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Meta-level design parameters for bio-inspired impact resistance: a case study in helmet design

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ABSTRACT: Bioinspiration offers an innovative approach to product design. A key challenge is selecting suitable biological features for complex engineering problems. The phenomenon of convergent evolution, where distantly related organisms independently develop similar functions, adds to this complexity. This study introduces novel meta-level design parameters to systematically select biological features with differing geometries yet similar functions. These parameters were derived through physical testing and numerical analysis of woodpecker-beak-inspired and Balanus-inspired structures, focusing on their impact resistance capabilities. These structures demonstrate potential for practical applications, such as in bicycle helmet liners.

KEYWORDS: bio-inspired design / biomimetics, new product development, design methods, early design phases

1. Introduction

Bioinspiration is among the most reliable sources of innovation for product design (Domke & Farzaneh, 2018). Through evolution, biological systems have developed ingenious strategies that serve as a foundation for solving modern engineering challenges. Nature-inspired solutions often outperform traditional designs. For example, Lotus (*Nelumbo nucifera*) leaf-inspired superhydrophobic surfaces (Zhang et al., 2016), Kingfisher (*Ceyx azureus*) beak-inspired low puncture force structures (McKeag, 2012; Velivela et al., 2021), Honeycomb-inspired energy absorbing structures (Zhang et al., 2019), etc. Abstraction of functions exhibited by biological features of over 50 organisms reveals that many biological features serve multiple functions and that analogous functions can arise in different organisms (Velivela & Zhao, 2023a). Despite the growing body of work in bio-inspired design, no quantitative parameters have been established to systematically select between the biological features from distant organisms that exhibit identical functionality. The challenge lies in distinguishing which biological feature is best suited for a specific engineering application, as multiple organisms may evolve similar traits to address comparable environmental demands. For instance, it is tough to choose between Shark scales and Dolphin skin that exhibits drag-reducing properties (Luo et al., 2015; Yu et al., 2020). In nature, this phenomenon is termed as convergent evolution. Convergent evolution refers to the process by which distantly related species independently develop similar biological features, to fulfill equivalent functional roles, such as drag reduction, impact resistance, or water repellence, which are crucial in bio-inspired design for selecting the most relevant biological analogy (Kasahara, 2010; Moore & Willmer, 1997). These traits, recognized as biological adaptations developed by different organisms for similar purposes, pose a unique challenge in early-stage product design, as it involves selecting the most relevant feature from a variety of analogous adaptations. To streamline this selection, designers rely on qualitative parameters, supported by Bio-inspired Design (BID) methods such as BioGEN (Badarnah & Kadri, 2015), System-of-Systems BID (Tan et al., 2019), Reduced Function-Means (RF-M) (Bhasin et al., 2021), and the Trimming method (Zhang et al., 2021). While these methods provide valuable qualitative criteria for identifying suitable biological analogies, quantitative parameters become essential to accurately differentiate traits evolved in similar environments and on comparable scales. To address this issue, quantitative metrics called meta-level design parameters are introduced to facilitate precise selection between biological features with similar characteristics (geometric designation) and functionalities. These parameters were verified through case studies involving impact resistance comparisons of woodpecker's beak and pomelo peel (Velivela et al., 2023) and drag reduction comparisons of sharkskin and dolphin skin (Velivela et al., 2024). Building on this foundation, this research extends these parameters by introducing novel meta-level design parameters that enable the selection of biological features based on shared functional capabilities, irrespective of geometric similarity. It emphasizes the development of parameters derived solely from the geometry of biological structures, independent of evolutionary influences. A case study of a multifunctional, bio-inspired helmet conceptual design is conducted to investigate the parameter through a comparative study of two different structures that solve the same function. For this study, the impact resistance of the Woodpecker's beak and Balanus exoskeleton that have the potential to be used as helmet liners are compared.

The paper is organized as follows. Section 2 provides an overview of the Domain Integrated Design (DID) method used for conceptualising the helmet, meta-level design parameters, and influence of geometry in bio-inspired design. Section 3 outlines the conceptual design of the bio-inspired helmet using DID, including geometric modelling and 3D printing of woodpecker beak and Balanus-shaped liners, along with a review of existing bio-inspired helmet liners and impact tests. Section 4 details the experimental and the numerical analysis used for deriving the proposed meta-level design parameters. Section 5 discusses the novel meta-level design parameters, followed by concluding remarks.

2. DID and meta-level design parameters

Domain Integrated Design (DID) categorizes biological features into geometric domains (e.g., Surfaces, Cellular Structures, Shapes and Cross-sections) based on their characteristics. By systematically combining features from different domains, DID enables the development of multifunctional bio-inspired designs across various applications (Velivela & Zhao, 2023b). As shown in Figure 1, the bio-inspired helmet integrates features from different doamins, including a penguin's spindle body shape for drag reduction (Yu et al., 2020) – Shape domain, a luffa sponge-inspired structure for effective sweat absorption (Shen et al., 2012) – Cellular Structure domain, and helmet liners inspired by a woodpecker's beak (Velivela et al., 2023) – Cellular Structure domain, and Balanus (San Ha & Lu, 2020) – Shape domain. This study applies the DID method to the conceptual design of a bio-inspired helmet, using it as a means to establish parameters for selecting between morphologically different biological features that perform the same function. Specifically, helmet liners inspired by a woodpecker's beak and Balanus were designed and evaluated through testing and numerical analysis, demonstrating how DID facilitates systematic decision-making in bio-inspired design.

