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Mechanical Durability of Contemporary Dental Materials: An Engineering Review and Research Roadmap

Amol B. Patil
PhD Research Scholar
Department of Mechanical Engineering
Srinivas University
Mangalore, Karnataka
✉ amolbpatil111@gmail.com

Amit S. Shelake
Associate Professor
Departmennt Mechanical Engineering
Ashokrao Mane Group of Institutions
Kolhapur, Maharashtra
✉ shelakeamit111@gmail.com

Jitendra B. Patil
PhD Research Scholar
Department of Mechanical Engineering
Srinivas University
Mangalore, Karnataka
✉ jitendrapatil11691@gmail.com

ABSTRACT

Dental restorations and implants operate under coupled cyclic loading, contact, sliding, moisture, thermal fluctuation, saliva chemistry and manufacturing-induced defects; therefore, static strength alone is an inadequate predictor of service life. This critical review synthesizes 50 peer-reviewed studies published in 2025-2026 and interprets zirconia/glass-ceramics, resin composites and additively manufactured polymers, PEEK/high-performance polymers, and titanium/Co-Cr systems through a process-structure-property-environment-life framework. Evidence shows that build orientation, layer thickness, firing or post-curing, milling, surface treatment and ageing alter defect populations and fatigue reliability; printed-resin durability remains protocol-dependent; and implant performance requires simultaneous treatment of micromotion, stress redistribution, corrosion and tribocorrosion. The review integrates service-representative testing, fracture/fatigue and wear metrics, reliability analysis and validated finite-element modelling into a compact experimental-computational methodology. Priority directions are standardized fatigue/wear protocols, defect-informed additive-manufacturing models, calibrated ageing, coupled bio-tribocorrosion-fatigue testing, experimentally validated probabilistic FEA, and multi-objective material-process-geometry optimization.

KEYWORDS *: Dental materials; Fatigue; Tribology; Additive manufacturing; Finite element analysis.*

NOTATIONS

a - flaw/crack size; b - specimen width or fatigue exponent (context dependent); C, m - crack-growth constants; d - specimen thickness; F - applied/fracture load; f - loading frequency; H - hardness; K_I - mode-I stress intensity factor; L - support span or sliding distance; N, N_f - cycle count and cycles to failure; P_f - failure probability; R - load ratio; V - wear volume; Y - geometry factor; σ, σ_a - stress and stress amplitude; σ0 - Weibull characteristic strength; FEA - finite-element analysis; DOE - design of experiments; PEEK - polyetheretherketone; SEM - scanning electron microscopy; XRD - X-ray diffraction; micro-CT - micro-computed tomography; DIC - digital image correlation.

INTRODUCTION

Contemporary restorative dentistry increasingly relies on materials and manufacturing routes that are also central to mechanical and materials engineering: transformation-toughened ceramics, glass-ceramics, particle- and fiber-reinforced polymers, high-performance thermoplastics, titanium alloys, cobalt-

chromium alloys, CAD/CAM machining and additive manufacturing. What differentiates a dental component from a conventional engineering component is not the absence of mechanics, but the unusually coupled service environment. A crown, veneer, denture base, abutment or implant experiences repeated multiaxial loading while its surfaces are simultaneously exposed to moisture, temperature excursions, pH changes, saliva, abrasive food particles, antagonistic contact and-in metallic systems-electrochemical reactions. The engineering question is therefore not merely whether a material is 'strong', but how defects initiate, evolve and interact until function is lost.

The 2025-2026 literature reinforces this distinction between strength and durability. Fatigue studies on lithium disilicate, multilayer zirconia and monolithic crowns show that thickness, contact configuration, support conditions, surface treatment and loading protocol change failure probability even when the nominal material class is unchanged [1, 2, 3, 4, 5]. In resin systems, print orientation, polymerization/post-curing and artificial ageing alter flexural response and fracture resistance, while clinical and laboratory wear studies demonstrate that surface damage develops progressively under function [6, 7, 8, 9]. These findings support a damage-mechanics interpretation in which processing determines the defect state, the defect state controls local stress amplification, and the service environment controls damage accumulation.

Digital manufacturing intensifies the need for this engineering viewpoint because it introduces controllable process variables and process-specific defects. Milled components may contain machining grooves, edge chipping, residual stresses or subsurface damage; vat-polymerized resins may exhibit orientation-dependent layer interfaces, incomplete conversion or post-cure gradients; printed zirconia may contain pores, interlayer defects and shrinkage-related heterogeneity; and printed metals may retain porosity, surface roughness and microstructural gradients. Systematic evidence published in 2025-2026 generally indicates that printed zirconia can achieve clinically relevant strength but still tends to show lower flexural strength or Weibull reliability than milled zirconia, with build orientation, layer thickness and firing history remaining important variables [10, 11, 12]. Bergler et al. [13] further connected flexural response with microstructural differences between 3D-printed and milled mono- and multilayer zirconia, reinforcing the need to characterize process-induced defects rather than report strength alone. Likewise, recent reviews of definitive printed resins emphasize heterogeneity and unresolved long-term durability relative to CAD/CAM-milled counterparts [14, 15].

A Mechanical Engineering PhD can contribute uniquely to this field by combining experimental mechanics, tribology, fracture and fatigue, surface engineering, metrology, additive manufacturing, finite-element analysis (FEA), design of experiments (DOE), reliability analysis and optimization. Such a contribution is most valuable when it goes beyond a simple comparison of commercial materials and establishes a causal chain: processing variable -> microstructure/defect -> local stress or contact state -> damage mechanism -> life/reliability -> design rule. Dynamic FEA studies already show that framework and abutment stiffness redistribute stress across implant components, but numerical predictions require experimental validation and realistic contact/loading assumptions before they can become predictive design tools [16, 17].

