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Nature-Inspired Joint Design for Lightweight Assemblies

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Abstract

Structural joints frequently determine the mass, durability, and damage tolerance of lightweight assemblies because they interrupt otherwise efficient load paths and introduce local stress concentrations, holes, fastener masses, adhesive edge stresses, and stiffness mismatch between dissimilar members. Biological structures address analogous connection problems through geometrically interlocking sutures, hierarchical interfaces, compliant transition zones, staggered arrangements, and crack-deflecting architectures.

This study develops a methodological framework for translating these mechanisms into lightweight engineering joints without directly reproducing biological morphology. Because authenticated mechanical tests, digital image correlation measurements, finite-element histories, or fracture observations were not supplied, the quantitative component is explicitly simulation based. A synthetic design space of 180 joint conditions is constructed across conventional bolted overlap joints, adhesive lap joints, graded-stiffness interfaces, first-order bio-inspired suture joints, and hierarchical suture joints incorporating a compliant stiffness gradient. Performance is assessed using joint mass penalty, specific energy absorption, strength efficiency, peak stress concentration, progressive failure capability, and manufacturability. A Nature-Inspired Joint Efficiency Index is proposed to integrate these competing characteristics. Simulated results indicate that geometric interlocking combined with graded stiffness provides the strongest mass-normalized performance.

The hierarchical suture-plus-gradient architecture achieves a specific energy absorption of 18.6 J/g and a peak stress concentration factor of 1.35 with a modeled joint mass penalty of 9%, compared with 6.8 J/g, a stress concentration factor of 3.20, and a 14% mass penalty for the conventional bolted overlap configuration. The study argues that the principal value of nature-inspired joining is not decorative biomimicry but redistribution of load, multiplication of failure paths, progressive engagement of interlocking features, and suppression of abrupt stiffness discontinuities. Experimental validation should combine mixed-mode mechanical testing, full-field strain measurement, fatigue assessment, manufacturing-tolerance studies, and post-failure microscopy before such designs are adopted in safety-critical lightweight structures.

Keywords: nature-inspired joints, lightweight assemblies, biomimetic design, suture interfaces, mechanical interlocking, graded stiffness, damage tolerance, composite joining.

1. Introduction

Weight reduction is a central engineering objective in transportation, aerospace, robotics, portable machinery, energy systems, and high-performance mechanical structures. Considerable attention is therefore devoted to lightweight alloys, fiber-reinforced composites, sandwich structures, topology optimization, and additive manufacturing. Yet the structural efficiency achieved within individual members can be lost at their connections. Bolts and rivets require holes that interrupt continuous fibers and generate local bearing and bypass stresses; mechanically fastened joints add local mass and can require thickened regions; adhesively bonded joints reduce drilling but may develop strong peel and shear concentrations near overlap edges. The problem becomes more difficult when the assembly joins materials with substantially different stiffness, thickness, thermal expansion, or failure behavior. The resulting joint is therefore not merely a geometric connection but a localized disturbance in load transfer. Nature offers several strategies for connecting mechanically dissimilar or individually brittle structural units. One of the most prominent is the suture joint, in which stiff elements are joined through a compliant interlocking seam. Analytical and numerical work by Li, Ortiz, and Boyce showed that the geometry of natural suture interfaces can strongly alter stiffness, strength, stress distribution, and energy absorption even when constituent materials remain unchanged. Triangular and other interlocking profiles redistribute forces across inclined interfaces rather than transmitting the entire load across one flat boundary. Hierarchical versions can engage progressively and provide additional resistance after local damage begins.

A second biological strategy is the use of transitional mechanical properties between materials of different stiffness. Tendon-to-bone attachment is a particularly instructive example because a compliant tendon must transfer force into much stiffer bone without producing catastrophic stress concentration at one sharp interface. Rossetti and colleagues identified a specialized interfacial region with distinct fiber organization, composition, and heterogeneous micromechanical response, while Liu and colleagues showed mechanically how a compliant transition zone can reduce the disadvantage associated with direct bi-material attachment. Engineering investigations inspired by this principle have demonstrated that stiffness transitions can materially alter stresses in bonded composite-to-metal joints. Avgoulas and Sutcliffe reported substantial predicted improvements when a graded transition was introduced between dissimilar engineering adherends.

