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Dynamic Mechanical Properties of Additively Manufactured Lattice Structures: A Comprehensive Review

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Zusammenfassung Die additive Fertigung (AM) hat die Herstellung von Gitterstrukturen revolutioniert. Sie bietet eine beispiellose Gestaltungsfreiheit und die Möglichkeit, die mechanischen Eigenschaften für spezifische Anwendungen anzupassen. Während sich die umfangreiche Forschung auf die statischen mechanischen Eigenschaften dieser Strukturen konzentriert hat, gewinnt ihr dynamisches mechanisches Verhalten unter unterschiedlichen Belastungsbedingungen aufgrund seiner Bedeutung für kritische Anwendungen wie Luft- und Raumfahrt, biomedizinische Implantate und Energieabsorptionssysteme zunehmend an Aufmerksamkeit. Die dynamischen Eigenschaften von AM-Gitterstrukturen werden durch eine Kombination von Materialeigenschaften, Prozessparametern, geometrischem Design und Belastungsszenarien beeinflusst, was komplexe Herausforderungen bei der Gewährleistung von Zuverlässigkeit und Leistung unter dynamischen Bedingungen mit sich bringt. Dieser Beitrag bietet einen umfassenden Überblick über die bestehenden Forschungsarbeiten zu den dynamischen mechanischen Eigenschaften von additiv gefertigten Gitterstrukturen. Die Untersuchung wurde in drei Phasen durchgeführt: Definition des Umfangs und der Schlüsselfragen, systematische Identifizierung und Auswahl relevanter Studien sowie deren Bewertung anhand definierter Kriterien. Die Ergebnisse zeigen erhebliche Forschungslücken auf, darunter das begrenzte Verständnis darüber, wie sich prozessbedingte Defekte und geometrische Unregelmäßigkeiten auf die dynamische Leistung auswirken, sowie den Bedarf an standardisierten Prüfprotokollen. Diese Übersicht unterstreicht die wachsende Bedeutung des Verständnisses dynamischer mechanischer Eigenschaften und soll als Leitfaden für künftige Forschungsanstrengungen dienen, um das Design und die Entwicklung neuer Produkte voranzutreiben.

Abstract Additive manufacturing (AM) has revolutionized the production of lattice structures, offering unparalleled design freedom and the ability to tailor mechanical properties for specific applications. While extensive research has focused on the static mechanical properties of these structures, their dynamic mechanical behavior under varying loading conditions is increasingly gaining attention due to its relevance in critical applications such as aerospace, biomedical implants, and energy absorption systems. The dynamic properties of AM lattice structures are influenced by a combination of material properties, process parameters, geometric design, and loading scenarios, presenting complex challenges in ensuring reliability and performance under

dynamic conditions. This paper provides a comprehensive review of the existing research on the dynamic mechanical properties of additively manufactured lattice structures. The review is conducted in three phases: defining the scope and key questions, systematically identifying, and selecting relevant studies, and evaluating them using defined criteria. The findings highlight significant research gaps, including the limited understanding of how process-induced defects and geometric irregularities affect dynamic performance, and the need for standardized testing protocols. This review emphasizes the growing importance of understanding dynamic mechanical properties and aims to guide future research efforts toward advancing the design and application of AM lattice structures in dynamic environments.

Keywords Additive Manufacturing · Lattice structures · Dynamic Mechanical Properties

Introduction and motivation

The research of metal fatigue has advanced dramatically since the nineteenth century, and fatigue tolerance is now considered a fundamental material characteristic in engineering practice [1]. Although additively manufactured (AM) metals' static strength is typically comparable or superior to that of metals made using conventional methods, their fatigue properties under cyclic loading exhibit significant variation based on various AM processes, limiting reliable applicability in fatigue-prone engineering structures such as aerospace components [2]. As AM technology advances, the study of fatigue characteristics of printed metals is becoming increasingly crucial for damage tolerance design. This uncertainty is especially prominent in structural properties of AM metal lattices. Metallic lattice structures provide a unique way for lightweight design and tailored mechanical properties through design features. However, the uncertainty in their dynamic properties poses a challenge for widespread industrial application [3]. It is typically expensive and time-consuming to conduct comprehensive fatigue testing of various components through different AM techniques and processing parameters. By analyzing previously published fatigue data on AM metals, researchers can develop predictive models and approaches for fatigue properties of lattices. Predictive models that reduce the requirement of extensive experimental tests for fatigue performance can save costs and time, making them highly desirable. The implementation of a digital twin framework can address these uncertainties by virtually simulating and optimizing lattice performance prior to physical testing, significantly enhancing design reliability and reducing development time. Several models for predicting fatigue properties of individual metals were presented in literature. However, a comprehensive overview of the modeling and prediction of AM metal fatigue characteristics is currently lacking. It is essential to identify gaps between these modeling and prediction methodologies in order to develop a suitable approach for future work. This paper aims to guide future research efforts toward advancing the design and application of AM lattice structures in dynamic environments.

