Materials, Structures and Reliability
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Topology Optimization Designs and Buckling Resistance across Lightweight Lattice Structures

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Abstract

The transition towards lightweight structural materials in aerospace, automotive, and biomedical engineering has driven significant advancements in topology optimization and the implementation of lattice structures. While these cellular materials offer exceptional strength-to-weight ratios and energy absorption capabilities, their integration into safety-critical applications is frequently hindered by uncertainties regarding structural reliability and susceptibility to buckling under compressive loads. This paper provides a comprehensive academic investigation into the reliability testing of topology-optimized designs, specifically focusing on buckling resistance within lightweight lattice structures. Through rigorous computational methodologies, the study evaluates how manufacturing-induced defects and geometric variations impact the critical buckling loads of strut-based and surface-based lattice configurations. The research systematically isolates the parameters influencing structural instability, demonstrating that optimized topologies inherently possess varying degrees of sensitivity to localized geometric perturbations. A robust reliability analysis framework, integrating probabilistic modeling and deterministic finite element simulations, is presented to quantify the probabilistic margins of safety. The findings underscore the critical necessity of incorporating buckling constraints and defect-informed reliability metrics directly into the initial stages of topology optimization algorithms. This approach ensures that the resulting lightweight structures maintain theoretical efficiency while demonstrating practical resilience against sudden catastrophic failure modes typical of cellular instability.

Keywords: Topology Optimization; Lattice Structures; Buckling Resistance; Reliability Testing; Structural Reliability

1. Introduction

1.1 Motivation and Context

The relentless pursuit of fuel efficiency, emissions reduction, and superior dynamic performance across industrial sectors has established lightweight engineering as a cornerstone of modern structural design. Central to this paradigm shift is the development and utilization of lightweight lattice structures, which are architected cellular materials characterized by their repeating unit cells. These structures mimic the optimized forms found in nature, such as trabecular bone and honeycomb configurations, offering an unprecedented balance of mechanical performance and minimal mass. The proliferation of additive manufacturing technologies has further catalyzed this field, enabling the fabrication of complex geometric features that were previously impossible to produce using traditional subtractive manufacturing techniques [1]. Additive manufacturing allows engineers to physically realize intricate internal architectures, paving the way for the widespread application of topology optimization. Topology optimization is a mathematical approach that spatializes material distribution within a defined domain to maximize system performance subject to specific constraints, such as a maximum allowable volume or mass [2]. By coupling topology optimization with additive manufacturing, designers can generate parts that place material strictly along primary load paths, effectively hollowing out low-stress regions and replacing them with mesoscale lattice networks.

Despite these profound advantages, the practical deployment of topology-optimized lattice structures in load-bearing, safety-critical systems remains challenging. The primary obstacle arises from the inherent slenderness of the struts and walls constituting the lattice matrix. As optimization algorithms aggressively remove material to minimize weight, the remaining structural members become increasingly thin and elongated. This slenderness significantly elevates the risk of elastic instability, commonly known as buckling, when the structure is subjected to compressive stress states [3]. Buckling is a catastrophic failure mode characterized by a sudden loss of structural stiffness and extreme lateral deflection, occurring at load levels that may be substantially lower than the material yield strength. In cellular materials, buckling can manifest locally, where individual struts collapse, or globally, where the entire structural envelope becomes unstable. The situation is further complicated by the reality of physical manufacturing processes. Additive manufacturing, while versatile, introduces a spectrum of microstructural and geometric anomalies, including surface roughness, internal porosity, variations in strut thickness, and incomplete fusion [4]. These manufacturing-induced defects act as geometric imperfections that drastically reduce the theoretical critical buckling load of the lattice, introducing a high degree of uncertainty into the mechanical performance of the final component.