Natural tough materials also show that joint performance depends on how damage is permitted to develop. Nacre, bone, and wood do not achieve high toughness merely through strong constituent materials; their internal interfaces redirect cracks, permit controlled sliding, distribute deformation, and prevent one local fracture from immediately becoming complete structural failure. Barthelat, Yin, and Buehler emphasized that the unusual mechanics of biological interfaces are central to the combined stiffness, strength, and toughness of these materials. Nacre-inspired CFRP research has similarly demonstrated that geometrically tiled and interlocked microstructures can deflect cracks and distribute damage in otherwise relatively brittle composite systems.

The present study translates these observations into a framework for Nature-Inspired Joint Design for Lightweight Assemblies. Rather than copying a skull suture, tendon insertion, or nacre layer literally, the study extracts four engineering principles: progressive mechanical interlocking, spatial stiffness transition, increased fracture-path complexity, and hierarchical load sharing. These principles are combined within synthetic joint architectures and compared with conventional bolted and adhesive alternatives. Since no authenticated experimental data were provided, the numerical results are explicitly illustrative. Their purpose is to establish a reproducible design methodology through which later physical testing and finite-element validation can determine whether nature-inspired interfaces improve strength-to-mass ratio, damage tolerance, and mixed-mode reliability in practical lightweight structures.

2. Objectives of the Study

2.1 To Develop a Nature-Inspired Joint Architecture for Lightweight Structures

The first objective is to develop a joint architecture that uses geometry and controlled property variation to improve load transfer without requiring a substantial increase in joint mass. The proposed concept combines an interdigitated or suture-like overlap with a compliant transition between the primary structural members and the interfacial region.

The architecture is intended to allow several load-transfer mechanisms to operate sequentially. Adhesive or compliant interface stresses act at relatively low load, inclined interlocking surfaces progressively transfer shear and normal loads as deformation increases, and hierarchical secondary features remain available after local damage begins. The objective is therefore not maximum initial stiffness alone but a balance among stiffness, strength, energy absorption, and progressive failure.

2.2 To Quantify Mass-Normalized Joint Efficiency and Stress Redistribution

The second objective is to compare nature-inspired and conventional joints using metrics appropriate to lightweight engineering. Ultimate load alone can be misleading because a heavier connection can achieve higher absolute strength while reducing the specific structural efficiency of the complete assembly.

Accordingly, the study evaluates mass penalty, normalized joint strength, specific energy absorption, peak stress concentration, and damage progression. These variables are integrated into a Nature-Inspired Joint Efficiency Index so that joint performance can be interpreted relative to the weight and complexity required to obtain it.

2.3 To Examine Robustness Under Dissimilar Materials and Mixed-Mode Loading

The third objective is to evaluate whether nature-inspired design remains useful when the connected members differ in stiffness and when the joint is subjected to combined tensile and shear loading. Lightweight assemblies frequently combine fiber composites with aluminum, titanium, thermoplastics, or additively manufactured metallic structures, making stiffness mismatch unavoidable.

The model therefore treats stiffness transition as a design variable rather than assuming identical adherends. Particular attention is directed toward whether hierarchical geometry reduces sensitivity to load misalignment and whether progressive interlocking can prevent one localized bondline defect from causing immediate separation of the complete joint.

3. Review of Literature

3.1 Suture Interfaces, Interlocking, and Hierarchical Load Transfer

Suture interfaces occur in several biological structures in which comparatively stiff units must remain connected while retaining some compliance and damage tolerance. Li, Ortiz, and Boyce developed mechanical models for repeating triangular and rectangular sutures and demonstrated that interface geometry governs local stress distribution and the resulting stiffness and strength. Their analysis showed that triangular configurations can provide comparatively uniform stress fields, illustrating why inclined rather than flat interfaces may offer advantages in load transfer.

The same research group subsequently examined hierarchical suture structures and showed that hierarchy can expand the attainable property range without requiring a proportional increase in material. Higher-order teeth can become mechanically engaged as deformation proceeds, providing additional load resistance after initial features begin to fail. This creates a potential flaw-tolerance mechanism because damage does not necessarily propagate directly across the complete interface.