State of the Art

Dynamic mechanical properties, including fatigue behavior, damping capacity, and dynamic stiffness, are pivotal for understanding the performance of additively manufactured (AM) lattice structures under cyclic loading. Fatigue behavior, commonly described through Wöhler curves (S-N curves), illustrates the relationship between stress amplitude and the number of cycles to failure. These curves provide indispensable insights into the endurance and reliability of AM lattice designs across critical applications, such as aerospace components, biomedical implants, and energy absorption systems (Figure 1). However, the performance of these structures under fatigue is profoundly affected by process-induced defects, such as porosity, surface irregularities, and residual stresses. These imperfections function as stress concentrators, significantly reducing the fatigue life and complicating predictive analyses. Furthermore, the anisotropic material properties that are intrinsic to AM processes exacerbate these challenges, underscoring the necessity for rigorous and standardized testing frameworks.

Experimental studies exploring the dynamic mechanical properties of AM lattice structures often employ fatigue testing under controlled loading conditions to generate S-N curves. Yet, investigations specifically addressing the physical testing of AM lattice structures remain sparse, representing a notable gap in the literature. These fatigue tests aim to

evaluate the structural response under cyclic loading at varying stress levels, providing essential data to quantify the influence of process parameters and geometric configurations on fatigue performance. For instance, stretch-dominated lattice structures frequently demonstrate enhanced fatigue resistance compared to bending-dominated designs. However, such advantages are contingent upon minimizing manufacturing imperfections. Advanced experimental techniques, such as in-situ crack monitoring via acoustic emission or digital image correlation, have begun to enhance data reliability. Nevertheless, the scarcity of comprehensive physical testing restricts both the validation of numerical models and the development of standardized testing methodologies tailored to AM-specific conditions.

Numerical modeling serves as an indispensable tool for complementing experimental efforts in characterizing the dynamic mechanical properties of AM lattice structures. Finite element methods (FEM) facilitate detailed analyses of stress distributions and enable predictions of fatigue life, making it possible to optimize lattice geometries for specific loading scenarios. However, despite these advancements, current modeling approaches often fail to fully encapsulate the complexities of AM-specific characteristics, including anisotropic material behavior, defect distributions, and non-linear responses. These omissions highlight the need for integrated approaches that combine computational techniques with robust experimental validation to achieve more reliable predictions.

Despite considerable progress in the field, significant research gaps remain. The absence of standardized protocols for testing and modeling dynamic mechanical properties hinders the comparability of results across studies. Furthermore, existing research predominantly emphasizes specific lattice topologies or material systems, leaving many potential configurations unexplored. Addressing these deficiencies is critical for fostering a comprehensive understanding of the factors that influence dynamic behavior and for advancing the design and application of AM lattice structures in high-performance and safety-critical environments.

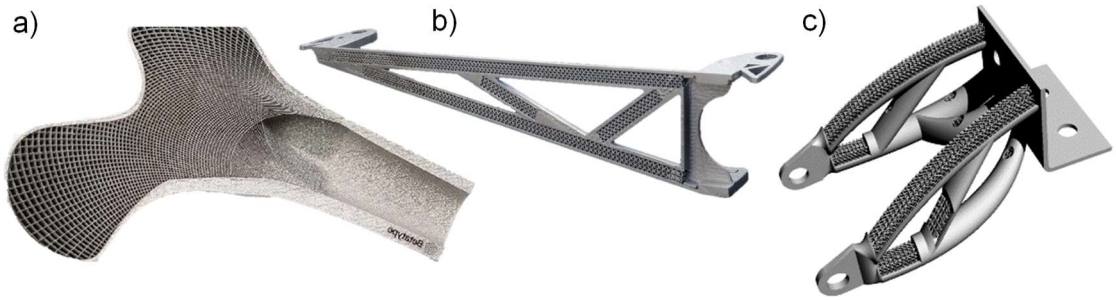

Figure 1: Keyword categories of the initial search query

Literature review

A scientific literature review is a systematic, clear, comprehensive, and reproducible process for identifying and evaluating existing approaches [6]. The following sections describe the procedure of the literature review used to identify research gaps from its results.

Methodology

There are various methods for conducting a systematic literature review, but they all share a common fundamental procedure [7]. The methodology adopted for this study involves the PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach, to identify, analyze, and synthesize existing research on the dynamic mechanical properties of additively manufactured (AM) lattice structures [8]. This process is structured into distinct phases to ensure a comprehensive and reproducible approach. The initial phase involves defining the scope and objectives of the review, followed by the systematic identification and selection of relevant literature. Subsequently, the selected studies are critically evaluated using predefined criteria to extract meaningful insights and identify research gaps.