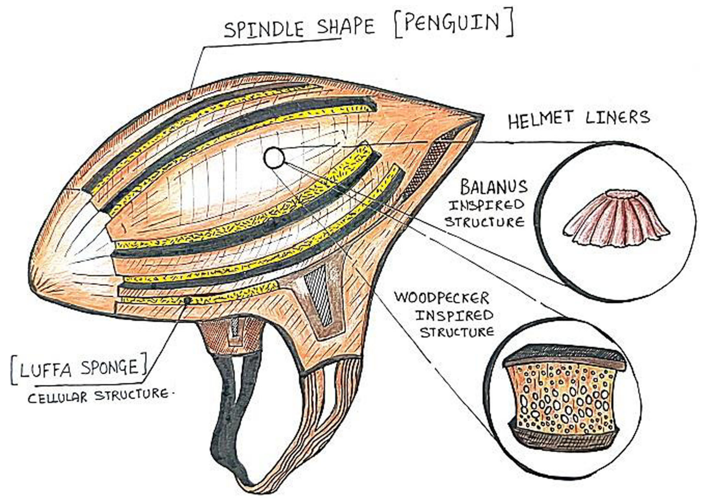

Figure 1. Conceptual sketch of the helmet liners inspired by woodpecker's cellular beak and Balanus shape. The helmet shape inspired inspired by a penguin's body for drag reduction and luffa sponge for sweat absorption

2.1. Meta-level design parameters

The meta-level design parameters shown in Table 1 (Velivela et al., 2024) are quantitative parameters that are integrated into the DID method (Velivela & Zhao, 2022) and the Expandable Domain Integrated Design model (xDID) (Velivela & Zhao, 2023b), enabling the selection between biological features exhibiting the same function and belonging to the same Domain (similar geometric relevance). These paramerts were verified through two independent case studies. The first study examines the impact resistance of a non-pneumatic tire inspired by woodpecker beaks and pomelo peels (Cellular Structures Domain) (Velivela et al., 2023). The second study compares drag reduction in swimsuits inspired by sharkskin and dolphin skin (Surfaces Domain), finding sharkskin more effective due to its smaller interaction area (Velivela et al., 2024).

Table 1. Meta-level design parameters

Domains	Meta-level design parameters
Surfaces	Interaction area
Cellular Structures	Interaction area; Porosity
Shapes	Scale
Cross-sections	Scale

2.2. Geometric influence in bio-inspired design

In this research, the biological features compared are the woodpecker's beak classified as the Cellular Structure Domain, and the Balanus-inspired conical structure classified as the Shapes Domain. These features were chosen because they represent distinct geometric adaptations that solve similar functional challenges – impact resistance. By comparing these features, this work aims to illustrate how different geometric strategies can be employed to achieve similar functional goals. As discussed earlier, this research emphasizes the development of parameters based solely on the geometry of biological structures, independent of their evolutionary pressures. For example, the cellular structure of a woodpecker's beak, adapted for enduring high-frequency repetitive axial loads, offers insights into shock absorption and energy dissipation through its geometry (Lee et al., 2013). Conversely, the geometric structure of a barnacle (Balanus) shell, adapted to withstand slower, continuous compressive forces from water pressure and wave impacts, illustrates principles of stability and load resistance (Shaw et al., 2024). While the woodpecker's beak is designed to prioritize impact deceleration and mitigation, the barnacle's shell emphasizes structural stability and resilience under compressive forces. However, by focusing on geometry alone, designers can gain insights into the structural benefits that shape can provide under various loading conditions, irrespective of the specific evolutionary stresses that shaped them.

3. Verification of Meta-level design parameters through design, fabrication, and testing

The DID method is employed to generate a multifunctional bio-inspired helmet design. This involves combining biological features, categorized based on their geometric attributes, to achieve diverse functionalities. The resulting helmet integrates a penguin's spindle body shape to enhance drag reduction for the outer body (Yu et al., 2020), a luffa sponge-inspired structure for efficient sweat absorption (Shen et al., 2012), and features inspired by a woodpecker's beak (Velivela et al., 2023) and Balanus (San Ha & Lu, 2020) for the helmet liners. Geometric modeling of the bio-inspired structures was carried out using LatticeQuery (Letov & Zhao, 2022), a software derived from CadQuery specifically for designing complex cellular structures. This tool was instrumental in accurately replicating the intricate geometries of biological inspirations, such as the gradient porosity of a woodpecker's beak and the corrugated surface of the Balanus exoskeleton. The gradient porosity characteristic of the woodpecker's beak, vital for its shock-absorbing capability, was emulated using a lattice structure based on the Schwarz Primitive topology. This design aspect was critical for replicating the beak's energy absorption efficiency (Letov et al., 2021). The Balanus structure was modeled to include its conical shape and distinctive corrugated surface attributes, that contribute to its resilience against compressive forces. A parametric sinusoidal waveform was utilized to capture the spiral form and corrugations accurately (Letov & Zhao, 2022). These models were fabricated using additive manufacturing, with Formlabs BioMed resin selected for its durability, flexibility, and biocompatibility, ensuring the structural integrity, safety of the helmet liners, and suitability for prolonged skin contact (San Ha & Lu, 2020).