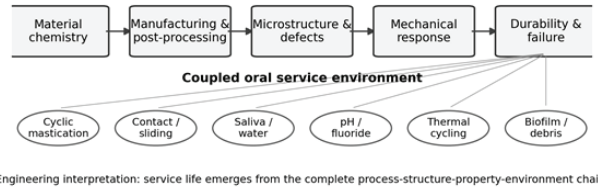


Fig. 1. Mechanical-engineering framework linking chemistry, manufacturing, defects, mechanical response and durability in the oral environment

This review therefore has two objectives. First, it synthesizes recent 2025-2026 evidence on mechanical behaviour, damage mechanisms and durability across the principal contemporary dental material families. Second, it converts that synthesis into a research roadmap for Mechanical Engineering scholars by identifying measurable variables, experimental methods, modelling strategies, knowledge gaps and candidate doctoral objectives. The central thesis is that dental durability should be treated as a coupled process-structure-property-environment-life problem rather

than as a collection of isolated strength values. Fig. 1 summarizes this organizing framework.

LITERATURE REVIEW / SURVEY

Zirconia and glass-ceramics

The contemporary ceramic landscape is shifting from a simple zirconia-versus-lithium-disilicate comparison toward composition gradients, ultra-translucent zirconias, multilayer blanks, minimally invasive thicknesses and additive manufacturing. These innovations improve esthetics and manufacturing flexibility but increase mechanical complexity. Multilayer zirconia is spatially non-uniform; a restoration's position within the blank can alter phase/composition and thus stiffness, strength or fatigue behavior. Bakitian [18] synthesizes manufacturer, laboratory, clinical and ageing factors affecting multilayer zirconia, making a strong case for layer-resolved reporting rather than treating a multilayer disc as homogeneous.

Fatigue and thickness studies reveal that material ranking is geometry dependent. Zurlo Dellazzana et al. [4] found that thickness affected 4YSZ and lithium disilicate differently in occlusal-veneer fatigue. Prott et al. [5] reported distinct fatigue/failure behavior for lithium disilicate and composition-gradient zirconia veneers across 0.5-1.5 mm thicknesses. Such data are ideal for developing a mechanistic 'minimum safe thickness' framework in which the relevant output is failure probability under a defined load spectrum rather than a universal thickness number.

Surface engineering can improve bonding, bioactivity or antimicrobial function but may also create stress raisers or interface failure modes. Cantelli et al. [2] and da Silva et al. [19] demonstrate that surface/coating interventions need fatigue evaluation and emphasize the dual response of crown fatigue and antagonist wear. The Mechanical Engineering opportunity is to optimize surface treatments using fatigue life, coating adhesion, roughness and antagonist loss simultaneously.

Additive zirconia remains a particularly fertile PhD topic. Pinelli et al. [10] and Ruggiero et al. [11] identify lower or more variable flexural reliability of printed material relative to milled controls and emphasize orientation/layer effects. Sabatini et al. [12] directly links firing process and build orientation with flexural/structural response, whereas Bergler et al. [13] adds microstructural comparison across printed and milled mono- and multilayer zirconia. A compelling doctoral program would combine print DOE, uCT porosity mapping, XRD phase analysis, surface topography, flexure/Weibull, step-stress fatigue and fracture-surface statistics, followed by a defect-informed finite-element or probabilistic life model.

Resin composites and 3D-printed polymers

Resin-based dental materials span direct composites, CAD/CAM polymer blocks, denture-base polymers, short-fiber systems and printable resins. Their durability is governed by a network of coupled mechanisms: polymerization shrinkage and residual stress, matrix viscoelasticity, filler-matrix debonding, water uptake, hydrolysis, wear and fatigue. Ribeiro et al. [20] illustrates how curing technology affects physicomechanical properties, while Mohammadi Ghayeghchi et al. [21] demonstrates chemistry-driven control of polymerization shrinkage stress. These mechanisms are directly accessible to Mechanical Engineering through DMA, shrinkage-force measurement, micro/nanoindentation, fracture testing and FE residual-stress analysis.

The strongest recent theme is additive manufacturing. Coldea et al. [22], Artopoulou et al. [23] and Alhotan et al. [24] show that denture-base mechanics cannot be generalized across printed formulations. Rizzante et al. [6] and Korkmaz et al. [9] show the importance of polymerization/post-curing protocols; Mudhaffer et al. [7] adds build orientation and ageing. Terán Lozada et al. [25] evaluates definitive crown resins, while Benalcázar-Jalkh et al. [26] brings fatigue into implant-supported definitive crowns. The umbrella synthesis by Dascanio et al. [15] concludes that long-term durability of printed resin-based composites remains uncertain and that milled CAD/CAM materials generally retain stronger mechanical/optical stability. This is precisely the type of evidence gap a Mechanical Engineering PhD can address with standardized fatigue and damage characterization.

Wear studies extend beyond static properties. Doumit et al. [8] provides 24-month functional wear data for 3D-printed minimally invasive restorations, creating an important bridge between laboratory simulation and

clinical behavior. Ghabchi et al. [27], Li et al. [28], Wu et al. [29] and Osiewicz et al. [30] demonstrate that material loss depends on both material architecture and tribological configuration. A high-value research design would calibrate a laboratory wear protocol against clinically observed roughness/volume-loss evolution rather than simply increasing cycle count.

Direct composites remain relevant because they reveal the interaction between intrinsic material design and restoration geometry. Tsujimoto et al. [31] found that material/filler type and the number of restored surfaces were associated with restoration longevity in a large retrospective dataset. Troha et al. [32] shows that filler content controls ageing response, and Watanabe et al. [33] addresses short-fiber reinforcement under fatigue. These studies suggest an integrated research direction: use clinical failure/survival patterns to select realistic geometries and loads, then resolve their mechanics experimentally and numerically.

PEEK and high-performance polymers

PEEK is attractive because its low modulus relative to ceramics/metals can change load transfer and because filler modifications can alter wear behavior. It should not be evaluated using strength alone. Li et al. [28] showed that certain filled CAD/CAM PEEK compounds achieved favorable simulated-chewing wear and low antagonist abrasiveness, with plastic deformation and debris-layer effects contributing to the mechanism. Sari et al. [34] compared PEEK and zirconia implant abutments produced by subtractive and additive routes after thermomechanical ageing, demonstrating the importance of manufacturing route and connection behavior.