Planning the Literature Review

The initial step in the literature review is to define an overall goal of the study. COOPER provides a model for determining the scope of the review [9]. The goal of this literature review is to identify overall research gaps in simulation-based prediction of dynamic mechanical properties of additive manufactured lattice structures. The focus is on identifying generally applicable methods and related theories. The perspective should be unbiased and focused on methodical-conceptual approaches. Complementing COOPER'S framework, an underlying research question is formulated for the literature review:

What deficits exist in current testing methodologies, modeling approaches, and validation frameworks for predicting the dynamic mechanical properties of additively manufactured lattice structures, and how can these gaps be addressed to enable reliable, standardized, and efficient industrial applications?

The scope of the investigation for existing approaches is limited to those that have undergone a scientific review process. Papers and publications published in English language between 2018-2024 have been considered.

Conducting the Literature Review

To ensure the inclusion of relevant and high-quality studies, a systematic multi-stage filtering process was employed. The first stage involved an extensive search across the academic database Scopus, employing a carefully constructed set of linked keywords withing the categories: 1. Influencing factors 2. Lattice structures 3. AM Technologies 4. Mechanical properties 5. Simulation according to Figure 2.

1. **Influencing factors** ("defect" OR "imperfection" OR "flaw" OR "porosity" OR "dislocation OR "crack" OR "microcrack" OR "microstructure")
2. **Lattice structure** ("lattice geometry" OR "lattice material" OR "lattice-based material" OR "lattice architecture" OR " lattice structure" OR "cellular structure")
3. **AM Technologies** ("SLM" OR "PBF" OR "Powder Bed Fusion" OR "Selective Laser Melting")
4. **Mechanical properties** ("Fatigue" OR "Endurance Limit" OR "S-N Curve" OR "SN Curve" OR "cyclic" OR "cycle" OR "dynamic")
5. **Simulation** ("simulation" OR "modelling")

Figure 2: Keyword categories of the initial search query

Initially, the search started with the first three components yielding 3929 papers. Refining the query by addition of keywords related to mechanical properties and simulation resulted in 258 papers. These keywords targeted critical aspects of dynamic mechanical properties, AM lattice structures, and fatigue behavior. For instance, terms like "defect," "imperfection," "fatigue," and "Selective Laser Melting" were combined with descriptors such as "lattice geometry" and "dynamic." The exact initial search query is given in the appendix.

In the next stage, the PRISMA framework was applied, involving the four phases: identification, screening, eligibility, and inclusion. Duplicates and studies without full-text availability were excluded, followed by a detailed review based on predefined evaluation criteria (EC). Ultimately, 38 highly relevant studies addressing dynamic mechanical properties of AM lattice structures were selected for in-depth analysis. Figure 3 illustrates this PRISMA process, highlighting the systematic progression from the 258 records to the final set of 38 selected papers.