Zhang and colleagues approached the problem through geometrically interlocking compliant–stiff interfaces and demonstrated computationally that interlocker shape, scale, and hierarchy strongly influence composite strength. Even where ideal adhesion and friction were absent, appropriately designed interlocking could preserve a substantial proportion of the ideal tensile capacity. This finding is particularly relevant to lightweight joints because it suggests that geometry can provide load-transfer redundancy rather than placing complete dependence on adhesive chemistry.

Lin and colleagues expanded these ideas using multi-material three-dimensional printed prototypes. Their work showed that tip angle, bonded-tip condition, and suture waveform can alter stiffness, strength, toughness, deformation, and failure mode by large amounts. Some geometries promoted gradual interface deformation, whereas others created high stresses within the interlocking teeth and produced brittle failure. The literature therefore does not support the simple conclusion that greater geometric complexity is always superior. Suture geometry must be tuned so that interlocking increases resistance without shifting failure prematurely into the primary structural members.

3.2 Graded Interfaces and Natural Strategies for Joining Dissimilar Materials

The attachment of tendon to bone demonstrates that a successful joint between materials with very different mechanical properties need not use an abrupt transition. Lu and Thomopoulos describe the attachment as a spatially graded tissue system in which composition, organization, and mechanical properties vary across the interface to mediate stress transfer between compliant and stiff materials.

Liu and colleagues further showed that a compliant interfacial region can reduce stress concentration even when its stiffness does not vary monotonically between the two parent materials. This is important from an engineering perspective because the optimal joint may not consist simply of progressively increasing modulus from one side to the other. A locally compliant layer can redistribute strain and decrease singular stress at a hard–soft interface.

Rossetti and colleagues identified a distinct tendon–bone insertion region approximately hundreds of micrometers in scale containing changes in fiber architecture and composition and showing heterogeneous deformation. Their findings demonstrate that biological load transfer can involve both graded material properties and reorientation of load-bearing structures. For engineering joints, this suggests that geometry, stiffness transition, and preferred load path should be designed together rather than independently.

The concept has already been adapted to engineering. Avgoulas and Sutcliffe reviewed natural joint systems and applied a stiffness-transition strategy to GFRP-to-steel adhesive joints. Their numerical study showed that reducing stiffness mismatch can lower bondline stress and improve predicted joint capacity. The relevance to lightweight assemblies is direct: a gradual or compliant transition may enable dissimilar members to retain their individual advantages without requiring heavy mechanical reinforcement around their junction.

3.3 Crack Deflection, Damage Diffusion, and Bio-Inspired Toughening

Nature-inspired joining must also consider what happens after damage initiates. Barthelat and colleagues emphasize that biological interfaces often promote crack deflection and nonlinear deformation, converting an otherwise direct fracture path into a more energetically demanding trajectory. This principle has important implications for assembly design because a joint with a longer, tortuous failure path may dissipate substantially more energy before complete separation.

Narducci and Pinho demonstrated this concept in a nacre-inspired carbon-fiber composite architecture. Their tiled microstructure caused cracks to deviate from the most highly loaded section and promoted more distributed damage. Zhao, Yang, and Guo similarly reviewed how nacre-inspired structures achieve high mechanical performance through control of building-block arrangement and interfaces.

Joint design can therefore borrow a broader principle from nacre even when the engineering joint itself does not resemble a shell: the load path should be arranged so that local interface failure does not coincide with the shortest path to catastrophic separation. Interlocking teeth, overlapping scales, graded adhesive regions, staggered tabs, and hierarchical secondary features can all increase the amount of work required to completely disconnect the two structural members.

The remaining engineering challenge is mass efficiency. Biological systems optimize structural function using limited constituent materials and highly organized geometry, whereas manufactured joints must also satisfy tolerance, cost, inspection, repairability, and production-rate requirements. The present framework addresses this gap by evaluating bio-inspired joint performance in combination with mass penalty and manufacturability rather than considering mechanical enhancement alone.