1.2 Objectives and Scope

Addressing the intersection of topology optimization, buckling resistance, and structural reliability forms the core objective of this research. Traditional topology optimization frameworks frequently prioritize structural compliance minimization, essentially maximizing stiffness, without adequately accounting for the nonlinear phenomena associated with large deformations and structural instability. Consequently, a design that appears mathematically optimal under a linear static analysis may fail prematurely in physical testing due to localized strut buckling induced by unpredicted manufacturing variations. The overarching aim of this paper is to establish a comprehensive understanding of how these optimized lattice configurations respond to compressive instabilities and to formulate a rigorous methodology for reliability testing that accounts for stochastic geometric imperfections.

To achieve this, the paper systematically dissects the parameters governing buckling in cellular materials generated through algorithmic optimization. The scope includes an evaluation of different unit cell topologies, comparing traditional strut-based architectures against more recent triply periodic minimal surface designs. The investigation explores the mathematical formulation of reliability in the context of load-bearing capabilities, emphasizing the transition from deterministic safety factors to probabilistic reliability indices [5]. By applying statistical distributions to represent manufacturing defects within a computational simulation environment, this research aims to quantify the variance in critical buckling loads. Furthermore, the study outlines the necessary testing protocols required to validate computational predictions, proposing a hybridized approach that leverages both advanced numerical simulation and scaled empirical testing. The ultimate goal is to provide engineering practitioners with actionable insights into designing lightweight structures that are not only theoretically optimal in weight and stiffness but also demonstrably reliable and resilient against buckling under real-world operating conditions and manufacturing constraints.

2. Literature Review and Background

2.1 Developments in Topology Optimization

Topology optimization has evolved from a niche theoretical concept into a foundational tool for modern mechanical and aerospace design. The discipline is primarily dominated by two major algorithmic families: the Solid Isotropic Material with Penalization method and the Bi-directional Evolutionary Structural Optimization technique. The Solid Isotropic Material with Penalization approach relies on continuous variables representing relative material density, interpolating these densities to penalize intermediate values and drive the solution toward a clear solid-void binary outcome [6]. This continuous approach is highly efficient for compliance minimization problems and has been widely adopted in commercial finite element software. Conversely, the Bi-directional Evolutionary Structural Optimization method utilizes a discrete approach, systematically adding material to highly stressed regions and removing it from underutilized areas based on a predefined sensitivity threshold [7]. Both methodologies have historically focused on maximizing global stiffness under linear elastic assumptions.

However, as the drive for extreme lightweighting accelerated, researchers began to recognize the limitations of purely compliance-based optimization. Structures optimized solely for stiffness often featured long, slender support members that were highly susceptible to instability. Consequently, the integration of buckling constraints into topology optimization frameworks became a critical area of academic pursuit. Formulating topology optimization with stability constraints is mathematically challenging due to the highly nonlinear nature of eigenvalue problems and the phenomenon of artificial localized buckling modes [8]. Artificial buckling occurs in low-density regions of the computational domain during the optimization process, causing the algorithm to erroneously assign high stress concentrations to void areas, which corrupts the optimization convergence. Overcoming this requires sophisticated mathematical treatments, such as the application of stress relaxation techniques or regional density filtering, to ensure the algorithm focuses exclusively on the structural instability of the solid material phases [9]. Recent advancements have proposed multiscale optimization strategies, where the macroscale topology and the mesoscale lattice unit cell parameters are optimized concurrently [10]. These concurrent strategies attempt to distribute varying densities of lattice structures throughout the macro-component, tailoring the local slenderness ratios to resist both yielding and buckling failure mechanisms simultaneously.

2.2 Buckling Mechanisms in Cellular Materials

Understanding the buckling mechanisms inherent to cellular materials is essential for assessing the reliability of lightweight lattices. Cellular structures, whether periodic lattices or stochastic foams, derive their macroscopic mechanical properties from the deformation mechanics of their microscopic constituent elements. Under compressive loading, these structures generally exhibit three distinct deformation regimes: an initial linear elastic response, a plateau region characterized by localized yielding or buckling, and a final densification phase where the crushed cell walls interact and stiffness sharply increases [11]. The initiation of the plateau phase is the critical threshold for structural integrity, as it marks the onset of permanent deformation or catastrophic instability.

