specimens ranged from 9.64 kN to 16.20 kN. This wide dispersion highlights inconsistent mechanical responses of the specimens during the plateau phase, indicating variability in progressive failure mechanisms.

The aluminium core specimens (Figure 4-b) exhibited a relatively stable mechanical response in the steady-state region, with an average sustained load of 14.50 kN. The measured values ranged from 12.69 kN to 16.95 kN, indicating moderate variability among the samples. Overall, the response suggests a reasonably consistent behaviour, although some dispersion in load-carrying capacity remains evident during the plateau phase.

Throughout the PLA cores, the CI configuration (Figure 5-a) showed an average sustained load of 22.94 kN, representing a significant increase compared to the aluminium and Nomex® baselines. However, this set also showed noticeable variability, with values ranging from 16.64 kN to 27.35 kN. The relatively wide range indicates an inconsistent plateau response and load-bearing capacity, suggesting a non-repetitive damage mechanism.

The CII specimens (Figure 5-b) demonstrated a lower average sustained load of 12.60 kN, with the highest dispersion among all the PLA configurations. The recorded values ranged from 10.74 kN to 15.47 kN. This pronounced variability reflects an unstable steady-state region, indicating a less reliable structural response and reduced repeatability compared to the other configurations.

The CIII configuration (Figure 5-c) provided one of the best overall performances, combining a high average sustained load of 20.05 kN with a relatively narrow variation range. The load values ranged from 18.30 kN to 22.23 kN, indicating stable and repeatable steady-state behaviour. This reduced dispersion suggests a more uniform load distribution and a consistent energy absorption mechanism, making CIII one of the most reliable configurations tested.

Among all the configurations, CIV (Figure 5-d) exhibited the most consistent behaviour. With an average sustained load of 18.70 kN and a very limited variation between 17.17 and 19.92 kN, this configuration demonstrated the lowest dispersion. The high stability and repeatability of the mechanical response highlight CIV as the best-performing configuration in terms of consistency, indicating a highly reliable structural behaviour under loading.

This observed stability in the load–displacement response is further supported by the analysis of the SEA parameter. Evaluating the SEA and its associated variability provides a complementary perspective, allowing the consistency of the crushing behaviour to be assessed in terms of both load-carrying capacity and energy absorption efficiency.

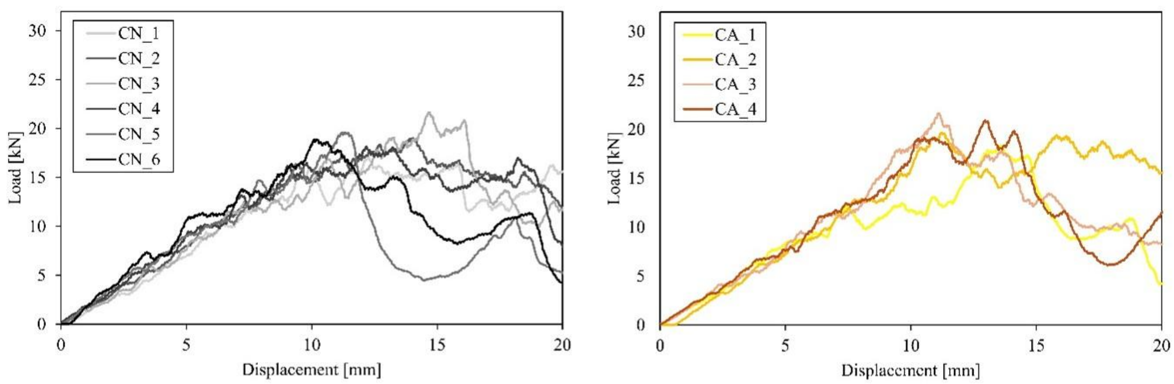

Figure 4. Nomex core (a) and Aluminium core (b) specimens, Load-Displacement curves.

The SEA results (listed in Table 1 and shown in Figure 6) are in good agreement with the trends observed in the load–displacement analysis. The Nomex cores achieved the highest SEA (262.64 J/g), whereas maintaining a relatively low coefficient of variation (CoV) of 5.56%, suggesting an efficient and repeatable energy absorption mechanism despite the previously observed variability in the steady-state region. The aluminium specimens exhibited an average SEA of 230.68 J/g with a CoV of 9.06%, indicating moderate dispersion and a less consistent response compared with the other material systems, which showed lower CoV values.

In contrast, the CII configuration showed the poorest consistency, with a CoV of 10.50%, reinforcing its unstable and unreliable crushing behaviour already highlighted in the load-based results. The CI configuration displayed intermediate behaviour, with a CoV of 8.00%, indicating moderate variability and only partial improvement in stability.