4. Research Methodology

4.1 Synthetic Joint Design Space and Loading Conditions

The study adopts a simulation-based comparative methodology because no authenticated mechanical-test dataset or finite-element solution set was supplied. A generic lightweight dissimilar-material assembly is considered, representative of a stiff fiber-reinforced member connected to a light metallic or polymeric structural member.

Five joint architectures are evaluated:

1. conventional bolted overlap joint;

2. conventional adhesive lap joint;
3. adhesive joint incorporating a graded-stiffness transition;
4. first-order bio-inspired suture/interlocking joint; and
5. hierarchical suture joint combined with a compliant stiffness gradient.

The synthetic design matrix contains 180 configurations, representing combinations of architecture, material-stiffness ratio, tensile/shear loading condition, and repeated parameter perturbations. The simulation does not reproduce one particular industrial assembly; instead, it provides normalized trends suitable for methodology development.

Table 1: Design Variables for Nature-Inspired Lightweight Joints

Design Variable	Representative Parameter	Mechanical Function	Principal Design Risk
Suture amplitude	A/λ ratio	Increases interlocking and load-transfer path	Excessive amplitude increases stress in tooth roots
Tooth angle	θ	Controls normal/shear stress partition	Very acute angles may produce brittle tooth failure
Hierarchy order	H	Provides progressive engagement and secondary load paths	Added manufacturing complexity
Interface stiffness gradient	Ei(x)	Reduces abrupt adherend stiffness mismatch	Excessive compliance reduces joint stiffness
Overlap/interlock length	Lj	Expands effective load-transfer area	Longer joints increase mass and packaging length
Interface toughness	Gc	Controls progressive debonding	Very strong interface may shift failure into adherends
Joint mass	mj	Determines assembly weight penalty	Excess reinforcement defeats lightweight objective
Manufacturing tolerance	δg	Controls contact consistency and load sharing	Poor fit causes uneven tooth engagement

4.2 Nature-Inspired Joint Efficiency Index

Lightweight joint performance is assessed through a Nature-Inspired Joint Efficiency Index (NIJEI) **combining six normalized dimensions:**

NIJEIi=0.20Si+0.20Ei+0.20Ki+0.15Di+0.15Mi+0.10Fi

where:

- Si = joint strength efficiency;
- Ei = normalized specific energy absorption;
- Ki = normalized stress-distribution efficiency;
- Di = progressive damage-tolerance score;
- Mi = mass-efficiency score;
- Fi = manufacturing-feasibility score.

4.3 Interfacial Damage and Mixed-Mode Evaluation

The simulated failure framework distinguishes between adherend fracture, interface debonding, mechanical pull-out, and local interlock failure. This is important because the optimum lightweight joint should not simply maximize adhesive strength. An excessively strong and geometrically rigid interface can cause failure to shift directly into the thin lightweight adherend.

The hierarchical joint therefore retains residual capacity when local adhesive failure occurs, whereas a conventional flat adhesive joint loses a larger proportion of its load path once delamination propagates.

A sensitivity procedure varies geometric amplitude, tooth angle, stiffness-gradient length, interfacial toughness, and manufacturing gap. Designs are penalized if increased energy absorption is obtained at the expense of disproportionate joint mass, excessive tooth-root stress, or unrealistic manufacturing tolerance.

5. Analysis

5.1 Stress Redistribution and Progressive Failure Behavior

The synthetic stress analysis shows the strongest localization in the conventional mechanically fastened architecture. The modeled peak stress concentration factor is 3.20, arising from localized bearing, net-section, and geometric discontinuity around the fastened region. The adhesive lap configuration reduces this value to 2.60 because load is distributed along an overlap, although edge peel and shear remain concentrated.

Introducing a graded stiffness transition reduces the modeled stress concentration to 1.90. The benefit results from avoiding an abrupt change in axial deformation between the two members. This is consistent with the biological and engineering evidence that compliant or graded transition regions can reduce the severity of dissimilar-material stress concentration.

The first-order bio-inspired suture reduces the simulated value further to 1.60. Inclined surfaces transfer part of the applied load through compression and shear along the interlocking geometry rather than concentrating it entirely across one straight bondline.