3.1. Reported bio-inspired helmet liner designs

Bicycle helmet liners draw inspiration from diverse composite and biologically inspired structures, aiming to safeguard the head against rotational accelerations. Ongoing research focuses on integrating bio-inspired designs into helmets, offering significant potential for energy absorption strategies. The outer shell's key roles include distributing impact loads across a wide area and preventing penetration by sharp objects to avoid skull punctures and brain injuries (Leng et al., 2022). The MIPS system, featuring a slip-layer between the outer shell and inner foam, allows sliding to mimic the protective properties of cerebrospinal fluid (Leng et al., 2022). Literature explores designs for anti-rotational helmet liners, drawing inspiration from various biological materials and structures, such as coconut material (Cocos nucifera) (Totla et al., 2020), pomelo fruit-inspired structures (Fischer et al., 2010), trabeculae bone (Mehta et al., 2016), sheep (Ovis aries) horn-inspired structures (Gennarelli, 1993), lattice arrays, woodpecker, honeycomb, and conch shell structures (Leng et al., 2022).

3.2. Reported study on impact resistance

Various helmet designs were tested for effectiveness in the literature. Examples include oblique impact tests on bicycle helmets using a free-falling head form and a moving sandwich with two aluminium plates, measured with tri-axial quartz force cells (McIntosh et al., 2013). Shin-guard structures' energy absorption was tested under low-velocity impacts using a twin-wire guided vertical impactor (Wang et al., 2023). The BMW Group conducted tensile testing of metal cellular structures (Fischer et al., 2010). A recent study compared the effectiveness of pomelo fruit, woodpecker beak, and shell designs using a polycarbonate impactor model in LS-DYNA, revealing that the Pomelo structure exhibited lower deformation than woodpecker and shell designs (Najmon et al., 2018).

4. Results

This section is divided into two main subsections that discuss physical experiment results and numerical analysis results, each providing insights into the performance and characteristics of the designed bio-inspired structures under various testing conditions.

4.1. Physical experimentation results

Physical tests were conducted in line with ASTM F1952 standards, employing a 1.6 m drop height to simulate impact conditions relevant to helmet safety (ASTM). The experiments involved bio-inspired structures inspired by the woodpecker's beak and Balanus, tested at incremental velocities to assess their impact resistance capabilities (Figures 2(a) and 2(b) illustrate the impact direction). Notably, the Balanus-inspired structures demonstrated a significantly higher impulse absorption compared to the woodpecker-inspired structures, as evident from the force-time graphs in Figure 3. This trend was consistent across various impact velocities, highlighting the Balanus-inspired design's superior performance in dissipating impact energy. These tests not only validate the theoretical models but also provide tangible evidence of the potential improvements in impact resistance offered by bio-inspired designs. The Balanus-inspired structures demonstrated remarkable impact absorption capabilities, reinforcing the concept that natural designs can be effectively translated into protective gear with superior performance characteristics (Fischer et al., 2010; San Ha & Lu, 2020).

4.2. Numerical analysis results

To further elucidate the experimental findings, a numerical analysis was conducted, spanning explicit dynamics and static structural analysis. This multi-phase approach aimed to explore the underlying factors contributing to the observed performance variation between the Balanus and woodpecker-inspired designs. Figure 4 (a) to (d) illustrate the CAD models of unit repetitive and single-strip structures used for explicit dynamic and static structural analysis. The numerical analysis, encompassing both explicit dynamics and static structural assessments, offers a comprehensive understanding of the intrinsic properties contributing to the efficacy of bio-inspired designs (Letov & Fiona Zhao, 2023), (Najmon et al., 2018). This analytical approach not only supports the physical testing outcomes but also provides deeper insights into the material and structural differences that support the enhanced performance of these designs. Through these simulations, the superior energy absorption and stress distribution characteristics of the Balanus-inspired designs were elucidated, highlighting the advanced protective capabilities that can be achieved by emulating nature's resilience.