PEEK also exposes a key modelling issue: a compliant component can reduce stress locally while increasing displacement or redistributing stress elsewhere. Dynamic and hybrid-abutment FEA studies show that material modulus changes the stress field across the framework/Ti-base/bone system [16, 17]. Therefore, a 'lower stress in the PEEK component' is not automatically a better biomechanical outcome. Research must evaluate the whole assembly, micromotion/contact, fatigue and bone-level response with experimental validation. Ateş and Gungormus [35] further show that thermal ageing responses differ among PEEK, fiber-reinforced and graphene-reinforced CAD/CAM polymers, reinforcing the need for material-specific constitutive data.

Titanium, Co-Cr and implant systems

Metallic dental systems generally possess greater fracture toughness than ceramics, but their durability is governed by different weak links: notch-sensitive fatigue at threads and connections, preload loss, fretting, corrosion and tribocorrosion. Schettini et al. [36] shows that Co-Cr microstructure and mechanical properties depend on whether the alloy is cast, milled or printed. For titanium, Vegas-Bustamante et al. [37], Mangal et al. [38], Hariprasad et al. [39] and Boffano et al. [40] collectively shift the focus from passive corrosion toward coupled mechanical-electrochemical degradation.

Table 1. Engineering taxonomy of contemporary dental material systems.

Material system	Dominant durability concern	High-value research direction
Zirconia / multilayer ceramics	Brittle fracture, slow crack growth, AM/machining flaws, ageing	Thickness/gradient design; AM defect control; fatigue-surface interaction
Lithium disilicate glass-ceramic	Surface flaws, contact fracture, moisture-assisted crack growth	Damage-tolerant minimum thickness; support/contact effects
Resin composites	Matrix fatigue, filler debonding, shrinkage, wear, hydrolysis	Filler-interface ageing; repair fatigue; process-life modelling
3D-printed photopolymers	Anisotropy, conversion gradients, water sorption, fatigue uncertainty	Orientation/post-cure optimization; long-term ageing calibration
PEEK / high-performance polymers	Creep, wear, bonding and interface failure	Fatigue-wear; filler/self-lubrication; surface activation
Ti / Ti alloys / Co-Cr	Fatigue, fretting, corrosion, tribocorrosion, ion release	Coupled electrochemical-mechanical life; AM/surface engineering
Interfaces / adhesives	Debonding, hydrolysis, mixed-mode cyclic damage	Interface fracture mechanics and life prediction

Alloy and surface design provide a materials-engineering route to improvement. Herbster et al. [41] investigates Cr additions to titanium implant alloys with the objective of improving corrosion/wear response. Yet any alloying or coating strategy must preserve biocompatibility and fatigue resistance; maximizing corrosion resistance while reducing fatigue strength would not constitute a successful dental material. Multi-objective optimization using corrosion current, wear, fatigue life, hardness, modulus and biological constraints is therefore more defensible than a single-property optimization.

For implant components, component-level testing and FEA should converge. Padullés-Roig et al. [42] demonstrates this combination after implantoplasty, while Sahin Hazir et al. [16] and Poovarodom et al. [17] show the sensitivity of stress distribution to framework and abutment materials. The research frontier is experimentally validated dynamic/contact FEA that includes realistic preload, nonlinear interfaces, patient-specific geometry, cyclic load spectra and material degradation.

METHODOLOGY: REVIEW DESIGN AND EVIDENCE FRAMEWORK

This article is a structured critical review rather than a formal meta-analysis. A focused literature search was updated through August 2026 using PubMed/MEDLINE and publisher-indexed web searches. Search combinations included dental material, zirconia, lithium disilicate, resin composite, 3D-printed resin, denture base, PEEK, titanium, cobalt-chromium, implant, fatigue, fracture, wear, tribology, corrosion, tribocorrosion, thermomechanical ageing, CAD/CAM, additive manufacturing and finite element. Priority was given to peer-reviewed papers with publication years 2025 or 2026 that reported mechanical, durability, manufacturing or modelling outcomes directly relevant to a Mechanical Engineering research question.

Fifty papers were selected as a deliberately recent evidence corpus: 25 from 2025 and 25 from 2026. The corpus includes primary laboratory studies, clinical/mechanical studies, systematic reviews, an umbrella review and computational investigations. It is not intended to replace broader historical literature; instead, it captures the current problem frontier and is used to identify where mature test concepts coexist with unresolved standardization and translation issues. Fig. 4 quantifies the corpus by year and primary material domain.

Evidence was synthesized along five engineering axes: (i) material system and microstructure; (ii) manufacturing and post-processing history; (iii) loading/contact/environmental boundary conditions; (iv) measured response or failure mode; and (v) unresolved mechanism or validation need. This framework avoids the common problem of comparing strength values obtained under incompatible geometries, supports, loading rates, ageing histories or failure definitions. A result is considered most useful for doctoral research when it reveals a controllable engineering variable and a mechanistic response, not simply a statistically significant material ranking.

RESULTS AND DISCUSSION

Oral service environment, contact and cumulative damage

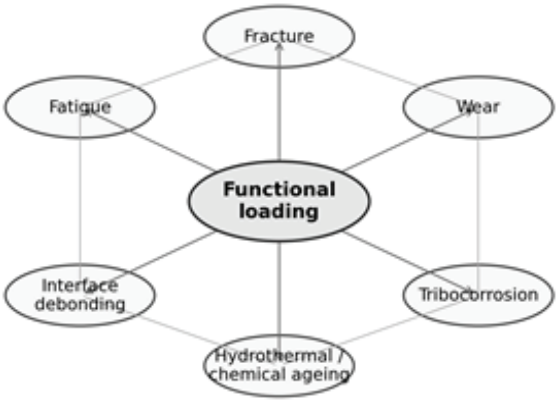
The oral cavity imposes a variable-amplitude, multiaxial and contact-dominated loading history. Mastication repeatedly loads restorations through a compliant chain comprising enamel/dentin or implant support, luting layer, restorative material and antagonist. Contact location migrates, friction introduces tangential traction, and local geometric features-fissures, connectors, screw-access channels, finish lines and layer transitions-produce stress concentrations. Therefore, a single axial compression test can rank materials but cannot reproduce the dominant damage mechanisms of many clinical components. The sensitivity of ceramic crowns to contact pattern and core material reported by Packaeser et al. [3], and the thickness-dependent fatigue behaviour reported for occlusal veneers by Zurlo Dellazzana et al. [4] and Prott et al. [5], illustrate why geometry, support and contact must be treated as test variables rather than incidental details.

