

Closing Editorial for the Special Issue “Fatigue Damage Behavior and Mechanisms: Latest Advances and Prospects”

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1. Introduction

Fatigue remains one of the principal causes of degradation and failure in engineering components subjected to cyclic, variable-amplitude, thermomechanical, corrosive, or otherwise complex loading conditions. Classical references on fatigue damage, cyclic loading, crack growth, and life prediction emphasize that fatigue assessment must connect localized damage accumulation with crack initiation, stable crack propagation, and final failure at the component scale [1–3]. In particular, Ellyin’s treatment of fatigue damage highlights the practical problem of predicting component life from limited experimental data, while also linking localized damage accumulation under alternating loads with crack formation, propagation, elastic–plastic modeling, damage monitoring, and microstructure-informed life extension [1]. Comprehensive structural integrity studies similarly frame cyclic deformation, low- and high-cycle fatigue, microscopic mechanisms, failure analysis, and crack-growth-based life prediction as mutually connected elements of fatigue assessment [2]. Despite decades of research, fatigue damage behavior continues to pose significant scientific and engineering challenges because it is governed by interactions between material microstructure, manufacturing route, surface condition, environmental exposure, loading history, and structural scale.

The Special Issue “Fatigue Damage Behavior and Mechanisms: Latest Advances and Prospects”, published in *Applied Sciences* by MDPI, was organized to collect recent progress in the understanding, characterization, modeling, and prediction of fatigue damage. Recent literature shows strong development in fracture-mechanics-based life prediction, multiscale modeling, defect visualization, monitoring, and prognosis systems for structural integrity assessment [4–7]. Recent reviews map the capabilities and limitations of closure-aware, elastic–plastic, environmental, probabilistic, short-crack, cohesive-zone, and effective-stress-intensity approaches, indicating that fracture mechanics remains a central framework for quantifying crack stability and fatigue crack growth [4,8]. Its aim was to provide a platform for studies that improve the mechanistic interpretation of fatigue processes and support the development of safer, more durable, and more efficient engineering structures.

This closing editorial briefly reviews the thematic scope of the Special Issue, summarizes the principal scientific contributions, and identifies emerging directions that may shape future fatigue research.

2. Scope of the Special Issue

The Special Issue addressed fatigue damage behavior and mechanisms from experimental, theoretical, computational, and applied perspectives. The scope reflects a research landscape in which fatigue is increasingly treated as a coupled micro–meso–macro problem, with multiscale frameworks being used to relate microstructural mechanisms,



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short-crack evolution, long-crack growth, and structural life [9–13]. Horstemeyer’s review is especially relevant in this context because it discusses concurrent multiscale methods, nonlocal temporal formulations based on homogenization, notch-size effects on fatigue life, inclusion-sensitive multistage cracking, and top-down fatigue modeling strategies [9]. Topics included, but were not limited to:

- Mechanisms of fatigue crack initiation and propagation;
- Low-cycle, high-cycle, very-high-cycle, multiaxial, and variable-amplitude fatigue;
- Fatigue behavior of metals, alloys, composites, polymers, ceramics, coatings, and additively manufactured materials;
- Microstructure–property relationships under cyclic loading;
- Fatigue under thermomechanical, corrosion, fretting, impact, or complex environmental conditions;
- Experimental techniques for fatigue testing, damage detection, and structural health monitoring;
- Analytical, numerical, probabilistic, and data-driven approaches to fatigue life prediction;
- Design methods for damage tolerance, residual life assessment, and structural integrity.

3. Overview of Published Contributions

The contributions included in this Special Issue are discussed below in relation to several complementary themes. The first theme concerns experimental characterization of fatigue behavior under controlled laboratory conditions. The Special Issue papers on AISI 1045 threaded components and DD11 low-carbon steel provide data on fatigue life, crack initiation, crack propagation, stress concentration, pre-strain, and notch sensitivity [14,15]. These contributions can be viewed against the broader literature on experimental and numerical fatigue-crack analysis, where three-dimensional crack characterization, defect visualization, and in situ monitoring have been used to reveal crack geometry, stress-intensity factors, defect evolution, and multiscale fatigue kinetics [6,7,16,17]. For example, synchrotron X-ray microtomography and three-dimensional volume correlation have been combined with numerical modeling to estimate stress intensity factors from actual crack geometry, directly linking empirical observation and computational mechanics [16]. Related studies on aluminum alloys and very-high-cycle fatigue further show that defect visualization, elastic modulus decrement, fracture surface morphology, fish-eye nucleation, Paris-regime transition, and scale-invariant roughness parameters can support the interpretation of damage localization and failure transitions [6,7,17,18].

