

Exploration of the Application of Biomimetic Structures in Lightweight Mechanical Design

Yuanshan Shou

Suzhou High School Affiliated to Xi'an Jiaotong University, Suzhou, 215000, China

Abstract: Lightweight design is one of the central goals of modern mechanical engineering. Lighter structures consume less energy, carry more payload, and produce fewer emissions over their service life. Nature has solved the same problem over millions of years of evolution, producing structures such as bone, bamboo, honeycomb and seashell that reach high strength and stiffness with very little material. This review summarises how these natural structures work, how their design principles have been transferred into engineering, and where they are now applied. Four groups of biomimetic structures are examined: honeycomb and cellular structures, bone-inspired lattices, plant-inspired tubular and venation structures, and shell-type sandwich structures. The review then discusses the two technologies that made modern biomimetic design practical, topology optimisation and additive manufacturing, and surveys applications in aerospace, automotive and robotic systems. Finally, it identifies the main challenges that remain, including manufacturing cost, fatigue behaviour and the lack of standard design tools. The overall finding is that biomimetic structures can reduce component mass by 20 to 50 percent in many cases, but that their wider adoption depends on better integration between biological knowledge, computational design and manufacturing.

Keywords: Biomimetics, bio-inspired design, lightweight structures, cellular materials, lattice structures, topology optimisation, additive manufacturing.

1. Introduction

Reducing the mass of mechanical components has become a priority across almost every engineering sector. In transport, mass is directly linked to fuel consumption and emissions: a widely quoted estimate is that a 10 percent reduction in vehicle mass improves fuel economy by roughly 6 to 8 percent. In aerospace, every kilogram saved on an aircraft structure translates into higher payload or longer range for the whole service life of the airframe. In robotics, lighter limbs allow faster motion and smaller motors. At the same time, the components must remain strong, stiff and safe. The challenge of lightweight design is therefore to remove material without losing function.

This is exactly where nature excels. Biological organisms must grow, move and survive with a limited supply of material and energy. Evolution has therefore produced structures that are extremely efficient: bone is porous but strong, bamboo is a hollow tube with a graded wall, honeycomb encloses a large volume with very thin walls, and the shell of a mollusc resists fracture despite being made of brittle mineral. These structures share a common principle [1, 2]. They place material only where it is needed, and they use hierarchy, with features repeated at several length scales, to obtain properties that a uniform solid cannot achieve.

Biomimetics, also called bio-inspired design, is the discipline that studies these biological solutions and transfers their principles into engineering [3]. The field has existed for decades, but two recent developments have transformed it from an academic interest into a practical design tool. The first is topology optimisation, a computational method that distributes material in a design space to maximise stiffness for a given mass [4]. Its results frequently look organic, with branching load paths that resemble bone or tree structures. The second is additive manufacturing, which can build the complex internal geometries that biomimetic designs require and that conventional machining or casting cannot produce

[5].

2. Fundamentals of Biomimetic Structural Design

2.1. Why Natural Structures Are Light

Biological structures are efficient for three main reasons. First, they are built from a small number of relatively weak base materials, such as collagen, chitin, cellulose and calcium minerals, so their performance must come from architecture rather than material strength. Second, they are hierarchical: a structure such as bone contains features at the nanometre scale (mineral platelets), the micrometre scale (lamellae and osteons) and the millimetre scale (trabecular struts and the cortical shell). Each level contributes a different function, such as stiffness, toughness or damage tolerance [6]. Third, they are adaptive. Bone remodels itself in response to load, adding material where stresses are high and removing it where they are low, a behaviour described by Wolff's law in the nineteenth century.

2.2. Common Structural Principles

Across very different organisms, a few recurring principles explain most of the lightweight performance:

Cellular architecture. Many natural materials are foams or honeycombs in which thin walls or struts enclose empty space. Gibson and Ashby showed that the stiffness of such a cellular solid scales with the square of its relative density for bending-dominated cells and linearly for stretch-dominated cells, so a well-designed lattice can retain much of the stiffness of the solid at a fraction of the mass [7, 8].

Hollow and graded sections. Bamboo, bird bones and plant stems are hollow tubes. A hollow tube resists bending and torsion far better than a solid rod of the same mass because material is placed far from the neutral axis. Nature often grades the wall, with denser material on the outside [1].