Buckling in lattice structures is broadly categorized into two modes: macro-buckling and micro-buckling. Macro-buckling involves the global instability of the entire cellular component, acting similarly to a solid column governed by classical Euler buckling theories, heavily dependent on the global geometric envelope and boundary conditions [12]. Micro-buckling, on the other hand, occurs at the unit cell level, where individual struts or walls lose stability independently of the global structure. Micro-buckling is particularly problematic because it can precipitate a cascading failure mechanism; the collapse of a single critical strut redistributes loads to adjacent members, triggering subsequent localized failures that rapidly compromise the entire structural network [13]. The topology of the unit cell plays a dominant role in dictating the dominant buckling mode. Stretch-dominated lattices, such as the octet-truss, generally provide higher specific stiffness and strength but are highly prone to sudden, catastrophic micro-buckling. Bending-dominated lattices, such as the body-centered cubic configuration, exhibit lower initial stiffness but offer more progressive failure and superior energy absorption characteristics [14]. The advent of surface-based lattices, notably those based on triply periodic minimal surfaces like the Gyroid or Diamond architectures, has introduced a new paradigm. These structures utilize continuous curved surfaces rather than discrete struts, significantly reducing localized stress concentrations and demonstrating enhanced resistance to both micro-buckling and manufacturing-induced defect sensitivity [15].

2.3 Reliability and Uncertainty Quantification

The concept of reliability in structural engineering refers to the probability that a system will perform its intended function under specified conditions for a designated period. In the context of lightweight lattice structures fabricated via additive manufacturing, reliability is inextricably linked to uncertainty quantification. Deterministic design approaches, which rely on single-value material properties and perfect geometric assumptions paired with arbitrary safety factors, are insufficient for capturing the complex realities of cellular mechanics. Additive manufacturing processes inherently introduce stochastic variations across multiple scales. At the microscale, issues such as grain boundary anomalies and localized porosity affect the bulk material properties, creating spatial variations in Youngs modulus and yield strength [16]. At the mesoscale, geometric deviations are prevalent, including variable strut diameters, cross-sectional eccentricities, and surface roughness, all of which act as initial geometric imperfections [17].

These imperfections drastically alter the load-bearing capacity of slender structures. Classical structural mechanics dictates that the critical buckling load of a theoretically perfect column is significantly higher than that of a column with even microscopic initial curvature or load eccentricity [18]. In complex lattice structures comprising thousands of interconnected struts, the cumulative effect of these random geometric perturbations can lead to a drastic reduction in macroscopic buckling resistance. Therefore, reliability testing must incorporate probabilistic frameworks, such as Monte Carlo simulations or first-order reliability methods. These techniques involve defining the uncertain parameters as probability density functions based on empirical manufacturing data, repeatedly sampling these distributions, and simulating the structural response to construct a probabilistic profile of the critical failure load [19]. This approach allows engineers to move beyond asking whether a structure will fail under a specific load, to quantifying the statistical likelihood of failure, thereby establishing robust reliability margins that account for the unpredictable nature of advanced manufacturing processes [20].

3. Methodology and Computational Framework

3.1 Design Parameterization and Optimization Algorithms

To systematically evaluate the reliability and buckling resistance of topology-optimized lightweight structures, a robust methodological framework was developed, integrating parametric design, advanced numerical optimization, and probabilistic simulation. The initial phase of the methodology involves the definition of the design domain and the application of macro-scale topology optimization. A standardized structural benchmark, specifically a three-dimensional cantilever beam subjected to a transverse end load, was selected as the foundational geometry. The topology optimization was executed utilizing a density-based algorithm, aiming to minimize structural compliance subject to a strict volume fraction constraint of thirty percent. To ensure manufacturability and prevent the generation of exceedingly thin features that would immediately succumb to premature instability, a projection-based length scale control was implemented within the optimization algorithm [21]. This control mechanism ensures a minimum member size, promoting a clear and robust load-path topology.