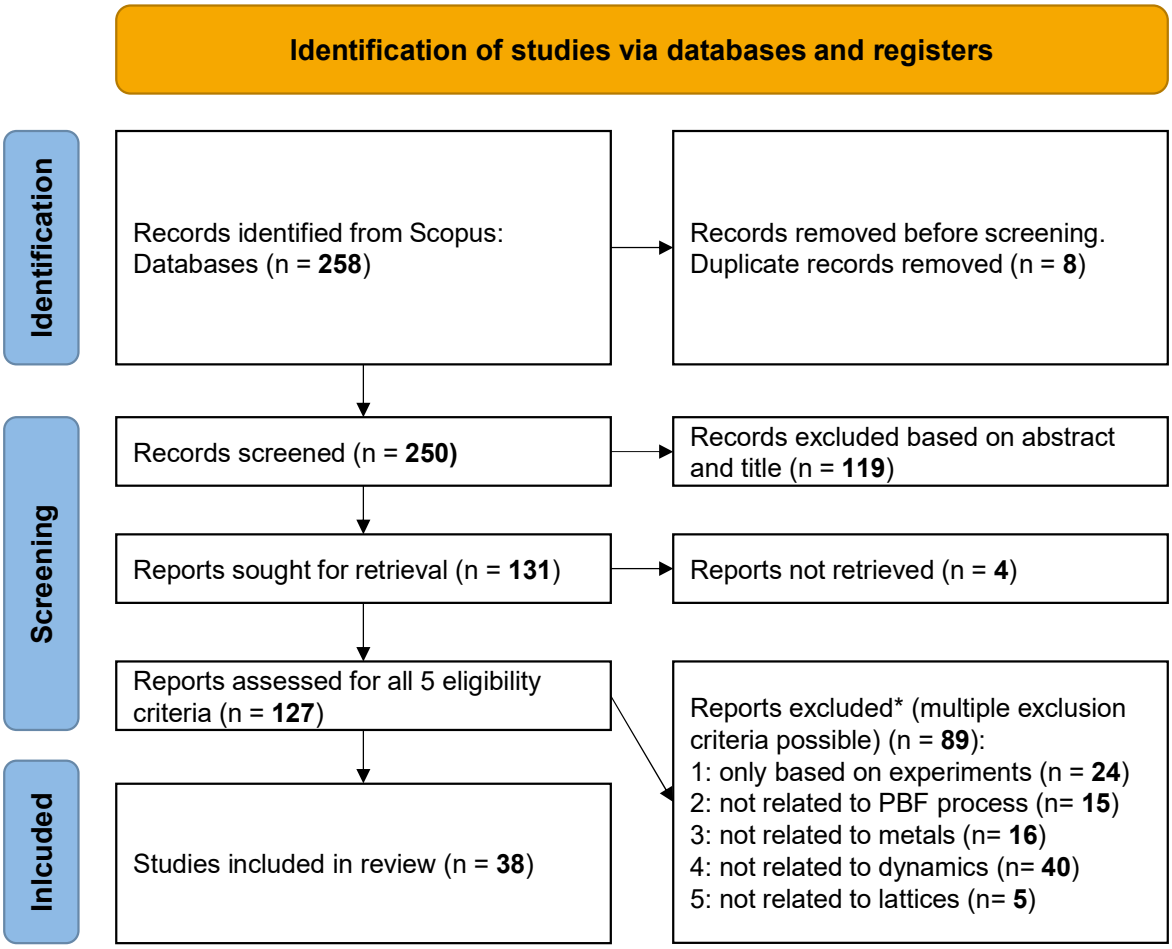

Figure 3: Conducting procedure according PRISMA four-phase flow diagram

To systematically assess the quality and relevance of the selected studies, a set of evaluation criteria (EC) was developed. These ECs cover five key dimensions: quality of numerical analysis, material behavior representation, generalizability, computational efficiency, and novelty of the models. Each study was systematically evaluated by comparing the reported methods and findings against predefined benchmarks within these

dimensions, resulting in classifications ranging from 'Very Low' to 'Very High,' according to Figure 4:

- Quality of Numerical Analysis: Studies with comprehensive, validated numerical simulations were rated higher. Those with limited validation or poorly described methodologies received lower ratings.
- Material Behavior Representation: Higher ratings were assigned to studies incorporating accurate and thorough experimental data, while lower ratings reflected insufficient material characterization.
- Generalizability: The ability of the study's findings to be applied across multiple lattice designs and loading conditions influenced this criterion.
- Computational Efficiency: Studies using highly efficient numerical approaches were rated higher, whereas those requiring extensive computational resources scored lower.
- Novelty of Models: This criterion assessed whether the models introduced innovative methodologies or built significantly upon existing approaches.

Criteria	**Very Low**	**Low**	**High**	**Very High**
EC1: Quality of Numerical Analysis	On assump-tions, lacks detail, misses PBF and lattices' complexities	Some detail but not critical aspects of PBF or lattices	Comprehensive, captures complexities, minor gaps	Highly detailed, capturing all complexities
EC2: Novelty of Models	Uses existing methods without new ideas	Some new ideas, lacks significant innovation	Novel approaches, contribute to field	Groundbreaking models, new standard
EC3: Material Behavior Representa-tion	Poor representation, unclear relationships	Basic representation, significant inaccuracies	Effective representation, with minor inaccuracies	Accurate, thorough representation, strong relationships
EC4: Generaliza-bility	Highly specific, not generalizable	Limited applicability specific cases	Reasonably generalized, some limitations	Highly and widely generalizable for most cases
EC5: Computa-tional efficiency	Highly inefficient, need excessive resources	Some efficiency, require significant resources	Efficient, use reasonable resource	Highly efficient, need minimal resources

Figure 4: Definitions of evaluation criteria and their classification levels used to assess the deficits in approaches

Results and discussion

Quantitative Analysis

The quantitative analysis of the 38 selected papers focused on two key aspects: the distribution of materials investigated and the focus areas within the studies, such as geometry or defects and imperfections.

Geometry was the most frequently analyzed parameter within 25 papers (≈65%), assumably due to its significant influence on mechanical properties. Defects and imperfections were the second most studied parameter, likely because of their direct impact on fatigue performance and their close connection to geometric design.

In terms of materials, titanium alloy Ti6Al4V was the most extensively studied, featuring in 18 out of 38 papers (≈47%), particularly for aerospace and biomedical applications. Aluminum alloys, prominent in aerospace and automotive contexts, accounted for ≈21% of studies, likely due to their high specific strength and low thermal expansion. Stainless steel 316L, valued for its corrosion resistance and biocompatibility, was frequently explored for nuclear, petrochemical, and biomedical applications.