The second theme addresses modeling and simulation of fatigue damage. In the Special Issue, this is represented by the equivalent fatigue constitutive model for concrete and the XFEM analysis of torsional fatigue in spot-welded structures [19,20]. These papers use different modeling strategies, but both illustrate the importance of connecting damage evolution or crack propagation algorithms with experimentally relevant structural configurations. In the wider fatigue literature, modeling approaches include crystal-plasticity-based damage criteria, statistical volume elements, homogenization, cohesive-zone concepts, and unified short- to long-crack formulations for predicting crack initiation sites, crack growth rates, and fatigue life [21–25]. These approaches range from micro–meso models that incorporate grain orientation effects and modified damage criteria for high-cycle fatigue, through RVE-based criteria with critical damage thresholds for crack initiation, to energy- and slip-based physics-informed formulations validated on aerospace structural details [21–24]. Unified crack-growth models further attempt to bridge microstructurally short, physically short, and long crack regimes for titanium and nickel alloys by introducing crack-driving-force descriptions suitable for early crack growth [25].

The third theme concerns diagnostic and monitoring methods. Although the Special Issue contributions considered here mainly emphasize fatigue experiments and numerical modeling, their findings are relevant for damage detection and residual-life assessment because they identify measurable fatigue-critical quantities such as strain-based damage variables, stress concentration factors, crack paths, notch response, and weld-size effects. In the broader literature, advanced sensing, imaging, non-destructive evaluation, acoustic emission, digital image correlation, infrared thermography, and data-driven interpretation techniques are increasingly important for detecting early fatigue damage and estimating residual life in service [4,5,8]. Structural integrity prognosis systems for aircraft illustrate this direction by combining actual usage tracking, anticipated usage modeling, microstructure-based degradation mechanisms, crack initiation at fractured constituent particles, crack propagation, and multistage life decomposition [5].

The fourth theme explores how material form, manufacturing route, and structural detail influence fatigue performance. Within the Special Issue, this theme is reflected through studies of concrete, threaded steel elements, pre-strained/notched low-carbon steel, and spot-welded assemblies, all of which show that fatigue life depends strongly on the interaction between material response, local geometry, damage evolution, and structural configuration. This theme is consistent with, but distinct from, broader studies of additively manufactured materials and advanced composites, where defect populations, anisotropy, residual stresses, and local material heterogeneity also require dedicated fatigue assessment [26–30].

The following four Special Issue papers provide the specific basis for the summary in Table 1. The first develops an equivalent fatigue constitutive model for high-cycle fatigue damage in concrete used in bridge decks and road pavements. By defining the fatigue damage variable through maximum fatigue strain and embedding the damage evolution law into the concrete damaged plasticity model in Abaqus, the study relates residual strength, residual stiffness, and residual strain to the descending branch of the monotonic stress–strain response and verifies the model against axial compression and bending fatigue data [19]. The second contribution compares knuckle and standard screw threads made of AISI 1045 steel under rotating bending fatigue. It reports lower stress concentrations for knuckle threads than for triangular screw threads and links this geometry effect with delayed defect initiation and slower circumferential crack propagation, whereas screw threads are associated with more localized initiation and faster radial crack growth [14]. The third contribution examines DD11 low-carbon steel and reports that an 11% pre-strain has only a minor effect on fatigue limit, while notched specimens show low notch sensitivity attributed to local plasticity and notch blunting around the hole [15]. The fourth contribution applies XFEM to torsional fatigue of spot-welded structures, showing that weld diameter and the number of spot welds can substantially influence crack propagation and may be used as design variables for improving torsional fatigue performance [20].

Table 1. Summary of selected contributions included in the Special Issue.

Contribution	Material/System	Main Methodology	Key Fatigue Topic
Equivalent fatigue constitutive model [19]	Concrete in bridge decks and pavements	Fatigue damage evolution law coupled with CDPM in Abaqus	High-cycle fatigue degradation, residual strength, residual stiffness, and validated and computationally efficient constitutive modeling
Rotating bending fatigue of knuckle and screw threads [14]	AISI 1045 steel threaded components	Rotating bending tests, stress concentration assessment, and fractography	Influence of thread geometry and stress concentration on crack initiation, crack propagation mode, and high-cycle fatigue life