Sandwich construction. Skulls, shells and leaves place two

stiff outer layers on a light core, which increases bending stiffness without adding much mass [7].

Branching and load-path alignment. Tree branches, leaf veins and trabecular bone align material along the principal

stress directions, which minimises wasted material [9].

Functional gradients and joints. Natural structures change properties gradually rather than abruptly, which avoids stress concentrations at interfaces.

Four natural templates place material only where load paths need it

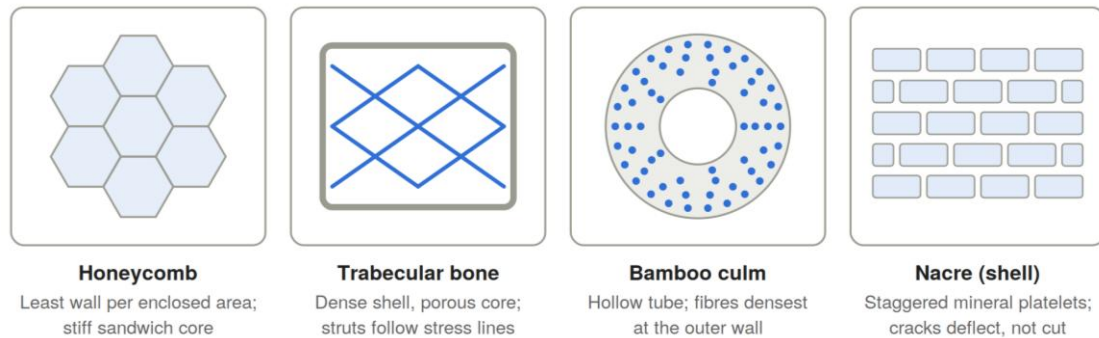


Figure 1. Schematic cross-sections of four natural lightweight structures and the principle each contributes to engineering design.

2.3. Design Methodology

Transferring a biological principle into an engineering component usually follows a problem-driven process. The engineer first defines the functional requirement, for example a bracket that must carry a given load with minimum mass. A biological analogue with a similar function is then identified and its working principle is abstracted into a form that is independent of biology, such as "align struts along principal

stresses" rather than "copy bone". The abstracted principle is then implemented through a design tool, most often parametric CAD, topology optimisation or lattice generation software, and the result is validated by simulation and testing [3]. Figure 2 summarises this workflow. It is important to note that biomimetic design is not direct copying. Biological structures are shaped by constraints that do not apply to machines, such as growth, self-repair and the need to carry fluids, so the principle must be adapted rather than reproduced.

Biomimetic design abstracts a natural principle, it does not copy the organism

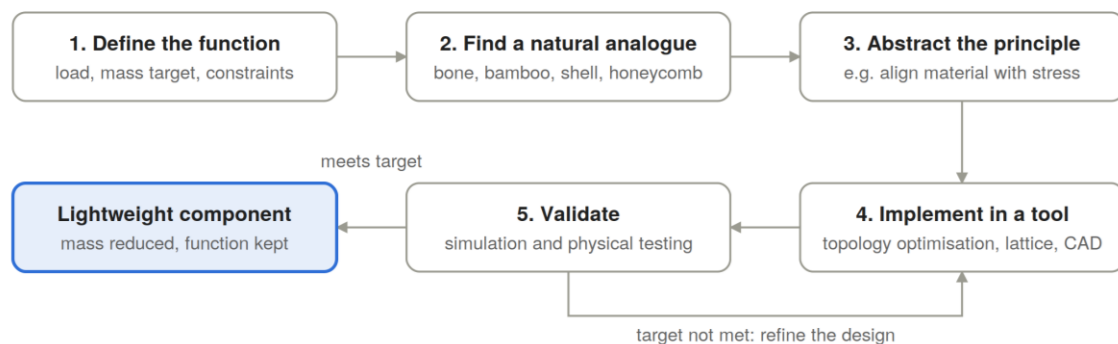


Figure 2. Problem-driven biomimetic design workflow. The loop between implementation and validation is repeated until the mass and performance targets are met.

3. Types of Biomimetic Lightweight Structures

3.1. Honeycomb and Cellular Structures

The honeycomb is the oldest and most widely used biomimetic structure in engineering. Bees build hexagonal cells because the hexagon tiles a plane with the least wall length per unit of enclosed area, which minimises the wax needed. The same geometry gives an engineering honeycomb a very high stiffness in the direction perpendicular to the cell plane, combined with very low density.