Qualitative Analysis

The qualitative assessment revealed significant variations in the methodological approaches and contributions of the selected studies. An overview of the papers' fulfillment to each of the ECs is given in Figure 5. Studies with "High" or "Very High" ratings in numerical analysis and material behavior representation demonstrated comprehensive experimental validations and advanced simulations. These papers often employed refined finite element analysis (FEA) techniques validated against empirical data, enabling the accurate prediction of complex behaviors such as anisotropy and defect interactions. For instance, high-rated studies effectively integrated microstructural data, including porosity and residual stress distribution, to improve model reliability. Papers such as those by Yu et al. and Ulbin et al. illustrate the value of advanced modeling techniques validated with real-world conditions [10, 11].

In contrast, studies with lower score often relied on standard FEA with isotropic assumptions, limiting their applicability to AM-specific challenges. These simpler approaches, while computationally efficient, failed to address key aspects like non-linear deformation or multiaxial loading conditions. Papers focused exclusively on geometric parameters also scored lower in material behavior representation, as they lacked integration of process-induced defects or material-specific characteristics.

Generalizability emerged as a critical factor, with top-performing studies demonstrating adaptability across multiple lattice topologies, material types, and loading conditions. This versatility was achieved through innovative frameworks, such as probabilistic modeling or multiscale approaches. However, many lower-rated papers concentrated on niche applications, reducing their broader applicability. In most cases, if the material behavior relationship increases (EC2), there is an increase in generalizability (EC3) as shown in Figure 6.

Reference	EC1	EC2	EC3	EC4	EC5
[10]	●	●	●	◕	◔
[11]	●	◕	○	○	◑
[13]	●	◕	○	○	◕
[14]	◕	◔	●	○	◑
[15]	●	◕	●	◕	◕
[16]	◕	◔	●	◑	◔
[17]	●	◕	●	◑	◔
[18]	◑	◔	◕	○	◕
[19]	◔	◔	◕	●	◑
[20]	◑	◔	◕	○	◑
[21]	●	◑	●	◕	◔
[22]	◑	◑	◑	◔	◕
[23]	◑	◔	○	○	◑
[24]	◕	◕	◕	○	◑
[25]	●	◔	◕	◑	◑
[26]	◑	◑	●	◑	◑
[27]	◑	◕	●	○	○
[28]	◕	◔	◕	◑	○
[29]	●	◔	●	○	◔
[30]	◕	◑	◕	◑	◔
[31]	◕	◔	●	●	◑
[32]	●	◕	◕	◕	◑
[33]	●	◕	◑	○	◔
[34]	◕	◑	◕	◑	◕
[35]	◕	◕	●	◔	◕
[36]	◕	◔	◕	◑	◑
[37]	◕	◑	◑	◔	◔
[38]	◕	◔	◑	◕	○
[39]	◕	◑	●	◕	◑
[40]	◕	◔	●	○	◑
[41]	◑	◔	◑	○	◑
[42]	◕	●	◕	◑	◕
[43]	◑	●	○	○	●
[44]	●	●	◕	◑	●
[45]	◕	●	◕	◕	◕
[46]	●	●	●	◕	◕
[47]	◕	●	◕	◑	◔
[48]	◕	●	◔	◔	◕

Figure 5: Visual representation of the fulfillment levels for evaluation criteria (EC1-5) using Harvey Balls

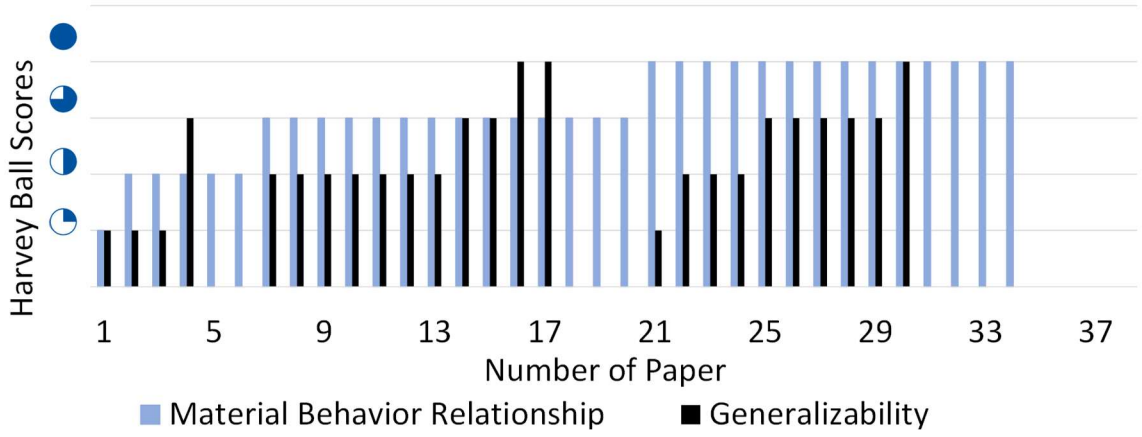

Figure 6: Relationship of EC2 and EC3 for investigated papers

Computational efficiency was another major point of divergence. Papers rated "Very High" utilized advanced techniques like homogenization, selective meshing, or parallel computation to optimize simulation time without compromising accuracy. Conversely, resource-intensive models that focused primarily on prediction accuracy often scored lower in this category, reflecting a trade-off between computational cost and model precision.