Following the generation of the macro-scale optimized layout, the solid domains were replaced with mesoscale lattice structures. Three distinct unit cell topologies were selected for comparative analysis: a traditional bending-dominated body-centered cubic lattice, a stretch-dominated octet-truss lattice, and a surface-based Gyroid triply periodic minimal surface structure. The relative density of the lattice structures was spatially graded to match the continuous density field generated by the macro-scale topology optimization. This multiscale approach ensures that material is concentrated in regions experiencing high bending moments and shear forces, while lower stress regions are populated with highly porous lattice networks to achieve extreme weight reduction [22]. The parameterization of these structures was conducted using implicit geometric modeling techniques, allowing for seamless transitions in lattice volume fraction and preventing stress concentrations at the interfaces between varying density zones.

Table 1: Material Properties and Computational Optimization Parameters

Parameter Description	Assigned Value	Unit of Measurement
Base Material Elastic Modulus	113.8	Gigapascals
Material Poisson Ratio	0.342	Dimensionless
Yield Strength Limit	910.5	Megapascals
Optimization Volume Constraint	30.0	Percentage
Minimum Feature Size Penalty	2.5	Millimeters
Mesh Element Target Size	0.25	Millimeters

3.2 Computational Setup for Buckling Analysis

The core of the structural evaluation relies on high-fidelity finite element analysis to extract the critical buckling loads and identify the corresponding mode shapes. The meshed geometries of the optimized lattice structures were imported into a commercial implicit finite element solver. Due to the complex nature of the cellular geometries, higher-order tetrahedral elements were utilized to accurately capture the stress gradients across the thin struts and curved surfaces. The boundary conditions were established to simulate the physical constraints of the cantilever benchmark, with one end perfectly fixed in all translational and rotational degrees of freedom, while a distributed compressive load was applied to the opposite face to induce global bending and localized compression within the lattice matrix.

The buckling analysis was conducted in two distinct stages. The first stage consisted of a linear eigenvalue buckling analysis. This mathematical procedure solves for the theoretical load multipliers that cause the stiffness matrix of the structure to become singular, indicating the onset of instability [23]. While computationally efficient, linear eigenvalue extraction assumes a perfectly linear elastic material response and a geometrically perfect structure, often overestimating the true buckling load. Therefore, the critical mode shapes identified in the linear analysis were extracted and utilized as initial geometric imperfections for the subsequent second stage. The second stage involved a fully nonlinear post-buckling analysis, incorporating both large deformation kinematics and nonlinear material behavior characterized by an elastoplastic constitutive model with isotropic hardening [24]. By seeding the perfect geometry with the scaled mode shapes from the linear analysis, the nonlinear simulation accurately captures the transition from elastic instability to plastic collapse, providing a highly realistic prediction of the ultimate load-bearing capacity of the cellular structures.

3.3 Reliability Testing Protocol

To transition from a deterministic prediction to a rigorous reliability assessment, a probabilistic framework was established based on the Monte Carlo simulation methodology. The primary objective of this protocol is to quantify how stochastic variations inherent to additive manufacturing impact the variance of the structural response. Based on extensive literature characterization of laser powder bed fusion processes, three primary random variables were defined to represent manufacturing defects: strut thickness variation, localized micro-porosity affecting the effective elastic modulus, and initial geometric straightness deviation [25]. Each of these parameters was modeled using a Gaussian normal distribution. For instance, the nominal strut thickness was assigned a mean value determined by the design parameterization, with a standard deviation derived from empirical dimensional accuracy studies of 3D-printed titanium alloys.