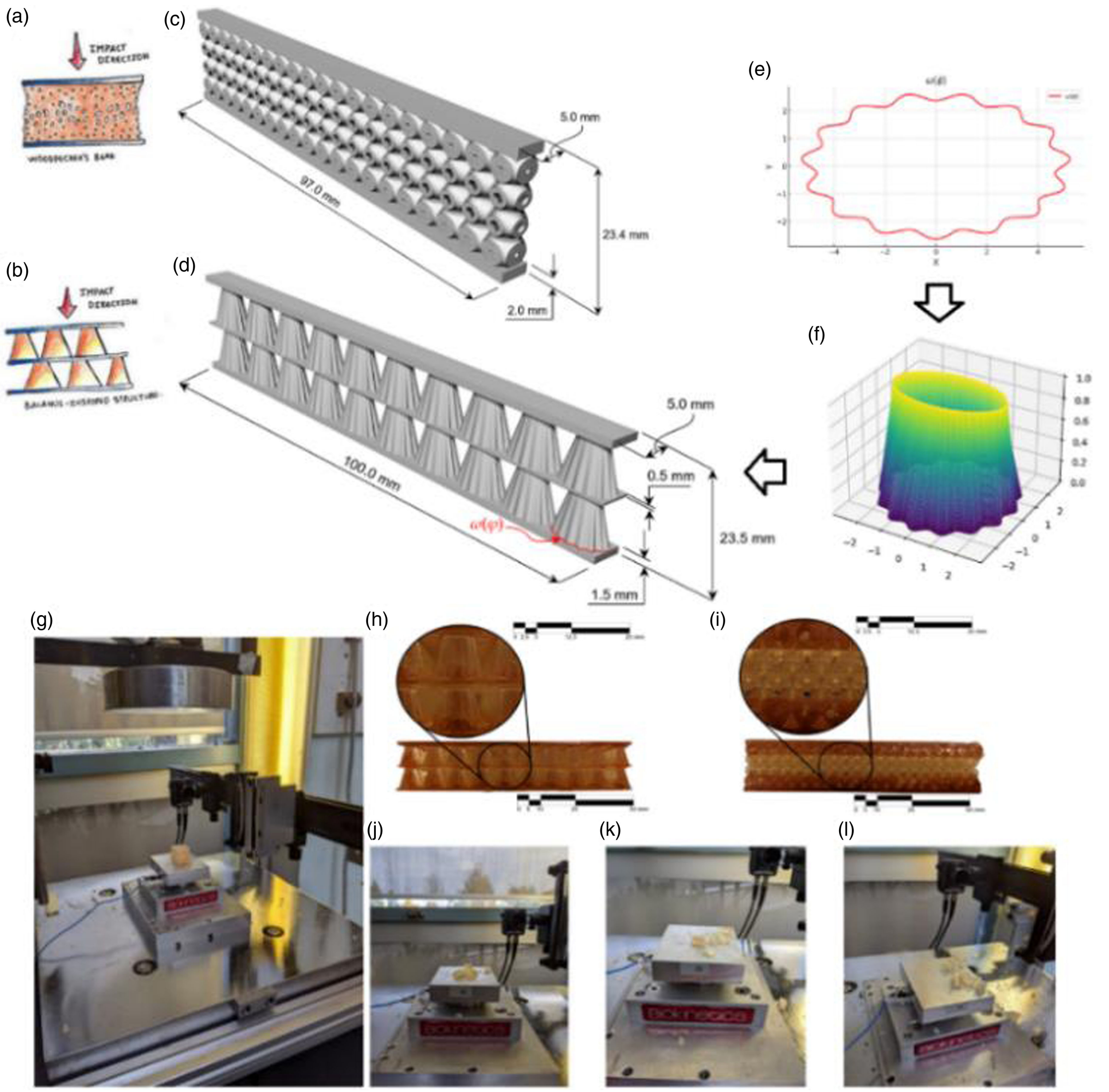

Figure 2. Illustrations showing the impact direction on the two designs, (a) Woodpecker's beak-inspired and (b) Balanus-inspired structures, (c) the Woodpecker beak-inspired structure of the helmet liner with gradient porosity that is mimicked by a Schwarz Primitive surface and (d) the Balanus-inspired structure of the helmet liner, (e) representation of the base and (f) the surface of the Balanus-inspired structure with corrugations, (g) 3D printed bio-inspired structures using Formlabs Biomed Amber under the testing equipment of Biokinetics (h) Balanus-inspired structure, (i) Woodpecker-inspired structure, (j) crushed samples of Balanus-inspired structure, (k) crushed sample of woodpecker-inspired structure, (l) Crushed samples of slender 3D printers

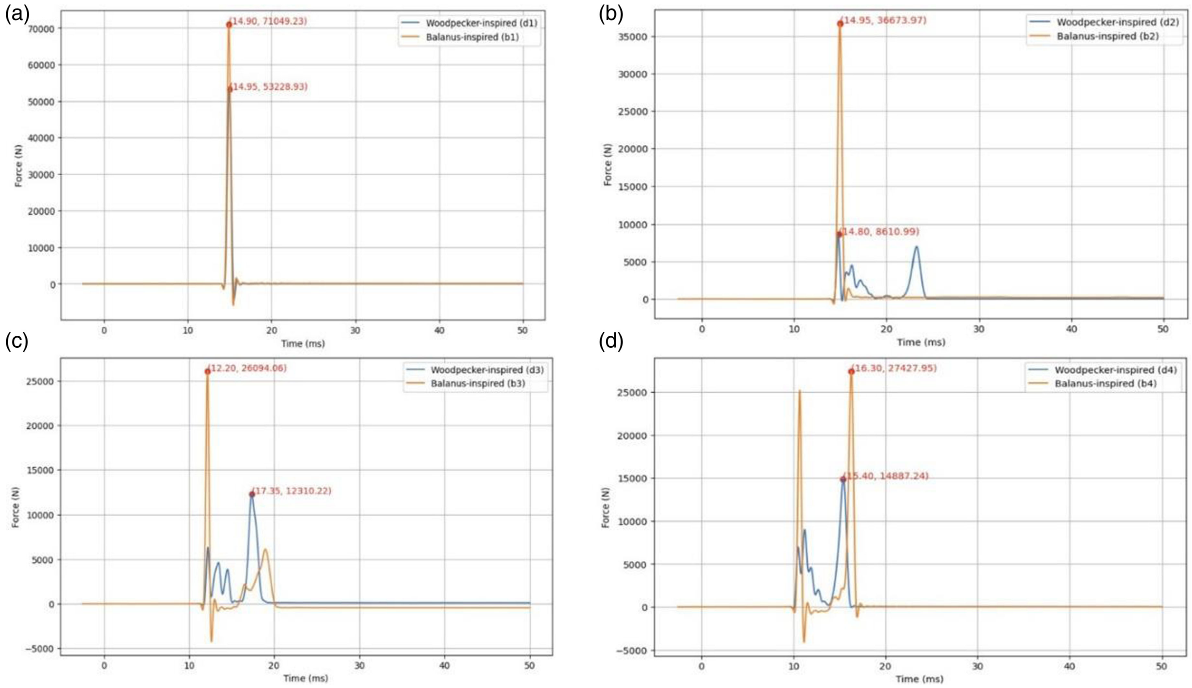

Figure 3. Force vs. time graphs obtained from the impact testing of bio-inspired structures with the velocities of (a) 3.96 m/s, (b) 3.98 m/s, (c) 4.84 m/s, and (d) 5.61 m/s