Cyclic load magnitude is only one element of the spectrum. Frequency controls test time and can influence viscoelastic or time-dependent materials; waveform changes dwell time; load ratio changes mean stress; sliding amplitude determines whether the problem resembles indentation fatigue, two-body wear or fretting; and antagonist geometry controls contact pressure. In fatigue experiments the relevant descriptors include maximum and minimum load, stress amplitude, mean stress, load ratio R, frequency f, number of cycles N, failure definition and run-out criterion. When a step-stress protocol is used, the increment schedule is part of the mechanical model and should not be compared directly with constant-amplitude data without appropriate statistics [1, 4].

Temperature and chemistry modulate these mechanics. Thermocycling generates repeated differential

expansion between matrix and filler, core and veneer, resin and ceramic, or implant and abutment. Water can plasticize polymer matrices, facilitate hydrolysis at silane-treated filler interfaces and change crack-growth kinetics. pH, fluoride and electrochemical potentials can destabilize passive titanium oxide, while micromotion repeatedly removes or disrupts the film. The resulting tribocorrosion is not the sum of wear and corrosion measured independently; the mechanical and electrochemical processes interact. Recent titanium evidence continues to emphasize this coupling and the need for service-representative protocols [37, 38, 39, 40].

For polymers and composites, ageing should be considered as a state variable. Thermal cycling, prolonged water storage and solvent exposure may alter modulus, hardness, residual stress and interface strength before cyclic loading is applied. Troha et al. [32] reported that filler amount and ageing protocol jointly influence the long-term mechanical stability of experimental composites, while Ateş and Gungormus [35] observed material-dependent surface and mechanical changes after thermal ageing of CAD/CAM polymers. These studies highlight a key methodological point: 'ageing' is not a universal dose. Its severity depends on material chemistry, exposure duration, thermal range, solution and whether mechanical loading is applied concurrently or sequentially.



Damage modes interact; ageing changes interfaces, wear changes contact stress, and corrosion modified fatigue initiation

Fig. 2. Coupled damage mechanisms: fatigue, fracture, wear, ageing, interface degradation and tribocorrosion can accelerate one another.

Table 2. Service variables and laboratory representation for durability research

Service feature	Laboratory representation / response	Critical reporting / interpretation
Repeated mastication	Servo/electrodynamic fatigue or chewing simulation; life, survival, stiffness loss	Fmax/Fmin, R, f, N, waveform, run-out and failure criterion
Contact / sliding	Reciprocating/ball-on-disc/chewing simulation; wear depth/volume, COF	Antagonist material/radius, pressure, path, lubricant and distance
Thermal / moisture ageing	Thermocycling and water/artificial saliva storage; property retention	Temperature range, dwell, chemistry and exposure time
Acid / fluoride / biofilm	Immersion/electrochemistry/biofilm-informed media; current, ion release	pH, ions, potential and simultaneous mechanical contact
Implant micromotion	Cyclic implant-abutment loading/fretting; preload loss, microgap, fatigue	Preload, displacement amplitude, friction/contact and geometry
Manufacturing defects	micro-CT/SEM/profilometry plus mechanical test; reliability/crack origin	Pore/flaw size, orientation, roughness and process history

A useful Mechanical Engineering interpretation of mastication is a moving contact problem superimposed on a structurally compliant assembly. The antagonist generates a local normal pressure field and, whenever sliding occurs, a tangential traction field. The resulting tensile stress that governs brittle fracture may occur away from the point of maximum compressive contact pressure, particularly near the intaglio surface, margins, connectors or interfaces. This distinction explains why compressive strength is a weak predictor of crown or veneer survival. A mechanically meaningful experiment should therefore document indenter/antagonist radius, contact location, support stiffness, sliding path and frictional condition in addition to the applied force. Packaeser et al. [3], Zurlo Dellazzana et al. [4], Prott et al. [5] and Spitznagel et al. [43] collectively reinforce the sensitivity of fatigue performance to contact pattern, restoration design and thickness.

For ceramic and hybrid restorations, three stress scales should be distinguished. The first is the nominal structural stress governed by thickness, curvature and support. The second is the contact-scale stress beneath the antagonist, which depends on local curvature and elastic mismatch. The third is the defect-scale stress amplification at pores, machining grooves, interlayer boundaries or edge flaws. Failure occurs when these scales interact so that a critical flaw experiences a crack-driving force above the material's resistance. This hierarchy suggests a powerful PhD strategy: characterize defect population experimentally, calculate structural/

contact stress numerically, and connect the two through probabilistic fracture or fatigue. The additive-zirconia comparisons of Pinelli et al. [10], Ruggiero et al. [11], Sabatini et al. [12] and Bergler et al. [13] are especially suitable for this process-defect-stress linkage.

Polymer-based restorations require an additional time-dependent layer. Their contact area and stress field can evolve because modulus, creep and viscoelastic relaxation depend on temperature, water uptake and loading rate. Thus, the same nominal load can produce a different local deformation after ageing. For printed resins, build orientation and post-curing may also make the response anisotropic or spatially non-uniform [7, 6, 9]. A robust research design should therefore pair contact or component testing with orientation-resolved modulus and strength, and should re-measure key properties after environmental conditioning rather than using as-printed values in FEA.

Implant-supported systems add screw preload, interface contact, microgap and bone/support stiffness to the problem. The load path is redistributed through crown, abutment, screw, implant and surrounding support. Simplifying every interface as perfectly bonded suppresses micromotion and can artificially reduce local stress gradients. Dynamic FEA by Sahin Hazir et al. [16] and hybrid-abutment modelling by Poovarodom et al. [17] illustrate the importance of material stiffness and component geometry, while Padullés-Roig et al. [42] demonstrates the value of combining component fatigue with simulation. The next step is experimentally measured contact/micromotion and preload-sensitive model validation.