In practice, honeycomb is almost always used as the core of a sandwich panel. Two thin, stiff face sheets of aluminium or fibre-reinforced polymer are bonded to a honeycomb core made of aluminium foil or aramid paper. The face sheets carry the bending loads, while the core keeps them apart and carries shear, exactly as the flanges and web of an I-beam do [7]. The result is a panel whose bending stiffness can be several times

that of a solid plate of equal mass. Aerospace manufacturers have used this configuration since the 1950s for floor panels, control surfaces and fairings, and it remains a standard solution in satellites, where a typical structural panel may have a mass of only a few kilograms per square metre.

Research over the past two decades has extended the basic hexagonal cell in several directions. Re-entrant or auxetic honeycombs have inverted cell walls and exhibit a negative Poisson's ratio, which improves indentation resistance and energy absorption. Hierarchical honeycombs replace each cell wall with a smaller honeycomb, mimicking the multi-level structure of natural materials [10], and have shown stiffness and strength improvements of around 2 to 4 times at the same density in analytical and experimental studies. Graded honeycombs vary cell size or wall thickness across the panel to match a non-uniform load, which is similar to how the cell size in a plant stem changes from the outside to the centre.

3.2. Bone-inspired Porous and Lattice Structures

Bone is perhaps the most studied natural lightweight structure. A long bone such as the femur has a dense outer shell, called cortical bone, surrounding a porous interior, called trabecular or cancellous bone. The trabecular region is a network of small struts and plates whose orientation follows the principal stress directions of the bone [1, 2]. This arrangement was already noted by the anatomist Hermann von Meyer and the engineer Karl Culmann in the 1860s, who observed that the trabeculae in the head of the femur matched the stress lines of a curved crane. The cancellous interior has a relative density of only 5 to 30 percent, yet it allows the bone to carry daily loads with a large safety margin.

Engineers have transferred this principle in two ways. The first is the use of lattice structures, which are ordered networks of struts or surfaces that fill the interior of a component. Common unit cells include the body-centred cubic (BCC), face-centred cubic (FCC), octet truss and, more recently, triply periodic minimal surfaces (TPMS) such as the gyroid and the Schwarz diamond. Strut-based cells are easy to generate but suffer from stress concentrations at their nodes [11]. TPMS cells, in contrast, are smooth, continuous surfaces that distribute stress evenly and are particularly good at absorbing energy. Several studies have reported that gyroid lattices made by laser powder bed fusion in titanium or aluminium alloys achieve specific energy absorption values comparable to those of natural bone and superior to equivalent strut lattices.

The second transfer is the use of functionally graded lattices, in which the strut thickness or cell size changes smoothly across the part. This reproduces the transition from dense cortical bone to porous trabecular bone [5, 11]. In a cantilever bracket, for example, the lattice can be made denser near the root where bending stresses are highest and sparser towards the free end. Graded lattices typically achieve 10 to 30 percent higher stiffness-to-mass ratios than uniform lattices in published comparisons, because material is removed from regions that contribute little to the overall stiffness.

A representative application is the lightweight bracket. Several aerospace companies have redesigned cabin brackets, hinge fittings and engine mounts by combining topology optimisation with internal lattices. Reported mass reductions range from about 30 to 60 percent relative to the original machined parts, with no loss of strength. Another important application is in medical implants, where a porous titanium lattice not only reduces mass but also lowers the stiffness of the implant closer to that of bone, reducing the problem of stress shielding and encouraging bone ingrowth.

3.3. Plant-inspired Structures: Bamboo, Stems and Leaf Venation

Plants must stand upright against gravity and wind using only the material they can grow, so they are a rich source of lightweight structural principles. Two examples are particularly relevant to mechanical design.

Bamboo is a hollow, segmented tube with a functionally graded wall. The density of vascular fibres increases from the inner to the outer surface of the wall, placing the strongest material where bending stress is highest [12]. Regular nodes along the length act as internal diaphragms that prevent the thin wall from ovalising and buckling. The culm also tapers,

and the spacing between nodes decreases towards the top where the bending moment is smaller. The result is a structure whose specific flexural strength rivals that of many engineering alloys. Engineers have applied these features to thin-walled tubes for vehicle crash structures, bicycle frames and robotic arms. A bamboo-inspired tube with internal diaphragms and a graded wall can increase energy absorption in axial crushing by 20 to 40 percent over a plain tube of the same mass, because the diaphragms force a stable, progressive folding pattern.