4.2.1. Simulation setup in ANSYS

The numerical analysis was conducted in ANSYS (student), leveraging the explicit dynamics and static structural solvers to simulate real-world impact scenarios: The explicit dynamics analysis phase involved simulating impacts at various velocities on unit strips of the designs, assessing their deformation, stress distribution, and energy absorption under dynamic conditions (Najmon et al., 2018). Additional analyses were performed under static conditions on single strips and unit-repetitive structures, evaluating their mechanical responses to incremental loads to understand their structural behavior and resilience (Li et al., 2019). A mesh convergence study was conducted to ensure the reliability of the simulation results, optimizing the mesh size to achieve a balance between computational efficiency and result accuracy (Dayyani et al., 2015).

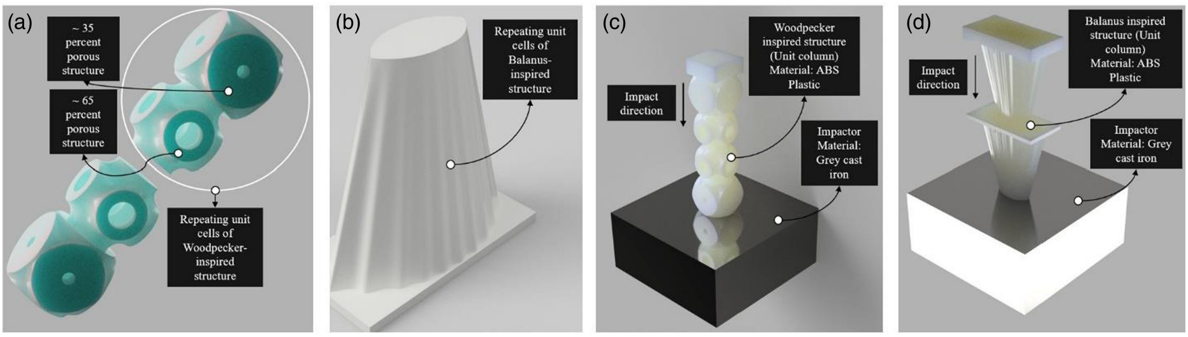

Figure 4. Illustrations of structures used for explicit dynamics and static structural analysis a) Unit repetitive structure of the woodpecker-inspired structure for static analysis; b) Unit repetitive structure of the Balanus-inspired structure for static analysis; c) Single-strip Woodpecker-inspired structure and the impactor for explicit dynamic analysis; d) Single- strip Balanus-inspired structure and the impactor for explicit dynamic analysis

Explicit dynamics analysis

Initial simulations focused on moderate and high-velocity impacts on unit strips of both designs. The Balanus-inspired structures exhibited enhanced deformation capabilities and lower maximum equivalent stresses compared to their woodpecker-inspired counterparts. The equivalent stress experienced by the Balanus-inspired and Woodpecker-inspired structures at 15 m/s are $2.78 \cdot 10^7$ Pa, $5.06 \cdot 10^7$ Pa, and at 60 m/s are $5.02 \cdot 10^7$ Pa and $2.56 \cdot 10^8$ Pa respectively. Figures 6 a, 6 b, and 6 c show explicit dynamic test results for moderate (6–15 m/s) and high (40–60 m/s) impact velocities v. These results suggest a more efficient energy absorption mechanism inherent to the Balanus design, even when subjected to high-impact velocities.

4.2.3. Static structural analysis

Subsequent static analysis on single strips under incremental loads further confirmed the superior performance of the Balanus design. The static analysis was performed under incrementally varying load conditions at 5000 N, 7500 N, and 10000 N respectively. The Balanus-inspired structures demonstrated lower total deformation and equivalent stress across all loading conditions. The maximum equivalent stress experienced by the Balanus and Woodpecker-inspired structures at a load of 10000 N are $1.58 \cdot 10^9$ Pa and $1.32 \cdot 10^{10}$ Pa respectively. Figures 6 d, e, f, g, and h show the static structural analysis results which indicate robust structural integrity conducive to impact resistance.

4.2.4. Unit-repetitive structure analysis

Focusing on unit-repetitive structures, the static-structural analysis revealed consistent trends, with Balanus-inspired designs outperforming the woodpecker-inspired structures in terms of deformation and stress distribution as depicted in Figure 6 d, e, f, g, and h with dashed lines, thus visually depicting the minimal deformation in the Balanus-inspired designs, emphasizing their superior structural efficiency. The structural analysis was performed under incrementally varying conditions at 5000 N, 7500 N, and 10000 N respectively. The maximum equivalent stress experienced by the unit-repetitive Balanus and Woodpecker-inspired structures at 10000 N load conditions are $9.68 \cdot 10^8$ Pa, and $1.27 \cdot 10^{10}$ Pa respectively. The Woodpecker-inspired structure experiences higher stress at the regions of higher porosity and is prone to failure at a faster rate. This observation using numerical analysis supports the results acquired through physical experimentation.