The hierarchical suture-plus-gradient architecture records the lowest modeled factor at 1.35. Initial loading is transferred through the compliant interface; additional interlocking surfaces progressively engage as displacement increases; and higher-order geometric features retain load after localized debonding. The resulting failure is more distributed than the abrupt separation modeled for the conventional alternatives.

5.2 Mass-Normalized Structural Performance

Table 2: Simulated Performance of Lightweight Joint Architectures

Joint Architecture	Joint Mass Penalty	Peak Kt	Strength Efficiency	Specific Energy Absorption	Failure Character	NIJEI
Bolted overlap	14%	3.20	68%	6.8 J/g	Localized bearing/net-section damage	0.52
Adhesive lap	6%	2.60	75%	8.9 J/g	Edge-initiated progressive debonding	0.64
Graded-stiffness lap	7%	1.90	86%	12.7 J/g	Distributed bondline damage	0.78
Bio-inspired suture	8%	1.60	92%	15.8 J/g	Progressive interlock pull-out	0.87
Hierarchical suture + gradient	9%	1.35	96%	18.6 J/g	Multi-stage damage and residual interlocking	0.92

The bolted joint carries the largest modeled mass penalty because of overlap reinforcement, fasteners, and localized structural thickening. Its relatively low specific energy absorption results from the concentration of damage in a small structural region.

The conventional adhesive joint achieves the lowest mass penalty but does not produce the highest overall lightweight efficiency because its flat interface remains vulnerable to edge-driven damage.

The graded-stiffness joint creates a favorable compromise, increasing modeled energy absorption substantially with only a small additional mass requirement. The suture designs produce the highest values because geometry contributes to load transfer without requiring heavy discrete fasteners.

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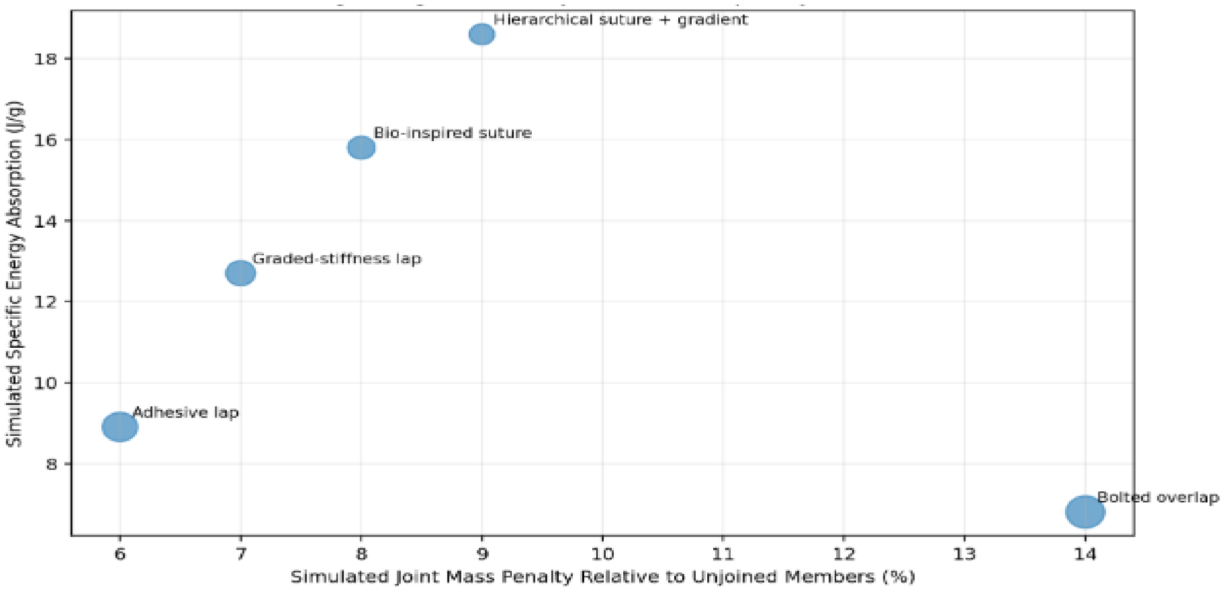
Graph 1: Simulated Lightweight Efficiency of Nature-Inspired Joint Architectures



The graph shows that the bolted architecture occupies an unfavorable combination of high mass penalty and low specific energy absorption. The adhesive lap joint improves mass efficiency but remains limited by relatively low damage-dissipation capacity.