Leaf venation provides a template for ribbing and stiffening patterns on plates and shells. The veins of a leaf form a hierarchical branching network that supports the thin blade against bending and distributes fluid efficiently. The pattern is not a uniform grid: major veins carry the main load and divide into progressively smaller veins, with loops that provide redundancy. Rib layouts generated from venation patterns or from analogous branching algorithms have been applied to the stiffening of automotive panels, aircraft skin panels and machine-tool tables. Compared with conventional orthogonal rib grids, venation-inspired layouts have been reported to achieve equal stiffness at roughly 10 to 20 percent lower mass, and they also show less sensitivity to the direction of the load because the branches cover multiple orientations.

3.4. Shell, Sandwich and Tubular Structures from Animals

Animals provide a complementary set of templates that focus on protection and impact resistance rather than pure stiffness.

Nacre, the inner layer of mollusc shells, is about 95 percent brittle aragonite mineral, yet its fracture toughness is roughly a thousand times that of the pure mineral. The reason is its "brick and mortar" architecture: micrometre-sized mineral platelets are stacked in layers and bonded by thin organic films. When a crack tries to pass through, it is deflected along the interfaces and the platelets slide and pull out, absorbing energy [1, 2]. Engineers have reproduced this architecture in layered ceramic and polymer composites, in aluminium and polymer laminates, and in 3D-printed panels. For lightweight design the value of nacre is that it allows a thin, light protective layer to survive impact without becoming thick and heavy, which is relevant to helmet shells, drone bodies and casings for portable equipment.

The toucan beak and the hedgehog spine illustrate the natural sandwich structure. The toucan beak is a thin keratin shell filled with a closed-cell bony foam, giving it a density of roughly 0.1 grams per cubic centimetre while remaining stiff enough to feed and fight [13]. Hedgehog spines are hollow tubes reinforced by internal longitudinal stringers and transverse plates, which allow them to bend and absorb energy without buckling. Both have inspired foam-core sandwich beams and stiffened tubular members for vehicles and sporting goods.

Insect cuticle and the beetle elytron are thin, layered shells with internal hollow columns called trabeculae connecting the upper and lower surfaces [1]. The elytron of a beetle is both a protective cover and a lightweight wing case. Several research groups have designed sandwich panels with hollow cylindrical cores arranged in the same pattern as the elytron and reported higher compressive strength and energy absorption than conventional honeycomb cores of the same mass.

4. Enabling Technologies: Topology Optimisation and Additive Manufacturing

The biomimetic structures described above were known for a long time before they could be used widely. Two technologies removed the barrier.

4.1. Topology Optimisation

Topology optimisation is a numerical method that finds the best distribution of material within a defined design space for a given set of loads, supports and constraints. The most common formulation minimises compliance (maximises stiffness) subject to a limit on volume [4]. The design space is divided into finite elements, each with a density variable between 0 and 1, and an iterative algorithm progressively removes material from low-stress elements and keeps it in

high-stress ones.

The interesting point for biomimetics is that this process is mathematically similar to bone remodelling, and its results look biological. Optimised brackets have smooth, branching load paths resembling tree limbs or trabecular bone. Some methods, such as the Soft Kill Option developed by Claus Mattheck, were explicitly built on observations of how trees and bones add and remove material [9]. More recent approaches add constraints for manufacturability, such as minimum feature size and overhang angle, so that the result can be built directly.

Topology optimisation is also increasingly combined with lattice generation. The optimiser first identifies which regions need solid material and which can be partly filled, and a lattice of appropriate density is then placed in the intermediate regions. This multi-scale approach reproduces the cortical-trabecular structure of bone in a systematic way [14].