Novelty of the models varied significantly. Of the 38 papers, 8 introduced genuinely novel approaches, including probabilistic models and energy-based frameworks that addressed AM-specific challenges like defect-sensitive fatigue prediction. The innovative methods provided fresh insights but were often computationally demanding. The remaining papers primarily extended traditional models with incremental improvements, such as incorporating anisotropic factors or refining crack growth predictions. A detailed overview of the identified approaches is given in Appendix Table A1 and Table A2. Due to the similar trends for the pairwise comparison among the different evaluation criteria a correlation matrix is employed to understand the dependencies among various variables. The correlation matrix is a statistical tool to examine relationships between key variables where a high positive factor (range from -1 to 1) indicates a strong positive correlation. The Matrix is calculated by pairwise correlation coefficients using the formula:

$$c = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \sum(y_i - \bar{y})^2}}$$

where x represents the fulfilment of the first criterium and y for the second compared criterium while i is the index of the paper. The matrix is displayed in Figure 7. Empty values (where no rating was given to the paper in the respective category) were not considered as to not distort the correlation.

For example, for EC2 (the novelty of models) we obtain a positive correlation with a factor of 0,36 with the quality of numerical analysis (E1). This means that if models tend to be novel or innovative, they tend to perform better in terms of numerical analysis.

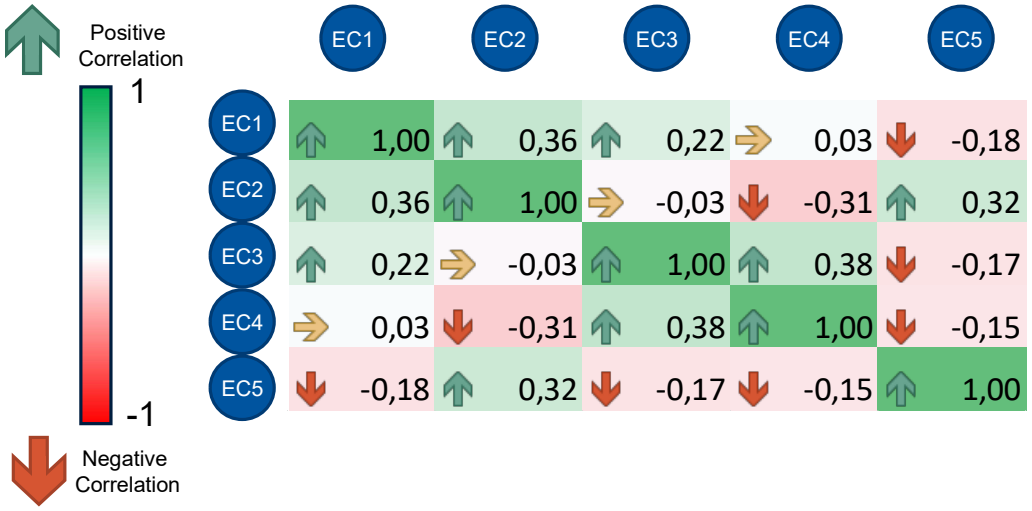

Figure 7: Correlation matrix showing relationships between evaluation criteria (ECs)

A value of -0,03 from EC2 to EC3 indicates no correlation on average between the novelty of models with the material behavior relationship, whereas a factor -0,31 shows a relatively strong negative correlation between the generalizability and novelty of models. This means that on average, innovative or novel models are less likely to be adaptable to all cases, i.e. they are more specific to certain lattice structures or loading scenarios. A value of 0,32 also shows an increase of computational efficiency for newer models on average. The correlation between material behavior and generalizability is the highest among all with 0,38, which aligns with the previous observations shown in Figure 6.

Further need for research

This review has highlighted that while existing models for predicting the dynamic mechanical properties of additively manufactured lattice structures have made significant advances, they remain insufficient to fully address industrial demands for reliable, accurate, and efficient calculations. The need for a strategic approach that balances generalizability and application-specific adaptations is evident. Generalizable models provide a foundational framework that can be adapted for diverse applications, materials, and structural configurations, while application-specific refinements address unique challenges and improve predictive accuracy in specialized contexts. Clearer guidelines are essential to determine when and how to apply general models versus tailored approaches, ensuring both efficiency and relevance in industrial adoption.