The reliability testing protocol automated the execution of hundreds of nonlinear finite element analyses. For each iteration, a unique set of parameters was randomly sampled from the defined statistical distributions. The geometric model was subsequently modified to reflect these specific defect parameters; struts were locally thinned or thickened, elastic moduli in specific regions were degraded to simulate porosity, and nodal coordinates were slightly perturbed to introduce geometric crookedness. The nonlinear post-buckling analysis was then executed on this unique, imperfect model to determine its specific ultimate load capacity [26]. By aggregating the results of these iterative simulations, a probability density function of the critical buckling load for each lattice configuration was constructed. This statistical distribution enables the calculation of a structural reliability index, defined as the shortest distance from the mean of the operating load distribution to the limit state surface of the structural capacity. This index provides a definitive, quantifiable metric of the design safety margin, fully accounting for the unpredictable nature of structural imperfections.

4. Results and Discussion

4.1 Topology Optimization Outcomes

The implementation of the macro-scale topology optimization, coupled with the minimum length scale constraints, yielded a highly defined structural layout characterized by clear, primary load-bearing branches originating from the fixed support and converging towards the application zone of the external load. The transition from solid domains to mesoscale lattice representations was successfully achieved across all three selected architectures. The body-centered cubic configuration, while visually consistent, demonstrated a distinct lack of material continuity at the nodal intersections, which preliminary linear static analyses identified as significant stress concentrators. Conversely, the octet-truss design exhibited excellent nodal connectivity and high initial global stiffness, accurately reflecting its stretch-dominated mechanical nature.

The most mechanically favorable material distribution was observed in the Gyroid triply periodic minimal surface design. The implicit mathematical formulation of the Gyroid lattice intrinsically ensures smooth, continuous geometric transitions irrespective of localized volume fraction variations [27]. This continuity effectively eliminated the singular stress concentration points prevalent in the strut-based designs. Furthermore, the surface-based architecture demonstrated superior conformance to the highly irregular boundaries generated by the macro-scale topology optimization algorithm, eliminating the need for arbitrary surface trimming that frequently compromises the structural integrity of peripheral strut members in traditional lattice structures.

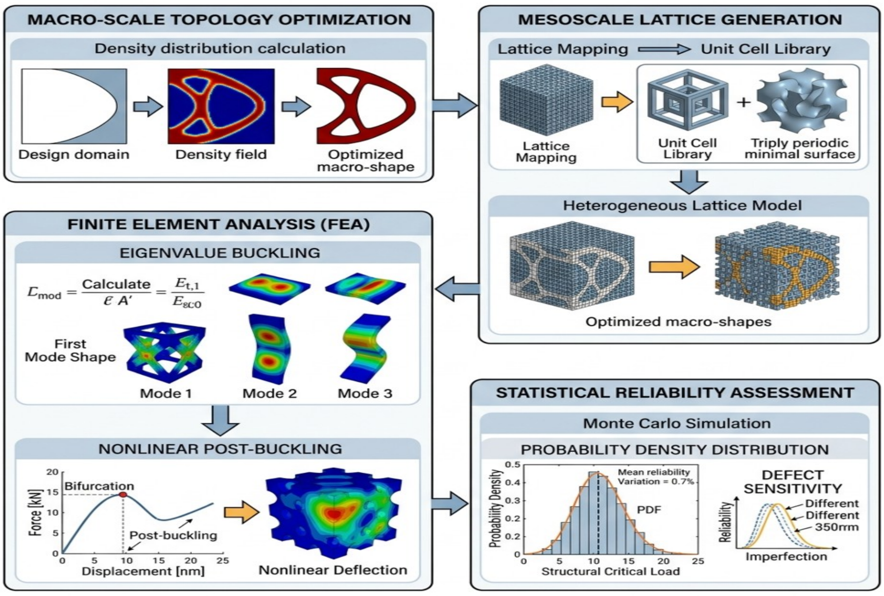

Figure 1: Comprehensive Schematic of Computational Reliability Testing Workflow for Lightweight Lattices

4.2 Buckling Resistance and Structural Stability

The results derived from the comprehensive linear eigenvalue and nonlinear post-buckling analyses reveal critical disparities in the stability characteristics of the evaluated lattice architectures. Under deterministic, defect-free conditions, the stretch-dominated octet-truss structure demonstrated the highest theoretical critical buckling load during the linear eigenvalue extraction. Its geometry, optimized for tensile and compressive stress distribution, effectively resisted the initial onset of global geometric instability. However, the subsequent nonlinear post-buckling analysis highlighted a severe limitation; once the critical load threshold was breached, the octet-truss experienced a rapid, catastrophic loss of load-bearing capacity. The failure mechanism was dominated by localized micro-buckling of individual slender struts, which immediately triggered a cascading collapse of adjacent unit cells, resulting in a virtually non-existent post-buckling energy absorption plateau.