Optimisation plus lattice infill reproduces the dense-shell, porous-core logic of bone

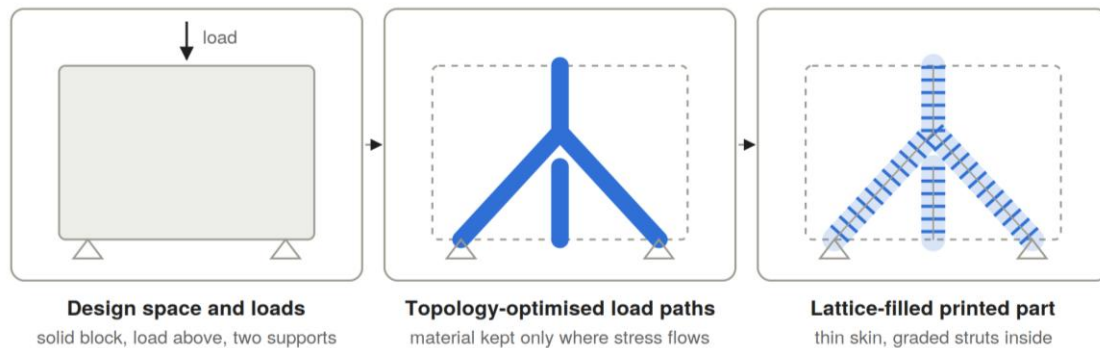


Figure 3. Multi-scale bio-inspired design: topology optimisation finds the main load paths, and a graded lattice fills the remaining volume, mirroring cortical and trabecular bone.

4.2. Additive Manufacturing

Additive manufacturing (AM), or 3D printing, builds parts layer by layer from powder, wire or filament. Its key advantage for biomimetic design is geometric freedom: internal lattices, graded walls, curved channels and organic surfaces cost little more to produce than simple shapes, whereas they would be impossible or extremely expensive by machining, casting or forming [5, 14]. Laser powder bed fusion in titanium, aluminium and nickel alloys is the

dominant process for structural metal parts, and fused filament fabrication and stereolithography are widely used for polymer prototypes and functional components.

5. Engineering Applications

Biomimetic lightweight structures have moved from the laboratory into products in three main sectors. Table 1 summarises representative examples and the mass savings typically reported.

Table 1. Representative applications of biomimetic structures in lightweight design (mass savings are typical published values and vary by case).

Sector	Component	Biological template	Structural principle	Typical mass saving
Aerospace	Cabin brackets, hinge fittings	Trabecular bone	Topology optimisation + graded lattice	30–60 %
Aerospace	Floor and fairing panels	Honeycomb	Sandwich with hexagonal core	40–70 % vs solid plate
Aerospace	Wing ribs, spars	Bird wing bone	Truss-like interior, hollow section	10–25 %
Automotive	Crash boxes, side-impact beams	Bamboo, plant stem	Graded hollow tube, internal diaphragms	15–30 % at equal energy absorption
Automotive	Body panels, seat frames	Leaf venation	Branching rib pattern	10–20 %
Robotics	Arm links, legs	Bamboo, bird bone	Hollow tube with internal lattice	20–40 %
Protective equipment	Helmet shells, drone bodies	Nacre, beetle elytron	Layered shell, hollow-column core	10–30 % at equal impact resistance

In aerospace, the strongest driver is the lifetime fuel saving per kilogram, which justifies the high cost of additive manufacturing. Topology-optimised, lattice-filled titanium brackets are now flying on commercial aircraft and satellites, and honeycomb sandwich panels have been standard for

decades.

In the automotive sector, cost per part is far more important, so the preferred biomimetic solutions are those compatible with stamping, casting and extrusion. Venation-inspired ribbing on cast aluminium components and bamboo-inspired

extruded tubes are typical, and the mass savings help to offset the weight of batteries in electric vehicles.

In robotics, lighter limbs reduce inertia and allow smaller actuators, so hollow, lattice-filled links printed in aluminium or polymer are increasingly common in collaborative and legged robots. Bio-inspired compliant structures are also used in grippers and soft robots, where the aim is controlled flexibility rather than stiffness.

6. Challenges and Future Directions

Despite clear benefits, several obstacles limit the wider use of biomimetic structures.

Manufacturing cost and scale. Most internal lattices depend on additive manufacturing, which remains slow and expensive for large or high-volume parts [11, 14]. Research into faster AM processes, hybrid casting of lattice cores, and bio-inspired designs compatible with conventional processes is needed to bring these structures into mass production.