From load spectrum to cumulative damage

Dental loading is variable-amplitude rather than a single repeated force. From an engineering standpoint, the central research problem is how a sequence of subcritical events accumulates damage. In brittle ceramics, repeated contacts can extend pre-existing flaws by environmentally assisted slow crack growth. In polymers and composites, cyclic deformation can generate matrix microcracking, filler-interface debonding, fiber pull-out or viscoelastic damage. In metals, fretting marks, corrosion pits and thread-root stress concentrations can become fatigue origins. Accordingly, the same number of cycles is not equivalent when maximum load, mean load, sliding distance, environment or damage state differs.

A PhD study should distinguish an exposure descriptor from a damage descriptor. Exposure descriptors include cycles, temperature, pH, load, sliding distance and time. Damage descriptors include stiffness loss, crack length, wear depth, roughness, interfacial fracture energy, corrosion current, microgap or residual strength. The latter are more transferable because they describe the physical state of the specimen. For example, a thermocycling protocol becomes more scientifically useful when it is linked to a measurable modulus or bond-strength change, and a wear protocol becomes more useful when residual fatigue strength is measured after a defined wear depth. Troha et al. [32], Stape et al. [44], Wu et al. [29] and Osiewicz et al. [30] collectively motivate this transition from cycle counting to state-variable-based degradation.

This concept also avoids the common but weak practice of assigning an arbitrary number of laboratory cycles to a fixed number of clinical years. The proposed alternative is an equivalent-damage framework: choose one or more measurable damage variables, quantify their evolution under accelerated and less-accelerated exposures, and calibrate the laboratory severity against clinical or long-term observations where available. The 24-month clinical wear evidence reported by Doumit et al. [8] is particularly valuable as a potential calibration target for laboratory wear simulations.

Process-structure-property-durability relationships

The most transferable framework for dental-material research is the process-structure-property-durability chain. ‘Process’ includes powder or resin formulation, milling toolpath, printing orientation, layer thickness, exposure dose, debinding, sintering, firing, post-curing, heat treatment, polishing, air abrasion, coating and cementation. These operations create a ‘structure’ that includes grains, phases, interfaces, filler distribution, porosity, layer boundaries, residual stress and surface topography. The structure determines elastic modulus, strength, toughness, hardness, viscoelasticity and chemical stability; these properties then determine how damage accumulates under oral loading.

Zirconia is an especially clear example. Its measured strength is probabilistic because failure is flaw-

controlled; manufacturing determines the flaw population. Printed zirconia introduces additional sensitivity to build orientation, layer formation, debinding and sintering, while milling can introduce surface and subsurface damage. Recent systematic analyses conclude that milled zirconia generally retains higher flexural strength and Weibull reliability, although printed zirconia has substantial potential if process-induced defects are controlled [10, 11]. Sabatini et al. [12] further demonstrate that firing and build orientation are not secondary details but variables that alter structural and flexural behaviour. Wu et al. [45] broaden the comparison by coupling mechanical characterization with biosafety, an important reminder that mechanical optimization cannot be isolated from material compatibility.

Photopolymerized resins show a parallel but chemically different process dependence. Printing produces green parts whose final network is established by post-curing. Orientation changes the relationship between layer interfaces and principal stress; exposure and post-cure influence degree of conversion; washing can remove unreacted material but also affect surface state; and water uptake subsequently changes the polymer network. Rizzante et al. [6], Mudhaffer et al. [7] and Korkmaz et al. [9] collectively support the need to report the complete print-to-test history. Reviews published in 2026 identify protocol heterogeneity as a major limitation in comparing definitive printed resins and in claiming long-term equivalence with milled materials [14, 15].

Conventional resin composites demonstrate that formulation itself is a mechanical design variable. Filler amount, filler morphology, matrix chemistry, photopolymerization and interfacial silanization determine modulus, shrinkage stress, wear and hydrolytic stability. Mohammadi Ghayeghchi et al. [21] showed how addition-fragmentation chain-transfer chemistry can reduce polymerization shrinkage stress while maintaining acceptable flexural properties over an optimized concentration range. Troha et al. [32] showed that the benefit of higher filler loading depends on ageing history. These examples argue for multi-response optimization rather than maximizing a single property.

For metallic implants, manufacturing and surface state interact with electrochemistry. Additive manufacturing can change microstructure and roughness; machining and implantoplasty alter cross-section and surface condition; alloying changes passive-film and wear response. Schettini et al. [36] compared Co-Cr produced by casting, milling and 3D printing, while Herbster et al. [41] investigated Cr-containing titanium alloy concepts for corrosion and wear resistance. Padullés-Roig et al. [42] combined implantoplasty-related fatigue testing with finite-element simulation, illustrating a model PhD pattern: introduce a clinically relevant geometry/process change, measure its structural consequence, and validate a mechanics model.

Static properties, reliability and failure statistics

Static properties remain essential inputs, but their role should be interpreted mechanistically. Elastic modulus controls stiffness and stress transfer; hardness contributes to indentation/contact response but is not a direct substitute for wear resistance; flexural strength provides a convenient flaw-sensitive screening measure; fracture toughness quantifies resistance to crack extension; and yield/ultimate strength are relevant for ductile metallic components. For polymeric systems, storage modulus, loss factor, creep and stress relaxation may be as important as nominal flexural strength because time, temperature and moisture change the constitutive response.

For a rectangular specimen in three-point bending, the nominal flexural strength is commonly represented as:

$$\sigma_f = 3 F L / (2 b d^2) \quad (1)$$

where F is the fracture load, L the support span, b specimen width and d specimen thickness. The simplicity of this expression can mask sensitivity to edge finish, span-to-depth ratio, surface location under tension, loading rate and specimen defects. Consequently, strength data should be paired with fractography and, for brittle materials, reliability statistics. A two-parameter Weibull representation is useful when the goal is to quantify scatter rather than merely report a mean:

$$P_f = 1 - \exp[-(\sigma / \sigma_0)^m] \quad (2)$$

where m is the Weibull modulus and σ0 a characteristic strength. The 2025 systematic review by Pinelli et al.

[10] specifically highlights flexural strength and Weibull modulus as complementary metrics for printed versus milled zirconia. For doctoral work, Weibull analysis is most informative when specimen volume, stressed area, flaw origin and processing history are controlled, because otherwise m conflates true material variability with test inconsistency.