The current state of research demonstrates that many models fail to account for additive manufacturing-specific factors, such as layer thickness, process-induced defects, and anisotropy. Incorporating these unique characteristics into predictive frameworks would significantly improve their accuracy. Furthermore, most predictive approaches operate on a single scale, limiting their ability to capture the relationship between microstructural features and bulk properties. Multi-scale models that integrate micro- and macro-level analyses offer a pathway to bridge this gap and enhance our understanding of dynamic behavior.

Standardized testing protocols and generalized models remain scarce, resulting in poor comparability across studies. Developing universally applicable models that can adapt to a wide range of materials and geometries would facilitate standardization and ensure greater

consistency in predictions. Additionally, computational efficiency continues to be a major barrier, especially for large-scale industrial applications. Leveraging machine learning techniques, supported by open-access datasets of fatigue properties across materials, geometries, and processing conditions could significantly reduce the computational cost of modeling without sacrificing accuracy.

Most studies to date have focused on uniaxial loading conditions, which do not adequately reflect the complex multi-axial and variable loading scenarios encountered in real-world applications. Expanding modeling capabilities to include these conditions is critical for improving the practical applicability of predictive tools. Hybrid modeling approaches, integrating machine learning with probabilistic and multi-scale techniques, show promise for balancing computational efficiency with accuracy and generalizability.

Ultimately, further research should not only aim to improve the technical aspects of predictive modeling but also provide clear, actionable guidance for industry. This includes decision-making frameworks to help practitioners select appropriate models based on computational resources, application-specific needs, and desired accuracy. Addressing these challenges will be essential for enabling the widespread adoption of AM lattice structures in high-performance, dynamic applications, such as aerospace and biomedical engineering.

Conclusion and outlook

In this paper, a systematic review of the dynamic mechanical properties of additively manufactured lattice structures was conducted. The review started with an initial identification of 3,929 records from databases, which were narrowed down through a systematic PRISMA workflow to 38 highly relevant studies. The analysis revealed that current models and methodologies for evaluating dynamic properties are limited to specific geometries, materials, or loading conditions. Additionally, there are significant trade-offs between accuracy, generalizability, and computational efficiency, with high demands for experimental validation. These findings highlight the pressing need for approaches that integrate additive manufacturing-specific characteristics, such as microstructural features (e.g., porosity, anisotropy), into predictive frameworks. Such integration would enable adaptive and hybrid models capable of addressing real-world dynamic applications. Moreover, this study provides a foundation for further developments to represent the dynamic mechanical properties of additively manufactured lattices in a digital twin framework. [12]

Acknowledgement

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Contributions

Henrik Kruse and Neha Kumari were the main contributors, leading the study's design, literature review, analysis, and manuscript writing. Gustavo Melo and Markus Sudmanns provided valuable feedback, reviewing the methodology, data interpretation, and manuscript, ensuring scientific rigor. Johannes Henrich Schleifenbaum served as the academic supervisor, guiding the research direction, and offering expert insights throughout the process.

Appendix

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( TITLE-ABS-KEY ( ( "defect" OR "imperfection" OR "flaw" OR "porosity" OR "dislocation" OR "surface quality" OR "surface roughness" OR "residual stress" OR "texture" OR "crack" OR "microstructure" OR "inclusion" OR "powder adhesion" OR "powder deposit" OR "Young's modulus" OR "Mass density" OR "specific heat" OR "yield " OR "thermal capacity" OR "elastic modulus" OR "thermal expansion" OR "Microstructure" OR "Grain structure" OR "Dislocation" OR "Crystallographic" OR "Texture" OR "Permeability" OR "Porosity" OR "Thermal conductivity" OR "Grain size" OR "grain boundar*" OR "precipitate" OR "crystal*" OR "pore" OR "Cell Size" OR "Lattice Size" OR "Boundary Condition" OR "Strut *" OR "Lattice geometry" OR "connectivity" OR "topology" OR "Overhang Angle" OR "Inclination Angle" OR "Tilt Angle" OR "Orientation" OR "loading axis" OR "unit cell" OR "Relative Density" OR "Density gradient" OR "node" OR "Laser power" OR "energy density" OR "power density" OR "Layer thickness" OR "layer height" OR "Scan*" OR "Printing speed" OR "Hatch" OR "Beam*" OR "laser diameter" OR "Printing direction" OR "Build direction" OR "layer orientation" OR "deposition direction" OR "Post process" OR "post-treatment" OR "Heat treatment" OR "Surface treatment" ) )
AND TITLE-ABS-KEY ( ( "lattice geometry" OR "lattice material" OR "lattice-based material" OR "lattice architecture" OR " lattice structure" OR "cellular structure" OR "metamaterial" OR "meta-material" OR "microlattice" ) )
AND TITLE-ABS-KEY ( ("Additive Manufacturing" OR "3D Printing" OR "SLM" OR "PBF" OR "Powder Bed Fusion" OR "Selective Laser Melting" OR "SLS" OR "DMLS" OR "Direct Metal Laser Sintering" OR "EBM" OR "Electron Beam Melting" ) )
AND TITLE-ABS-KEY ( ( "Fatigue" OR "Endurance Limit" OR "S-N Curve" OR "SN Curve" OR "cyclic *" OR "cycle" OR "dynamic" ) ) )
AND TITLE-ABS-KEY ( ( "simulation" OR "modelling" OR "Modeling" OR "predict*" OR "Finite Element" ) )
AND PUBYEAR > 2017 AND PUBYEAR < 2025 AND ( LIMIT-TO ( LANGUAGE , "English" ) )
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Figure 8: Full research query of conducted literature research