On the other hand, CIII and CIV clearly stand out as the most consistent configurations, with CoV values of 2.99% and 3.23%, respectively. In particular, CIII combines low dispersion with relatively high SEA (208.68 J/g), representing the best compromise between performance and repeatability, whereas CIV, despite exhibiting the lowest SEA (178.55 J/g), demonstrates one of the most stable and predictable responses. Overall, these results confirm that CIII and CIV exhibit the most reliable energy-absorption behaviour, whereas CII remains the least consistent configuration. This confirms the superior crashworthiness performance of the bio-inspired configuration, which can be attributed to its geometric architecture. It promotes a more uniform load distribution across the structure and encourages stable, progressive failure modes that engage a greater proportion of the material volume in energy dissipation compared to conventional designs.

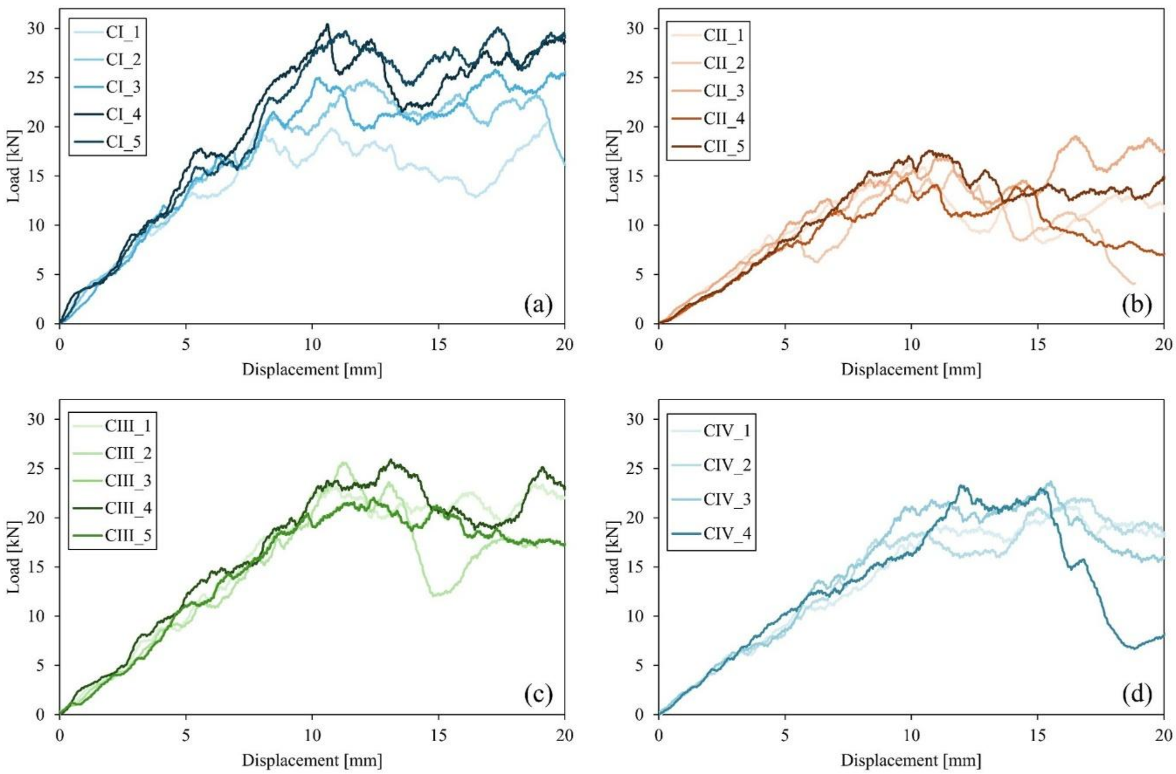

Figure 5. PLA core specimens, Load-Displacement curves. Each graph corresponds to the core geometry shown in Figure 1.

Table 1. Average SEA values for different core configurations.

Core Configuration	Avg. SEA (J/g)	St. Dev. (J/g)
Aluminium	230.68	20.90
Nomex	262.64	14.59
CI	195.05	15.60
CII	223.90	23.51
CIII	208.68	6.24
CIV	178.55	5.76

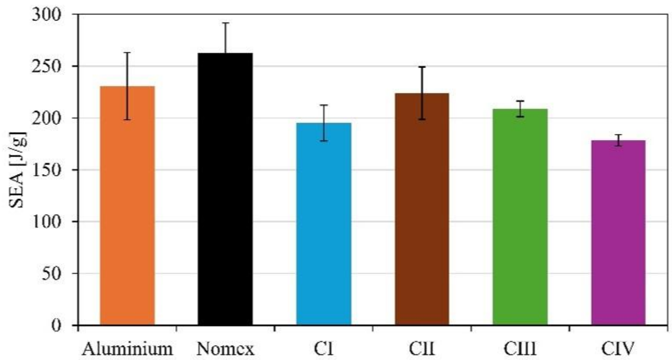

Figure 6. SEA values with standard deviation shown as error bars.