In stark contrast, the Gyroid surface-based lattice exhibited profound superiority in overall structural stability and progressive failure mechanics. While its initial linear eigenvalue buckling load was slightly lower than that of the stretch-dominated strut lattice, its performance in the nonlinear regime was exceptional. The continuous curvature of the structural walls inherently suppresses localized buckling modes by continuously redistributing compressive stresses across the surface area rather than concentrating them along a singular slender axis. Consequently, the Gyroid structure demonstrated a prolonged, stable plastic deformation plateau following the onset of initial yielding. This behavior signifies that the surface-based topology optimization design is substantially less susceptible to abrupt catastrophic failure, providing a significantly safer failure mode that absorbs substantial energy prior to total structural collapse, a highly desirable trait in aerospace and automotive crashworthiness applications.

Table 2: Comparative Analysis of Deterministic Critical Buckling Loads

Lattice Architecture Type	Linear Eigenvalue Load Multiplier	Nonlinear Ultimate Load Capacity
Body-Centered Cubic (Strut)	12.45	9.82
Octet-Truss (Strut)	18.76	13.15

Lattice Architecture Type	Linear Eigenvalue Load Multiplier	Nonlinear Ultimate Load Capacity
Gyroid (Surface-Based)	17.52	16.48

4.3 Reliability Analysis and Defect Sensitivity

The execution of the probabilistic Monte Carlo simulation framework provided profound insights into the defect sensitivity and overall reliability of the topology-optimized designs. The introduction of stochastic geometric variations and material degradations systematically reduced the critical buckling loads across all configurations compared to their idealized deterministic counterparts. However, the magnitude of this reduction, representing the structural sensitivity to manufacturing defects, varied drastically depending on the chosen lattice topology. The probabilistic data indicated that the octet-truss structure is highly sensitive to geometric imperfections. The distribution of its ultimate load capacity was characterized by a wide variance and a significant negative shift in the mean value. A mere localized reduction in strut thickness or slight load eccentricity, simulating a printing defect, was sufficient to precipitate premature micro-buckling, fundamentally compromising the entire structure.

The Gyroid lattice configuration demonstrated unparalleled robustness in the reliability testing protocol. The statistical distribution of its ultimate failure load was notably narrow, with the mean value remaining relatively close to the deterministic prediction. This indicates a low sensitivity to the modeled manufacturing defects. The geometric nature of the continuous surface acts as a self-stabilizing mechanism; a localized manufacturing anomaly, such as a microscopic pore or surface deviation, does not result in a catastrophic loss of section modulus in the same manner as it does in a discrete cylindrical strut. The load is seamlessly transferred around the defect through the adjacent continuous material. Consequently, the calculated reliability index for the Gyroid-based optimized structure was substantially higher than that of the strut-based alternatives, definitively proving that structural reliability and buckling resistance are not merely functions of mass and stiffness, but are fundamentally governed by the specific geometric topology chosen at the mesoscale level.