Fatigue and reliability. Thin struts and sharp cell corners are sensitive to surface roughness and internal defects [11]. Fatigue data for lattices are still limited, and certification bodies in aerospace require extensive testing before a new structural concept is accepted. Standardised test methods and design allowables for lattice materials are an active area of work.

Lack of design standards and tools. There is no accepted method for choosing which biological template suits a given engineering problem, and most successes have come from case-by-case studies. Databases that link biological structures to their mechanical functions, together with generative design tools that can call on them, would make biomimetic design more systematic.

Multifunctionality. Natural structures rarely do only one job: bone carries load and makes blood cells, leaves carry load and transport water. Future lightweight components are likely to combine structural function with heat transfer, energy storage or sensing, following the same logic [6]. Multi-material additive manufacturing and 4D printing (structures that change shape in response to stimuli) are opening this direction.

7. Conclusion

Biomimetic structures offer a proven route to lighter mechanical components. Honeycomb and cellular materials, bone-inspired lattices, plant-inspired tubes and ribs, and animal-inspired layered shells each embody a simple principle: place material only where load paths require it and use hierarchy to obtain properties that a uniform solid cannot. Topology optimisation and additive manufacturing have turned these principles into practical design tools, and documented mass savings of 20 to 50 percent are now common in aerospace, automotive and robotic applications.

The next stage of development depends less on discovering

new biological templates than on integration. Reliable fatigue data, standard design methods, cheaper manufacturing and multifunctional design will determine how quickly biomimetic structures move from high-value niche parts into everyday products. As these barriers fall, the lessons of bone, bamboo and seashell are likely to become a standard part of the mechanical designer's toolkit.

References

- [1] Meyers, M. A., Chen, P.-Y., Lin, A. Y.-M., & Seki, Y. (2008). Biological materials: structure and mechanical properties. *Progress in Materials Science*, 53(1), 1–206.
- [2] Wegst, U. G. K., Bai, H., Saiz, E., Tomsia, A. P., & Ritchie, R. O. (2015). Bioinspired structural materials. *Nature Materials*, 14, 23–36.
- [3] Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A.-K. (2006). Biomimetics: its practice and theory. *Journal of the Royal Society Interface*, 3(9), 471–482.
- [4] Bendsoe, M. P., & Sigmund, O. (2003). *Topology optimization: Theory, methods and applications*. Springer.
- [5] Du Plessis, A., Broeckhoven, C., Yadroitsava, I., Yadroitsev, I., Hands, C. H., Kunju, R., & Bhate, D. (2019). Beautiful and functional: a review of biomimetic design in additive manufacturing. *Additive Manufacturing*, 27, 408–427.
- [6] Eder, M., Amini, S., & Fratzl, P. (2018). Biological composites: complex structures for functional diversity. *Science*, 362(6414), 543–547.
- [7] Gibson, L. J., & Ashby, M. F. (1997). *Cellular solids: Structure and properties* (2nd ed.). Cambridge University Press.
- [8] Ashby, M. F. (2006). The properties of foams and lattices. *Philosophical Transactions of the Royal Society A*, 364(1838), 15–30.
- [9] Mattheck, C. (1998). *Design in nature: Learning from trees*. Springer.
- [10] Ajdari, A., Jahromi, B. H., Papadopoulos, J., Nayeb-Hashemi, H., & Vaziri, A. (2012). Hierarchical honeycombs with tailorable properties. *International Journal of Solids and Structures*, 49(11–12), 1413–1419.
- [11] Maconachie, T., Leary, M., Lozanovski, B., Zhang, X., Qian, M., Faruque, O., & Brandt, M. (2019). SLM lattice structures: properties, performance, applications and challenges. *Materials & Design*, 183, 108137.
- [12] Amada, S., Ichikawa, Y., Muneakata, T., Nagase, Y., & Shimizu, H. (1997). Fiber texture and mechanical graded structure of bamboo. *Composites Part B: Engineering*, 28(1–2), 13–20.
- [13] Seki, Y., Schneider, M. S., & Meyers, M. A. (2005). Structure and mechanical behavior of a toucan beak. *Acta Materialia*, 53(20), 5281–5296.
- [14] Plocher, J., & Panesar, A. (2019). Review on design and structural optimisation in additive manufacturing: towards next-generation lightweight structures. *Materials & Design*, 183, 108164.