5. Discussion and conclusion

Empirical and numerical analyses highlight the superior impact resistance of Balanus-inspired structures over woodpecker-inspired designs. While the woodpecker's cranial and beak morphology enables it to withstand repetitive high-velocity impacts (Najmon et al., 2018). This biological marvel inspires the design of helmet liners that can offer similar protective benefits for human users, particularly in scenarios involving abrupt head movements or collisions. Balanus shells' conical shape and corrugated exterior provide exceptional resistance to compressive forces and extreme marine stresses (SPIVEY, 1988; Tuzgel et al., 2022). Applying these bioinspired principles to helmet liners enhances their ability to absorb and dissipate impact energy, reducing injury risks. Tests show Balanus-inspired designs achieve higher impulse resistance and lower stress levels compared to woodpecker-inspired structures, making them more effective for impact protection. Two key factors contribute to the superior performance of the Balanus-inspired structure:

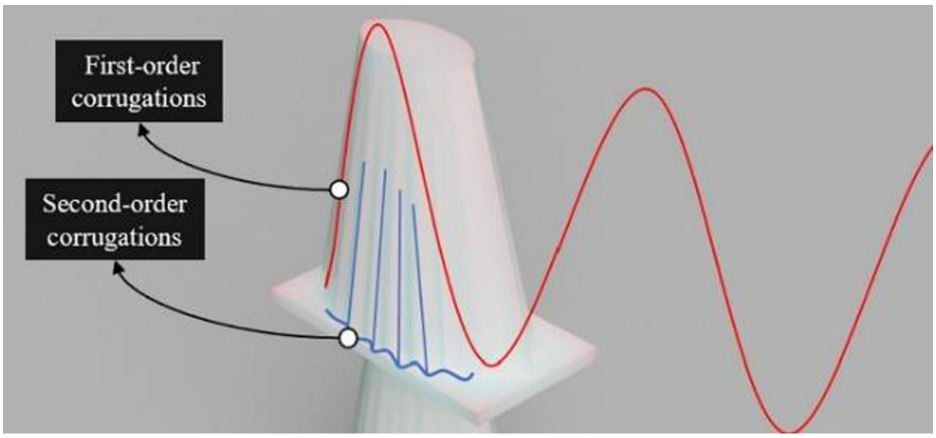

Figure 5. Higher order corrugated structure: the conical structure represents first-order corrugations (depicted in red), and the surface corrugations represent the second order corrugations (depicted in blue)

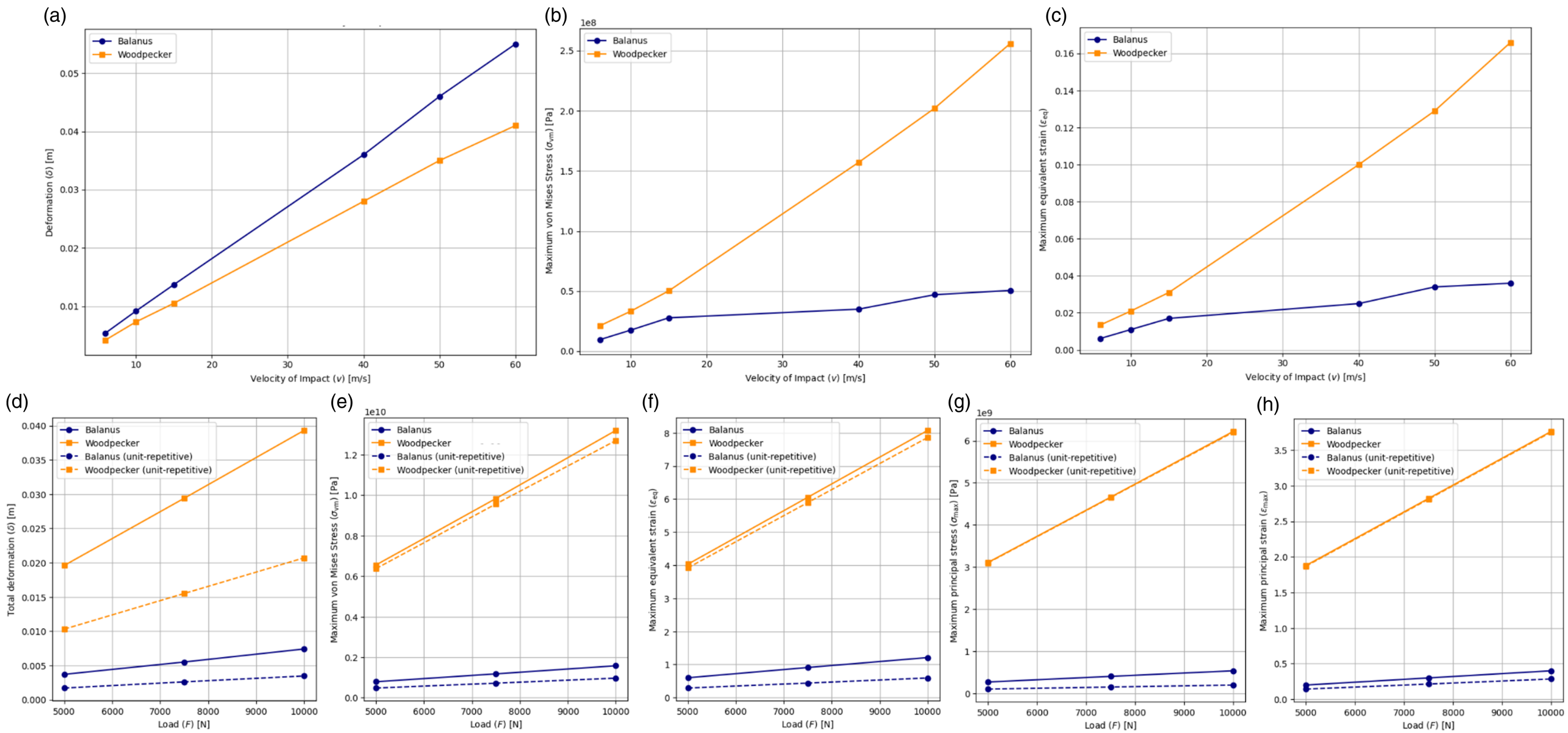

Figure 6. Numerical analysis results: explicit dynamics analysis results of (a) deformation Δ, (b) maximum von Mises stress σ_{vm}, (c) maximum equivalent strain ε_{eq}; static structural analysis of (d) deformation Δ, (e) maximum von Mises stress σ_{vm}, (f) maximum equivalent strain ε_{eq}, (g) principal stress σ_{max}, and (h) principal strain ε_{max}