5. Conclusion

5.1 Summary of Key Findings

This comprehensive academic investigation has systematically evaluated the reliability and buckling resistance of lightweight lattice structures generated through advanced topology optimization frameworks. The research highlights the critical necessity of moving beyond traditional, deterministic compliance-minimization strategies, which frequently produce structures prone to premature instability under compressive loading. Through rigorous computational testing and probabilistic analysis, the study demonstrates that the mechanical performance and safety margins of these structures are deeply intrinsically linked to their mesoscale topological architecture. The comparative analysis conclusively established that traditional strut-based unit cells, particularly stretch-dominated configurations, while offering high theoretical stiffness-to-weight ratios, exhibit extreme sensitivity to localized manufacturing defects and geometric imperfections. This sensitivity manifests as abrupt, catastrophic localized buckling, severely compromising the overall structural reliability. Conversely, continuous surface-based architectures, exemplified by the Gyroid triply periodic minimal surface, demonstrated remarkable resilience. Their inherent geometric curvature suppresses localized instability, facilitates progressive energy absorption during failure, and provides a robust insensitivity to the stochastic variations typical of additive manufacturing processes.

5.2 Broader Implications for Engineering Practice

The findings presented in this paper carry significant implications for the future of lightweight engineering and structural design. The reliance on arbitrary safety factors applied to perfect deterministic models is increasingly inadequate for the implementation of complex, additively manufactured cellular materials in critical applications. Engineering practice must pivot towards integrated computational frameworks that embed reliability analysis and buckling constraints directly into the earliest stages of the topology optimization process [28]. By adopting probabilistic design methodologies that actively account for anticipated manufacturing variations, designers can ensure that the theoretical efficiencies gained through weight reduction translate successfully into safe, robust physical components. Furthermore, the demonstrated superiority of surface-based lattices suggests a necessary paradigm shift in how internal void spaces are structured within optimized components. As computational capabilities expand, future research must focus on the integration of machine learning algorithms to rapidly predict defect sensitivities and guide the spatial grading of intricate lattice structures, ultimately enabling the realization of optimized materials that are both radically lightweight and unconditionally reliable [29].

References

1. EN 1992-1-1:2015; Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings, Bridges and Civil Engineering Structures. European Committee for Standardization (CEN): Brussels, Belgium, 2015.

2. ÖNORM EN 1990:2013; Eurocode—Basis of Structural Design. Austrian Standards: Vienna, Austria, 2013.

3. Rackwitz, R.; Flessler, B. Structural reliability under combined random load sequences. Comput. Struct. 1978, 9, 489–494.

4. Ditlevsen, O.; Madsen, H.O. Structural Reliability Methods; John Wiley & Sons: Chichester, UK, 1996.

5. Tan, L.; Yu, X.; Wan, P.; Yang, K. Biodegradable Materials for Bone Repairs: A Review. J. Mater. Sci. Technol. 2013, 29, 503–513.

6. Xie, J.; Zhang, T.; Jiang, J.; Xue, W.; Wang, W.; Ni, J.; Zhang, X.; Liu, X. Advances in Magnesium-Based Implants for Biomedical Applications: A Comprehensive Review and Future Perspectives. J. Magnes. Alloys 2025, 13, 2978–3003.

7. Zhang, Y.; Wang, D.; Gong, H.; Tang, H.; Dong, G.; Wang, B.; Xia, H. A biomechanical study of a polymer material bundled rib fracture fixator. Technol. Health Care 2024, 32, 4681–4694.

8. Novák, D.; Rusina, R.; Vořechovský, M. FREeT: Feasible Reliability Engineering Tool, Version 1.7 2024; Červenka Consulting: Prague, Czechia, 2024. Available online: http://www.freet.cz (accessed on 25 March 2026).

9. Melchers, R.E.; Beck, A.T. Structural Reliability Analysis and Prediction, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2018.

10. Schneider, J. Introduction to Safety and Reliability of Structures; IABSE: Zürich, Switzerland, 2006.

11. Goodno, B.J.; Gere, J.M. Mechanics of Materials, 9th ed.; Cengage Learning: Boston, MA, USA, 2018.

12. Elgohary, H.A. Comparative reliability analysis of punching shear design for edge column–flat slab connections without shear reinforcement. J. Umm Al-Qura Univ. Eng. Archit. 2025, 16, 682–693.