A second common misconception is to infer wear resistance directly from hardness. Recent PEEK and composite studies show why this is unsafe. Li et al. [28] found that filled PEEK compounds could display favorable impact-sliding wear despite lower baseline hardness than enamel, with deformation and debris-layer mechanisms contributing to performance. Osiewicz et al. [30] found that filler volume and hardness helped explain three-body wear in BPA-free composites but did not fully determine it. Wear is therefore an emergent tribosystem property defined by both surfaces, the intermediate medium, contact stress, motion and evolving debris.

Table 3. Compact mechanics and durability metrics

Metric / expression	Engineering use	Complementary method
Flexural: σ_f = 3FL/(2bd²)	Flaw-sensitive static screening	Fractography + Weibull statistics
Weibull: P_f = 1-exp[-(σ/σ₀)^m]	Strength scatter and reliability	Crack-origin mapping; stressed-area control
Fracture: K_I = Yσ√(πa)	Crack-driving force / defect sensitivity	Toughness / slow-crack-growth testing
Fatigue: σ_a = σ_f (2N_f)^b	Stress-life representation	Step-stress/S-N + survival statistics
Crack growth: da/dN = C(ΔK)^m	Initial flaw to remaining life	Environment-specific calibration
Wear: V = kWL/H	First-order tribological descriptor	3D profilometry + contact analysis
Tribocorrosion: Vtot = Vmech + Vcorr + Vsyn	Synergistic electro-mechanical loss	Force/friction/electrochemistry

Fracture and fatigue mechanics

Ceramics fail when a pre-existing or process-generated flaw experiences a local stress intensity sufficient to extend. In linear elastic fracture mechanics, mode-I crack driving force is approximated by:

$$K_I = Y \sigma \sqrt{(\pi a)} \quad (3)$$

where a is flaw size and Y a geometry factor. This simple relation is valuable for dental research because it explains why two specimens of the same chemistry can show different strength after grinding, polishing, printing or coating: the process changes a, Y and residual stress. In zirconia, transformation toughening and phase composition further modify crack resistance; in glass-ceramics, subcritical crack growth in moisture can reduce long-term reliability. Surface-treatment studies such as Cantelli et al. [2] demonstrate that procedures intended to improve bonding also influence fatigue survival, so bond optimization must include the possibility of mechanically introduced flaws.

Restoration thickness changes both nominal stress and the crack-driving field. The 2026 occlusal-veneer study by Zurlo Dellazzana et al. [4] showed a material-thickness interaction: 4YSZ and lithium disilicate did not respond identically as thickness decreased. Prott et al. [5] similarly demonstrated that conclusions about ultrathin lithium disilicate cannot simply be transferred to composition-gradient multilayer zirconia. Spitznagel et al. [43] likewise showed that restoration configuration and thickness interact with fatigue performance and post-fatigue failure load in composition-gradient multilayer zirconia. For Mechanical Engineering, this creates a clear research opportunity for defect-sensitive thickness design using cohesive fracture, XFEM, probabilistic FEA or critical-defect mapping validated by fractography.

Fatigue is the central durability mechanism for many restorations because mastication applies millions of subcritical load cycles. In a stress-life representation, the Basquin-type relation provides a useful conceptual form:

$$\sigma_a = \sigma_f' (2N_f)^b \quad (4)$$

where σa is stress amplitude, σ'f a fatigue-strength coefficient and b a fatigue exponent. Dental literature often uses step-stress or chewing-simulator survival rather than complete S-N characterization, but the engineering principle remains the same: cyclic life depends on load amplitude, mean stress, environment, defect state and geometry. Fig. 3 illustrates why a high static-strength ceramic may still show substantial fatigue degradation while a lower-modulus polymer may dissipate or redistribute contact stresses differently. The curves are schematic and are not pooled data.

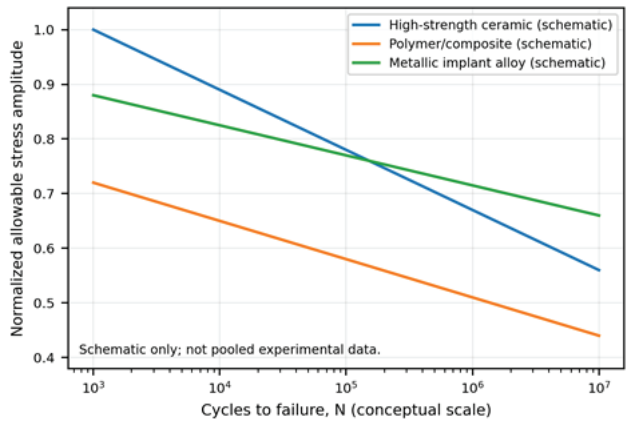


Fig. 3. Conceptual normalized S-N map across broad material classes; curves are schematic rather than pooled experimental data.

Recent fatigue studies offer several mechanistic lessons. Buser et al. [1] emphasize protocol sensitivity when comparing pressed lithium disilicate and 5Y-TZP. Packaeser et al. [3] show that core and occlusal-contact conditions alter ceramic-crown fatigue, while Pilecco et al. [46] links milling protocols to CAD/CAM fatigue. Benalcázar-Jalkh et al. [26] directly compares implant-supported 3D-printed and milled definitive resin crowns under fatigue. Watanabe et al. [33] brings reinforcement architecture into the problem by studying short-fiber flowable composite. Together these studies suggest that a high-value PhD should not ask 'which material is strongest?' but 'which process/geometry/environment combinations control fatigue initiation and propagation, and can the resulting life be predicted?'

Karevan et al. [47] further compared the fatigue behaviour of CAD/CAM composites with lithium-disilicate glass-ceramic, reinforcing the need for common cyclic-damage criteria across material classes.

Where crack-growth measurements are feasible, the Paris-type relation provides a mechanistic bridge between initial flaws and remaining life:

$$da/dN = C\,(\Delta K)^m \qquad (5)$$

The parameters C and m are environment- and material-dependent and should not be assumed from engineering handbooks for dental systems. For ceramics and bonded interfaces, subcritical growth may be strongly affected by moisture; for polymer composites, crack paths may deflect through matrix, filler interface or fiber bridges; and for metallic implants, corrosion-assisted fatigue can change both crack initiation and growth. Fatigue modelling should therefore be calibrated on the specific material/process state under a justified oral analogue.