1. Surface Corrugations: The conical structure's surface corrugations delay elastic buckling by distributing stresses more effectively. A comprehensive review of corrugated structures shows that local corrugations significantly enhance stability under load (Dayyani et al., 2015).
2. Higher Stiffness-to-Weight Ratio: Increased structural hierarchy, resulting from additional corrugations, raises the stiffness-to-weight ratio, improving stability and resistance to buckling. Studies report that higher-order hierarchical sandwich structures exhibit better strength than the first-order corrugated structures, significantly increasing the critical buckling load and overall shell stability (Dayyani et al., 2015).

Figure 5 visually explains the second-order corrugations of the Balanus-inspired structure. The first-order corrugation is the conical shape of the Balanus-inspired structure as depicted in colour red, and additional corrugations on the surface of the conical shape represent the second-order corrugated structure as depicted in blue. It could be argued that the woodpecker's beak-inspired structure also possesses a second-order hierarchical nature, considering the two changes in porosity within it, from 35% to 65% and vice versa. However, in such instances, an additional factor, namely the stiffness-to-weight ratio, plays a critical role in determining effective impact resistance. The comparison of the stiffness-to-weight ratios was estimated in this work through k/V at loads 5000 N and 10000 N, where $k = F/\delta$ is stiffness, F is the force acting on the structure, δ is the deformation of the body, and V is the volume of the structure as the material remains the same. $k/V = 2.45 \times 10^{12}$ Nm for the Balanus-inspired structure and $k/V = 2.45 \times 10^{12}$ Nm for the woodpecker-inspired structure. Empirical and numerical results helped identify key parameters for selecting between biological features with different geometries that exhibit similar functions.

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Data Availability: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Reference

ASTM. *ASTM F1952-00 Standard Specification for Helmets Used for Downhill Mountain Bicycle Racing*. Retrieved September from https://www.astm.org/f1952-00.html

Badarnah, L., & Kadri, U. (2015). A methodology for the generation of biomimetic design concepts. *Architectural Science Review*, 58(2), 120–133. https://doi.org/10.1080/00038628.2014.922458

Bhasin, D., McAdams, D. A., & Layton, A. (2021). A product architecture-based tool for bioinspired function-sharing. *Journal of Mechanical Design*, 143(8).

Dayyani, I., Shaw, A., Flores, E. S., & Friswell, M. (2015). The mechanics of composite corrugated structures: A review with applications in morphing aircraft. *Composite Structures*, 133, 358–380.

Domke, M.-L., & Farzaneh, H. H. (2018). *Research in bio-inspired design-what is its current focus? DS 89: Proceedings of The Fifth International Conference on Design Creativity (ICDC 2018)*, University of Bath, Bath, UK,

Fischer, S. F., Thielen, M., Loprang, R. R., Seidel, R., Fleck, C., Speck, T., & Bührig-Polaczek, A. (2010). Pummelos as concept generators for biomimetically inspired low weight structures with excellent damping properties.*Advanced Engineering Materials*, 12(12), B658-B663.

Gennarelli, T. A. (1993). Mechanisms of brain injury. *The Journal of emergency medicine*, 11, 5–11.

Kasahara, M. (2010). Genome duplication and T cell immunity. *Progress in molecular biology and translational science*, 92, 7–36.

Lee, N., Horstemeyer, M., Seely, D., & Williams, L. N. (2013). The Woodpecker's Beak: An Optimally Designed Structure/Material for Energy Absorption and Shock Mitigation. *Proceedings of the International Conference on Creationism*,

Leng, B., Ruan, D., & Tse, K. M. (2022). Recent bicycle helmet designs and directions for future research: A comprehensive review from material and structural mechanics aspects. *International Journal of Impact Engineering*, 168, 104317.

Letov, N., & Fiona Zhao, Y. (2023). Beam-based lattice topology transition with function representation. *Journal of Mechanical Design*, 145(1), 011704.

Letov, N., Velivela, P. T., Sun, S., & Zhao, Y. F. (2021). Challenges and opportunities in geometric modeling of complex bio-inspired three-dimensional objects designed for additive manufacturing. *Journal of Mechanical Design*, 143(12), 121705.

Letov, N., & Zhao, Y. F. (2022). A geometric modelling framework to support the design of heterogeneous lattice structures with non-linearly varying geometry. *Journal of Computational Design and Engineering*, 9(5), 1565–1584. https://doi.org/10.1093/jcde/qwac076

Li, D., Liao, W., Dai, N., & Xie, Y. M. (2019). Comparison of mechanical properties and energy absorption of sheet-based and strut-based gyroid cellular structures with graded densities. *Materials*, 12(13), 2183.