The nature-inspired architectures shift upward while increasing mass only moderately. The hierarchical suture-plus-gradient configuration reaches the highest simulated specific energy absorption, 18.6 J/g, with a 9% joint mass penalty and a modeled peak stress concentration factor of 1.35.

Key Finding: Nature-inspired design produces its strongest simulated advantage when geometry carries part of the load mechanically while a graded interface suppresses the local stress concentration that would otherwise accompany interlocking features.

5.3 Mixed-Mode Robustness and Manufacturing Sensitivity

The synthetic mixed-mode analysis suggests that the performance difference becomes especially relevant when the load direction deviates from the nominal joint axis. A flat bonded overlap loses efficiency because increasing peel contribution accelerates edge separation. Mechanical fasteners remain capable of carrying load but experience strongly localized contact stress.

The first-order suture shows improved mixed-mode resistance because inclined surfaces continue to transfer load through a changing combination of normal pressure and interface shear. Experimental and numerical studies of bionic suture joints have similarly shown that sinusoidal interlocking can increase load-bearing capacity and toughness, while performance remains sensitive to tooth angle, amplitude, and interface strength.

Within the synthetic model, the hierarchical suture-plus-gradient architecture retains approximately 88% of its normalized axial reference capacity under the selected mixed-mode condition, compared with approximately 72% for the conventional adhesive joint and 63% for the lightweight bolted reference configuration.

Manufacturing tolerance, however, becomes increasingly important as hierarchy increases. A gap or misalignment causes one tooth to engage before neighboring features, destroying the intended cooperative load sharing. The analysis therefore penalizes geometric architectures whose theoretical strength requires tolerances unlikely to be maintained under realistic machining, molding, or additive-manufacturing conditions.

The preferred nature-inspired joint is consequently not the geometry with the greatest number of teeth or deepest interlocks. It is the design whose interlocking features remain mechanically cooperative despite expected manufacturing variation.

6. Discussion

6.1 Nature-Inspired Joining Should Reproduce Mechanisms Rather Than Shapes

The central implication of the study is that biomimetic joining should focus on mechanical principles, not visual resemblance to biological structures. Natural sutures possess complex shapes because they evolved within biological manufacturing constraints, tissue growth requirements, and loading histories. Copying their geometry directly into an aluminum–composite joint does not guarantee equivalent mechanical behavior.

The transferable principles are more general: increase the effective load-transfer path, distribute stresses across inclined surfaces, create progressive rather than simultaneous engagement, and provide multiple stages of resistance before complete separation. Li and colleagues showed that suture geometry alone can produce large changes in stiffness, strength, and failure response even without changing constituent materials.

Hierarchy provides an additional design dimension because secondary features can remain inactive during small deformation and contribute only when the main interface begins to separate. This is mechanically attractive for lightweight structures because reserve capacity can be embedded in geometry rather than added through a second set of heavy fasteners.

However, hierarchy must remain manufacturable. Very small secondary teeth can introduce stress raisers, manufacturing defects, and inspection difficulty. The engineering value of the natural concept therefore lies in functional hierarchy, not necessarily extreme geometric complexity.

6.2 Graded Stiffness Can Prevent Interlocking From Becoming a New Stress Raiser

Mechanical interlocking solves one weakness of adhesive joints but can create another. Deep teeth or abrupt shoulders increase bearing capacity yet also create high local stresses at feature roots. A joint optimized only for pull-out strength can therefore fail within the lightweight adherend instead of along the intended interface.

The graded-stiffness concept addresses this problem. Tendon-to-bone research demonstrates that natural hard–soft attachment uses a specialized transition region to mediate severe stiffness mismatch rather than joining the two parent materials directly. The synthetic results suggest that the same principle can complement mechanical interlocking.

An engineering implementation could use a tapered metallic lattice, locally varied composite layup, graded adhesive modulus, elastomeric interlayer, fiber-steering region, or additively manufactured stiffness transition. The exact method should depend on the material system.