Wear, interfaces, tribocorrosion and ageing

Dental wear is a contact-mechanics problem in which material loss and surface evolution change the future stress field. Two-body wear involves direct contact between opposing surfaces, whereas three-body wear includes particles/debris between them. Impact-sliding in chewing simulators can combine indentation, tangential traction and repeated plastic or brittle deformation. A simplified Archard relationship is often useful as a first engineering descriptor:

$$V = k\,W\,L\,/\,H \qquad (6)$$

where V is wear volume, W normal load, L sliding distance, H hardness and k an empirical wear coefficient. However, contemporary dental data repeatedly show why k cannot be treated as a material constant. Ghabchi et al. [27] compared zirconia, ceramic and printed nano-hybrid resin crowns; Li et al. [28] showed a distinctive filled-PEEK wear mechanism under simulated chewing; Osiewicz et al. [30] separated two- and three-body wear of BPA-free composites; and Wu et al. [29] examined wear resistance of repaired composites after simulated oral ageing. The tribosystem-antagonist, lubricant, debris, contact pressure, roughness and motion-must therefore be reported completely.

A particularly important clinical-mechanical interaction is antagonist wear. A hard restorative surface can be mechanically durable while damaging opposing enamel if roughness or fractured grains increase abrasivity. Coatings and polishing should consequently be evaluated with at least two responses: restoration wear/fatigue and antagonist loss. da Silva et al. [19] explicitly combined fatigue life and antagonist wear for coated ultra-translucent zirconia, an approach that is well suited to multi-objective engineering optimization.

Many restorations are layered systems rather than monolithic materials. A resin-cemented ceramic, resin-dentin interface or Ti-base/hybrid abutment transfers load across interfaces whose stiffness, thickness, roughness and chemistry affect the global stress state. Static bond strength can miss progressive hydrolytic

damage and mixed-mode crack growth. Stape et al. [44] specifically examined fatigue strength of resin-dentin interfaces after prolonged ageing, while Chen et al. [48] studied fatigue of direct and CAD/CAM restoratives bonded to a dentine-analogue substrate. These studies support interface fatigue as a distinct doctoral topic rather than a secondary bonding test.

From an engineering standpoint, interface durability can be framed using cohesive-zone parameters-peak traction, fracture energy and damage evolution-or experimentally through double-cantilever, notched, push-out or cyclic bonded-specimen configurations appropriate to the geometry. The key is to connect interface microstructure and ageing to an energy-based failure parameter that can be transferred into FEA. This would directly improve the predictive value of crown, veneer and implant-abutment simulations.

Titanium derives corrosion resistance from a passive oxide film, but repeated contact and micromotion can mechanically disrupt this film while the electrochemical environment controls repassivation. Tribocorrosion therefore creates a synergistic damage term. A useful accounting identity is:

$$V_{total} = V_{mechanical} + V_{corrosion} + V_{synergy} \quad (7)$$

The final term is precisely why independent wear and corrosion tests are insufficient. Vegas-Bustamante et al. [37] directly examined tribocorrosion effects on titanium implant mechanical behavior, while Hariprasad et al. [39] synthesizes bio-tribocorrosion in the oral environment. Mangal et al. [38] highlights metal-ion release when titanium/titanium-alloy implants are coupled with dissimilar abutment materials, and Boffano et al. [40] reviews corrosion features across titanium alloys. A Mechanical Engineering thesis can contribute by synchronizing tangential force, coefficient of friction, electrochemical current/potential, wear depth and fatigue damage in one test platform.

Geometry changes are equally important. Implantoplasty removes material and changes surface topography, creating a combined section-loss and fatigue problem. Padullés-Roig et al. [42] combined fatigue experiments with FEA after implantoplasty, providing an example of validated computational mechanics. Future work can extend this by including realistic defect distributions, thread geometry, preload loss, corrosion-fatigue and patient-specific load spectra.

Accelerated ageing is valuable only if its damage mechanism corresponds to service degradation. Thermal cycling can accelerate interfacial mismatch; water storage can plasticize polymers and hydrolyze interfaces; ethanol may exaggerate matrix softening; and simultaneous mechanical loading can produce interaction effects not captured by sequential protocols. Troha et al. [32] provides a particularly important caution by comparing real-time and accelerated ageing: 12-month real-time storage did not map trivially onto the accelerated protocols for all mechanical responses. This means that accelerated tests should be calibrated rather than assumed equivalent to a fixed number of clinical years.

For printed resins, ageing interacts with conversion and layer architecture. Alhotan et al. [49] reported material-dependent property changes after thermal cycling, while Alhotan et al. [24] studied high-impact printed denture resins after thermomechanical ageing. Ateş and Gungormus [35] showed that CAD/CAM polymer systems respond differently to thermal ageing in surface and mechanical outcomes. A robust PhD can therefore compare sequential versus simultaneous ageing, identify a damage marker such as modulus loss or crack density, and construct a time-temperature-moisture-fatigue superposition model where scientifically justified.

Manufacturing, post-processing and experimental mechanics

Manufacturing should be treated as part of the material definition. A ‘zirconia’ or ‘resin’ specimen without a complete process history is an incompletely specified engineering material. For CAD/CAM milling, tool condition, bur wear, machining direction, coolant, minimum wall thickness, finishing and polishing determine surface integrity. Pilecco et al. [46] demonstrates that milling protocol can influence fatigue behavior; this motivates direct measurement of machining damage rather than treating it as uncontrolled scatter.

For vat-polymerized resins, a minimum reporting set should include printer/technology, resin lot, build orientation, layer thickness, support strategy, exposure

settings if available, wash solvent/time, post-cure device, time/temperature, storage before test and ageing condition. Rizzante et al. [6], Mudhaffer et al. [7], Korkmaz et al. [9] and Flottes et al. [14] show that these variables are capable of shifting physical/mechanical outcomes. The engineering goal is to convert them into quantitative process maps that predict conversion, shrinkage, anisotropy, surface condition and fatigue life.