Table A1 Summary of Approaches found during evaluation categorized as "Basic"

Model/Method	Key Findings	Advantages	Limitations	Ref.
Basquin Stress-Life Model	Fatigue life for HCF	Simple to implement; widely validated	Not for LCF, not considering mean-stress	[13–18]
Coffin-Manson Strain-Life Model	Fatigue life under LCF conditions	Applicable to high plastic strain	Complex calibration; limited to LCF	[11, 19]
Energy-Based Models	Analyze deformation energy during cyclic loading; predict fatigue crack initiation and growth	Captures nonlinear deformation; suitable for multiaxial loading	Require material data in detail; high computational demand	[20–23]
Kitagawa-Takahashi Model	Define critical crack length for fatigue limit calculations	Boundary between crack and no-crack propagation zone	Does not consider transition at the critical zone	[24, 25]

Murakami Model	Fatigue limit in transitional zone; account for defect size and location	Considers defect type; describes fatigue crack propagation	Limited applicability in complex loading; requires more parameters	[24, 25]
El-Haddad Model	Continuous representation for short- and long-crack fatigue limits	Smooth transition of short- to long-crack regions; clear, efficient	Limited to specific material types; may lack accuracy in early fatigue stages	[24, 25]
Continuum Damage Mechanics (CDM)	Predict fatigue life by modeling cyclic degradation with damage variables	Comprehensive, accounts for microstructural degradation; adaptable to multiaxial loading	Complex calibration; computationally intensive for large-scale applications	[26–36]
Probabilistic and Statistical Models	Estimate failure likelihood based on defect characteristics	Accounts for uncertainty and defect distribution; suitable for confidence interval-based predictions	Requires large statistical dataset; limited applicability for precise fatigue prediction	[37–40]
Paris Equation	Predict crack growth rate under cyclic loading	Widely used; effective for engineering application	not suited for small crack growth or fracture zone	[41]

Table A2 Summary of Approaches found during evaluation categorized as "Novel"

Approaches	Key Purpose	Advantages	Limitations	Reference
Probabilistic Average Strain Energy Density (ASED)	Predict fatigue strength with multistep FEA and statistical modeling	Reduces computational effort; accurate prediction	Requires detailed μ-CT data & statistical calibration	[42]
De-Homogenization Process	Simplify fatigue prediction with homogenization and de-homo. cycle	Reduces computational load; focuses on critical cells; adapts to real-world conditions	Limited in capturing microstructure details	[43]
Strain-Based Method	Predict failure position with strain-based	Accurate failure location prediction in HCF; validated	Complex calibration and validation are required for different lattice	[44]

	parameters and FE model	by experimental fatigue data		
Statistical Finite Element Model (SFEM)	Incorporate real geometric defects into fatigue analysis to predict stress-strain response	Captures realistic defect impact; accurate stress prediction	Complex statistical modeling of defects required	[10]
Microplasticity-Based Constitutive Theory	Predict fatigue crack initiation using microplasticity models	Models early microcrack formation; uses cumulative plastic dissipation	Computationally demanding; requires precise material parameters	[45]
Unified Multivariable Linear Regression Model	Optimize mechanical properties by adjusting lattice parameters	Simplifies design process; accurate correlation between structural parameters and mechanical response	Limited to specific types of stochastic lattices; requires regression calibration	[46]
Digital Volume Correlation (DVC) + μCT-based FE models	Analyze fatigue damage progression under multiaxial loading	Gives detailed damage progression maps; validates FEM	Require special equipment for μ-CT and DVC analysis	[47]
Equivalent Diameter Method	Estimate mechanical properties using cylindrical models	Simplifies FEA; reasonable approximation for mechanical behavior	Inner voids, pores not in model; assumes cylindrical shape	[48]

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