5. Conclusions

This study demonstrates that while traditional aluminium and Nomex® honeycomb cores offer high Specific Energy Absorption, they exhibit significant variability in collapse behaviour, undermining predictability in safety-critical applications. In contrast, additively manufactured PLA cores, specifically the bio-inspired graded configurations, provide a superior balance of structural stability and reliability. These gradient designs achieved low coefficients of variation (as low as 2.99%) compared with conventional materials (5.56 % to 9.06%). Although the absolute SEA of PLA remains lower than that of Nomex®, the CIII configuration emerged as a highly effective compromise, delivering robust energy dissipation with a predictable, repeatable steady-state response. These findings suggest that 3D-printed architectures with tailored internal geometries represent a viable pathway for developing the next generation of high-consistency, crashworthy structures in the aerospace and automotive sectors.

6. References

[1] Mohammadi H, Ahmad Z, Petru M, Mazlan SA, Faizal Johari MA, Hatami H, et al. An insight from nature: honeycomb pattern in advanced structural design for impact energy absorption. Journal of Materials Research and Technology 2023;22:2862–87. https://doi.org/10.1016/J.JMRT.2022.12.063.

[2] Sun G, Chen D, Zhu G, Li Q. Lightweight hybrid materials and structures for energy absorption: A state-of-the-art review and outlook. Thin-Walled Structures 2022;172:108760. https://doi.org/10.1016/J.TWS.2021.108760.

[3] Tarlochan F. Sandwich Structures for Energy Absorption Applications: A Review. Materials 2021, Vol 14, 2021;14. https://doi.org/10.3390/MA14164731.

[4] Zuhri MYM, Guan ZW, Cantwell WJ. The mechanical properties of natural fibre based honeycomb core materials. Compos B Eng 2014;58:1–9. https://doi.org/10.1016/J.COMPOSITESB.2013.10.016.

[5] Li X, Lu F, Zhang Y, Lin Y, Meng Y. Experimental study on out-of-plane mechanical and energy absorption properties of combined hexagonal aluminum honeycombs under dynamic impact. Mater Des 2020;194:108900. https://doi.org/10.1016/J.MATDES.2020.108900.

[6] Aktay L, Johnson AF, Kröplin BH. Numerical modelling of honeycomb core crush behaviour. Eng Fract Mech 2008;75:2616–30. https://doi.org/10.1016/J.ENGFRACMECH.2007.03.008.

[7] Foo CC, Chai GB, Seah LK. Mechanical properties of Nomex material and Nomex honeycomb structure. Compos Struct 2007;80:588–94. https://doi.org/10.1016/J.COMPSTRUCT.2006.07.010.

[8] Isaac CW, Sokołowski A, Duddeck F, Adamiak M, Pakieła W, Aremu A. Mechanical characterisation and crashworthiness performance of additively manufactured polymer-based honeycomb structures under in-plane quasi-static loading. Virtual Phys Prototyp 2023;18. https://doi.org/10.1080/17452759.2023.2273296.

[9] Hidayat D, Istiyanto J, Sumarsono DA, Kurniawan F, Ardiansyah R, Wandono FA, et al. Investigation on the Crashworthiness Performance of Thin-Walled Multi-Cell PLA 3D-Printed Tubes: A Multi-Parameter Analysis. Designs 2023, Vol 7, 2023;7. https://doi.org/10.3390/DESIGNS7050108.

[10] Naleway SE, Porter MM, McKittrick J, Meyers MA. Structural Design Elements in Biological Materials: Application to Bioinspiration. Advanced Materials 2015;27:5455–76. https://doi.org/10.1002/ADMA.201502403;REQUESTEDJOURNAL:JOURNAL:15214095;WGROUP:STRING:PUBLICATION.

[11] Liu Z, Meyers MA, Zhang Z, Ritchie RO. Functional gradients and heterogeneities in biological materials: Design principles, functions, and bioinspired applications. Prog Mater Sci 2017;88:467–98. https://doi.org/10.1016/J.PMATSCI.2017.04.013.

[12] Zhang Z, Chen Z, Hu X, Ding Z, Li C, Xie L, et al. Bio-inspired gradient composite honeycomb with programmable three-stage plateau response: Sequential crushing mechanism and theoretical modeling. Compos B Eng 2026;317:113593. https://doi.org/10.1016/J.COMPOSITESB.2026.113593.