13. Kania, H.; Liberski, P. Synergistic influence of the addition of Al, Ni and Pb to a zinc bath upon growth kinetics and structure of coatings. Solid State Phenom. 2014, 212, 115–120.

14. Bull, S.J. Failure modes in scratch adhesion testing. Surf. Coat. Technol. 1991, 50, 25–32.

15. Feldt, L. S., & Kim, S. (2006). Testing the difference between two alpha coefficients with small samples of subjects and raters. Educational and Psychological Measurement, 66(4), 589–600.

16. Liao, Q.; Yu, J.-T.; Su, Y.-R.; Chen, W.-G. Reliability-based design method for shear capacity of steel reinforced engineered cementitious composites (ECC) beams. Case Stud. Constr. Mater. 2023, 19, e02681.

17. EN 1997-1; Eurocode 7: Geotechnical Design—Part 1: General Rules. European Committee for Standardization (CEN): Brussels, Belgium, 2004.

18. Zhang, Y.; Wang, J.; Tang, H.; Zheng, M.; Ma, D.; Huang, J.; Li, W.; Zhao, Q.; Sun, Z.; Li, W.; et al. Effect of LIPUS on the Degradation Behavior of Magnesium Alloy Scaffolds for Bone Repair: Insights from In Vitro and In Vivo Studies. J. Magnes. Alloys 2025, 13, 4950–4965.

19. Rosch, D. M., Collier, D., & Thompson, S. E. (2015). An exploration of students' motivation to lead: An analysis by race, gender, and student leadership behaviors. Journal of College Student Development, 56(3), 286–291.

20. Kuklík, V.; Kudláček, J. 5—Morphology of hot-dip galvanized coatings. In Hot-Dip Galvanizing of Steel Structures; Butterworth-Heinemann: Waltham, MA, USA, 2016; pp. 41–65.

21. Dachasa, K.; Chuni Aklilu, T.; Gashaw Ewnete, B.; Mosisa Ejeta, B.; Fufa Bakare, F. Magnesium-Based Biodegradable Alloy Materials for Bone Healing Application. Adv. Mater. Sci. Eng. 2024, 2024, 1325004.

22. Thomas, K.K.; Zafar, M.N.; Pitt, W.G.; Husseini, G.A. Biodegradable Magnesium Alloys for Biomedical Implants: Properties, Challenges, and Surface Modifications with a Focus on Orthopedic Fixation Repair. Appl. Sci. 2024, 14, 10.

23. Strauss, A.; Frangopol, D.M.; Bergmeister, K. Assessment of existing structures based on identification. J. Struct. Eng. 2010, 136, 86–97.

24. Strauss, A.; Bergmeister, K.; Novák, D.; Lehký, D. Stochastische Parameteridentifikation bei Konstruktionsbeton für die Betonerhaltung. Beton-Und Stahlbetonbau 2004, 99, 967–974.

25. Finch, W. H., & French, B. F. (2018). A Simulation investigation of the performance of invariance assessment using equivalence testing procedures. Structural Equation Modeling, 25(5), 673–686.

26. Sales, J.R.; Ellis, T.J.; Gillard, J.; Liu, Q.; Chen, J.C.; Ham, B.; Mayberry, J.C. Biomechanical Testing of a Novel, Minimally Invasive Rib Fracture Plating System. J. Trauma 2008, 64, 1270–1274.

27. Pilkey, W.D.; Pilkey, D.F. Peterson's Stress Concentration Factors, 3rd ed.; John Wiley & Sons: Hoboken, NJ, USA, 2008.

28. Vispoel, W. P., Hong, H., Lee, H., & Jorgensen, T. D. (2023). Analyzing complete generalizability theory designs using structural equation models. Applied Measurement in Education, 36(4), 372–393.

29. Liu, Z., Rattan, A., & Savani, K. (2023). Reducing gender bias in the evaluation and selection of future leaders: The role of decision-makers' mindsets about the universality of leadership potential. Journal of Applied Psychology, 108(12), 1924.