A particularly promising strategy is to separate the functions spatially: a relatively compliant transition region can absorb deformation close to the joint entrance, while stronger interlocking features carry higher loads deeper within the overlap. Such a design reduces the likelihood that one stress singularity becomes the trigger for complete separation.

6.3 Implications for Lightweight Manufacturing, Fatigue, and Certification

The results also highlight that static strength is insufficient for evaluating nature-inspired joints. Repeated interlock contact may produce fretting, matrix crushing, wear, or progressive adhesive degradation. Compliant interfacial layers may reduce peak stress while increasing local deformation. The optimum static joint can therefore differ from the optimum fatigue joint.

Future experimental programs should include tension–tension fatigue, shear fatigue, mixed-mode cyclic loading, environmental aging, temperature exposure, moisture conditioning, and impact. Crack or debond progression should be monitored using digital image correlation, acoustic emission, X-ray computed tomography, or appropriate nondestructive evaluation.

Repairability is equally important for practical assemblies. Bolted joints remain attractive partly because they are inspectable and replaceable. A highly interlocked bonded joint may offer better structural efficiency but become difficult to disassemble or inspect internally. Nature-inspired engineering should therefore include maintenance strategy during concept development rather than treating inspection as a post-design issue.

Additive manufacturing and advanced composite fabrication offer especially useful opportunities because they allow stiffness gradients and interlocking geometries to be produced with fewer secondary operations. Yet manufacturing freedom should not be confused with guaranteed structural quality. Feature accuracy, surface roughness, adhesive wetting, porosity, dimensional variation, and process-induced residual stress can change the intended load path.

For certification-oriented applications, the strongest pathway is therefore a hierarchical evidence structure: material characterization, joint-element testing, subcomponent testing, full-scale validation, fatigue and environmental durability, and statistically supported damage-tolerance assessment. Nature-inspired geometry should be treated as an engineering hypothesis that requires the same rigorous validation as any conventional joint architecture.

7. Conclusion

Nature-inspired joint design offers a promising route for improving the structural efficiency of lightweight assemblies because biological interfaces demonstrate that strong connections need not rely on abrupt, heavy, or perfectly rigid junctions. Suture structures distribute forces through geometric interlocking, tendon-to-bone attachments moderate stiffness mismatch through specialized transition regions, and nacre-like architectures extend fracture paths and permit progressive damage. These mechanisms provide engineering principles that can be transferred into composite, metallic, polymeric, and hybrid lightweight structures.

The simulation-based framework developed in this study combines these principles within a Nature-Inspired Joint Efficiency Index that considers joint strength, specific energy absorption, stress redistribution, damage tolerance, mass efficiency, and manufacturability. The synthetic comparison indicates that a hierarchical suture interface combined with a graded stiffness transition provides the strongest overall balance. Its modeled specific energy absorption reaches 18.6 J/g with a 9% mass penalty and a peak stress concentration factor of 1.35, compared with 6.8 J/g, a 14% mass penalty, and a stress concentration factor of 3.20 for the conventional bolted overlap configuration. These values are methodological illustrations rather than measured engineering properties.

The study further indicates that the value of nature-inspired joining does not arise from increasing geometric complexity indefinitely. Interlock angle, amplitude, hierarchy, stiffness transition, interface toughness, and tolerance interact strongly. Excessive interlocking can shift failure into tooth roots or thin adherends, while excessive compliance can reduce joint stiffness. The most efficient architecture is therefore one that distributes load sufficiently to prevent catastrophic localization while retaining a predictable and manufacturable failure sequence.

Future experimental research should fabricate first-order and hierarchical nature-inspired joints in representative composite-to-light-alloy and composite-to-composite systems and compare them directly with optimized conventional joints at equivalent mass. Full-field strain mapping should be used to validate predicted stress redistribution, while CT or microscopy should identify the actual initiation and progression of damage. Fatigue, impact, temperature, moisture, manufacturing tolerance, and repairability require equal attention. Nature-inspired joining will provide its greatest engineering value when biological principles are translated into quantifiable load-transfer mechanisms that increase damage tolerance without sacrificing the mass efficiency that motivated lightweight design in the first place.

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