Luo, Y., Yuan, L., Li, J., & Wang, J. (2015). Boundary layer drag reduction research hypotheses derived from bio-inspired surface and recent advanced applications. *Micron*, 79, 59–73.

McIntosh, A. S., Lai, A., & Schilter, E. (2013). Bicycle helmets: head impact dynamics in helmeted and unhelmeted oblique impact tests. *Traffic injury prevention*, 14(5), 501–508.

McKeag, T. (2012). *Auspicious Designs Zygote Quarterly Summer 2012*. https://issuu.com/eggermont/docs/zq_issue_02r_final

Mehta, P. S., Solis Ocampo, J., Tovar, A., & Chaudhari, P. (2016). *Bio-inspired design of lightweight and protective structures*.

Moore, J., & Willmer, P. (1997). *Convergent evolution in invertebrates. Biological Reviews*, 72(1), 1–60.

Najmon, J. C., Jacob, D. J., Wood, Z. M., & Tovar, A. (2018). Cellular helmet liner design through bio-inspired structures and topology optimization of compliant mechanism lattices. *SAE International journal of transportation safety*, 6(3), 217–236.

San Ha, N., & Lu, G. (2020). A review of recent research on bio-inspired structures and materials for energy absorption applications. *Composites Part B: Engineering*, 181, 107496.

Shaw, J., Kang, Y., Triano, C., Hoppe, C. J., Aldred, N., Metzler, R. A., & Dickinson, G. H. (2024). Comparative Assessment of Shell Structural, Mechanical, and Elemental Properties in Adult Acorn Barnacles. *Diversity*, 16(8), 482.

Shen, J., Xie, Y. M., Huang, X., Zhou, S., & Ruan, D. (2012). Mechanical properties of luffa sponge. *Journal of the Mechanical Behavior of Biomedical Materials*, 15, 141–152.

SPIVEY, H. R. (1988). Shell morphometry in barnacles: quantification of shape and shape change in Balanus. *Journal of Zoology*, 216(2), 265-294.

Tan, N., Sun, Z., Mohan, R. E., Brahmananthan, N., Venkataraman, S., Sosa, R., & Wood, K. (2019). A system-of-systems bio-inspired design process: conceptual design and physical prototype of a reconfigurable robot capable of multi-modal locomotion. *Frontiers in neurorobotics*, 13, 78.

Totla, S. K., Pillai, A. M., Chetan, M., Warad, C., Vinodkumar, S., Patil, A. Y., & Kotturshettar, B. (2020). Analysis of helmet with coconut shell as the outer layer. *Materials Today: Proceedings*, 32, 365–373.

Tuzgel, F., Akbulut, E. F., Guzel, E., Yucesoy, A., Sahin, S., Tasdemirci, A., & Guden, M. (2022). Testing and modeling blast loading of a sandwich structure cored with a bio-inspired (balanus) core. *Thin-Walled Structures*, 175, 109185.

Velivela, P. T., Letov, N., Kong, L., & Zhao, Y. F. (2023). A case study of multifunctional non-pneumatic tire design for the validation of meta-level design parameter in domain integrated design (did) metHOD. *Proceedings of the Design Society*, 3, 39–48.

Velivela, P. T., Letov, N., Liu, Y., & Zhao, Y. F. (2021). APPLICATION OF DOMAIN INTEGRATED DESIGN METHODOLOGY FOR BIO-INSPIRED DESIGN-A CASE STUDY OF SUTURE PIN DESIGN. *Proceedings of the Design Society*, 1, 487–496.

Velivela, P. T., Ridard, A., & Zhao, Y. F. (2024). Parameters for selecting biological features in multifunctional bio-inspired design: a convergent evolution approach. *Bioinspiration & biomimetics*, 19(3), 036020.

Velivela, P. T., & Zhao, Y. F. (2022). A Comparative Analysis of the State-of-the-Art Methods for Multifunctional Bio-Inspired Design and an Introduction to Domain Integrated Design (DID). *Designs*, 6(6), 120.

Velivela, P. T., & Zhao, Y. F. (2023a). BIKAS: Bio-Inspired Knowledge Acquisition and Simulacrum—A Knowledge Database to Support Multifunctional Design Concept Generation. *Data Intelligence*, 1–28.

Velivela, P. T., & Zhao, Y. F. (2023b). Supporting Multifunctional Bio-Inspired Design Concept Generation through Case-Based Expandable Domain Integrated Design (xDID) Model. *Designs*, 7(4), 86.

Wang, C., Chen, Z., Roy, A., & Silberschmidt, V. V. (2023). Energy absorption of composite shin-guard structure under low-velocity impacts. In Dynamic Deformation, Damage and Fracture in Composite Materials and Structures (pp. 623-637). Elsevier.

Yu, C., Liu, M., Zhang, C., Yan, H., Zhang, M., Wu, Q., Liu, M., & Jiang, L. (2020). Bio-inspired drag reduction: from nature organisms to artificial functional surfaces. Giant, 100017.

Zhang, M., Feng, S., Wang, L., & Zheng, Y. (2016). Lotus effect in wetting and self-cleaning. Biotribology, 5, 31-43.

Zhang, P., Li, X., Nie, Z., Yu, F., & Liu, W. (2021). A Trimming Design Method Based on Bio-Inspired Design for System Innovation. Applied Sciences, 11(9), 4060.

Zhang, W., Yin, S., Yu, T., & Xu, J. (2019). Crushing resistance and energy absorption of pomelo peel inspired hierarchical honeycomb. *International Journal of Impact Engineering*, 125, 163-172.