Table 1. *Cont.*

Contribution	Material/System	Main Methodology	Key Fatigue Topic
Pre-strain and notching in DD11 steel [15]	DD11 low-carbon steel with pre-strain and holes	Fatigue experiments supported by finite element modeling in SolidWorks	Fatigue limit, notch sensitivity, notch blunting, and local plasticity around structural holes
XFEM analysis of spot-welded structure [20]	Spot-welded box-like structure under torsion	XFEM crack propagation simulation with supporting fatigue tests	Torsional fatigue, weld diameter/number optimization, crack growth reduction, and fatigue-resistant design

4. Key Lessons and Scientific Advances

Several general observations emerge from the collected contributions. First, fatigue damage is inherently multiscale: local microstructural events such as slip localization, inclusion cracking, void nucleation, interface debonding, or defect-assisted crack initiation may determine macroscopic life. This conclusion is consistent with multiscale approaches developed for ductile metals, heterogeneous materials, composites, and metallic structural details [10,11,23,28,31]. In ductile materials, homogenization-based formulations decompose fatigue into fast microchronological and slow macrochronological problems while tracking microvoid accumulation and macrocrack propagation with modified Gurson-type damage models [10]. In heterogeneous and composite materials, spatial homogenization, temporal block-cycle-jump schemes, reduced-order models, and continuum damage mechanics enable efficient simulation of long cyclic histories and distributed damage evolution [11,31]. Second, the reliability of fatigue assessment improves when experiments and models are integrated, particularly when local measurements are used to calibrate or validate predictive frameworks. Third, fatigue-critical behavior is often governed by local features such as pores, notches, holes, thread roots, weld nuggets, residual stress gradients, anisotropic microstructures, and heterogeneous interfaces.

Another important lesson is that fatigue life prediction must increasingly account for realistic service conditions. Components rarely experience ideal constant-amplitude uniaxial loading; instead, they are exposed to spectrum loading, multiaxial stress states, temperature variations, corrosive environments, contact conditions, and maintenance constraints. Recent systematic reviews of fracture-mechanics-based approaches highlight the need to include elastic–plastic crack-tip response, short-crack effects, probabilistic uncertainty, environmental influences, and monitoring data in structural integrity assessments [4,8]. They also show that future structural integrity analyses will likely rely on combinations of fracture mechanics, multiscale modeling, machine learning, digital twins, acoustic emission, digital image correlation, and structural health monitoring [8,32]. Therefore, the next generation of fatigue assessment tools should combine mechanistic accuracy with practical robustness.

5. Future Prospects

The advances reported in this Special Issue point to several promising research directions:

1. Mechanism-informed life prediction: Future models should more explicitly incorporate microstructure, defects, residual stresses, and local cyclic plasticity, following recent advances in crystal-plasticity-based and physics-based fatigue criteria [22,24].
2. Integrated experimental–computational workflows: High-resolution measurements, in situ testing, and validated simulations can improve the transferability of fatigue predictions, particularly when three-dimensional crack characterization and image-based simulations are combined with numerical analysis [16,33].

3. Data-driven and hybrid modeling: Machine learning methods may support fatigue assessment when combined with physics-based constraints, multiscale simulations, and high-quality datasets; recent work on fiber-reinforced composites combines multiscale finite element modeling with neural networks to balance computational efficiency and accuracy in fatigue life and residual-life prediction [30,32].
4. Fatigue of defect- and geometry-sensitive structures: Pores, notches, holes, thread profiles, weld size, and manufacturing-related heterogeneity should be explicitly considered in fatigue-resistant design [14,15,20,26].
5. Structural health monitoring and digital twins: Real-time sensing, acoustic emission, digital image correlation, probabilistic updating, and online digital-twin architectures can improve residual life estimation and maintenance planning [5,8].
6. Sustainability and durability: Fatigue-resistant design is increasingly linked to resource efficiency, lightweight structures, repairability, and longer service life.

6. Concluding Remarks

The Special Issue “Fatigue Damage Behavior and Mechanisms: Latest Advances and Prospects” reflects the breadth and vitality of current fatigue research. The published contributions, considered together with the broader literature, indicate continuing progress in understanding fatigue mechanisms, improving experimental characterization, developing predictive models, and applying these advances to engineering materials and structural details [1–4,34]. Across the reviewed sources, the most consistent message is that reliable fatigue assessment requires simultaneous attention to localized damage accumulation, crack initiation, stable and unstable crack growth, microstructural heterogeneity, experimental validation, and computational efficiency.

At the same time, fatigue remains a demanding interdisciplinary problem. Continued collaboration among materials scientists, mechanical engineers, computational modelers, experimentalists, and designers will be essential for translating scientific insights into reliable engineering solutions. We hope that this Special Issue will serve as a useful reference for researchers and practitioners and will stimulate further work on fatigue damage behavior and mechanisms.

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