For zirconia AM, print settings interact with debinding and sintering. Orientation and layer thickness influence flaw orientation; sintering shrinkage and thermal gradients influence density, distortion and microstructure; support removal and surface finishing create additional damage. Recent systematic and experimental literature is sufficiently mature to justify full factorial or response-surface DOE on a limited set of high-impact variables, but the outputs should include fatigue/reliability-not only flexural strength [11, 12].

Surface engineering creates another multi-objective design space. Air abrasion may increase micromechanical retention but introduce flaws; polishing can reduce antagonist wear but alter bonding; coatings may improve bioactivity or antimicrobial behavior but introduce an adhesion interface; laser texture can change roughness, residual stress and wettability. Cantelli et al. [2] and da Silva et al. [19] demonstrate why a surface treatment should be evaluated under fatigue and wear. For implants, any surface intervention should additionally be assessed under corrosion/tribocorrosion.

Reproducible experimental mechanics

A coherent PhD experimental program should be designed around a causal hypothesis. If the hypothesis is that print orientation changes fatigue because it changes interlayer flaw orientation, then the minimum evidence chain is orientation -> quantified defect/anisotropy -> static response -> fatigue -> fracture origin. If the hypothesis is that a coating improves zirconia clinical durability, the chain is coating process -> roughness/adhesion/residual stress -> fatigue/wear -> antagonist response -> failure mode. Mechanical testing without microstructural or failure characterization rarely establishes causality.

Specimen design must balance standardization and clinical relevance. Rectangular bars/discs are useful for material screening because stress fields are interpretable; anatomically shaped crowns and implants are useful for system-level validation but introduce geometry and contact complexity. A strong doctoral design uses both: standardized specimens to identify material/process mechanisms, then component-level specimens to validate transferability. Replicate numbers should be justified by expected scatter and statistical model, especially for brittle/Weibull or fatigue survival analysis.

Fractography is not optional when the research question concerns fracture. SEM or high-quality optical fractography can identify crack origin, flaw type, hackle/river patterns, filler pull-out, interlayer failure or coating delamination. Surface profilometry or 3D optical metrology should quantify roughness and wear volume rather than relying only on mass loss. For printed materials, uCT can characterize internal pores non-destructively and create a direct bridge to defect-informed simulation. For composites, FTIR/Raman and DMA can connect conversion/network state to mechanical response. For metals, electrochemical monitoring synchronized with tribological force provides a mechanistic tribocorrosion signature.

The most useful experiment is one in which the boundary conditions are recorded well enough to reproduce the test in FEA. Contact geometry, friction, support compliance, load location, specimen dimensions and material constitutive data should therefore be treated as model inputs from the start. This reduces the common disconnect between a laboratory paper and a separate numerical paper that uses idealized assumptions.

A major reason dental-material studies are difficult to compare is incomplete reporting of variables that strongly influence mechanics. Reproducibility requires more than naming the test machine and specimen material. For fatigue, the report should include specimen geometry, surface preparation, support stiffness, indenter/contact geometry, waveform, frequency, load ratio, loading schedule, environment, failure definition, run-out and statistical treatment. For wear, it should include antagonist material and radius, normal load, motion path, frequency/speed, lubricant, temperature, total sliding distance, debris handling

and the method used to calculate wear. For additive manufacturing, printer/process type, orientation, layer thickness, support strategy, wash/post-cure or debind/sinter history, surface finishing and conditioning should accompany the mechanical result. The heterogeneity highlighted by Flottes et al. [14], Dascanio et al. [15], Pinelli et al. [10] and Ruggiero et al. [11] makes such reporting essential.

Uncertainty should also be treated as data. Dimensions, load-cell accuracy, roughness, temperature, material batch and alignment each contribute to experimental scatter. A high-quality doctoral study should report repeatability of the measurement system, justify sample size from the targeted effect or reliability analysis, identify outliers using predefined criteria rather than post-hoc deletion, and preserve specimen-level data for survival or regression analysis. Larrañaga-Ordaz et al. [50] makes reproducibility itself an explicit scientific topic for accelerated dentin-composite fatigue, demonstrating that test-system variability can be a meaningful research outcome rather than background noise.

Mechanism confirmation is the final reporting layer. A strength or fatigue number should be accompanied by evidence that the intended damage mechanism occurred. Fractography should identify crack origin and propagation region; wear testing should distinguish material loss from transferred debris or antagonist wear; tribocorrosion should track electrochemical response during mechanical contact; and interface fatigue should determine whether failure is adhesive, cohesive or mixed. Without mechanism confirmation, statistical differences may reflect unintended test artifacts.

Fractography and metrology-informed failure analysis

Failure analysis is the bridge between mechanical testing and mechanistic modelling. For ceramics, fracture-surface examination should be planned before the test so that pieces are recovered, orientation is preserved and the loaded/contact surface is traceable. The objective is to locate the origin, determine whether it coincides with a pore, machining groove, margin, interface or contact damage zone, and then relate the origin to the calculated tensile stress. This origin-specific workflow is more informative than classifying a specimen only as 'fractured'. Cantelli et al. [2], da Silva et al. [19], Packaeser et al. [3], Pilecco et al. [46] and the 2026 veneer studies collectively support the importance of surface, contact and geometric conditions in ceramic fatigue.

For additively manufactured materials, metrology should be three-dimensional whenever possible. A 2D polished cross-section can miss connected porosity, oriented interlayer defects or subsurface voids. uCT can quantify pore size, sphericity, orientation and location; surface profilometry or optical scanning can quantify roughness and waviness; SEM can characterize local morphology; and XRD can quantify crystalline phase changes in ceramic systems. These descriptors can then be transformed into model inputs or predictors. Bergler et al. [13], Sabatini et al. [12] and Wu et al. [45] illustrate the value of linking structural characterization to mechanical response rather than treating microstructure as a decorative image.

For composites and interfaces, the relevant morphology includes filler exposure, matrix plucking, interfacial gaps, fiber bridging/pull-out and cohesive versus adhesive fracture. For titanium systems, pits, fretting scars, oxide-film disruption and crack origins should be co-located with electrochemical history when possible. The result is a failure atlas that can support mechanism-based clustering of specimens and reduce the risk of fitting one life model to multiple unrelated failure modes.

Computational mechanics, reliability and life prediction

FEA is most valuable when it tests a mechanistic hypothesis and is validated against experiment. Dental models frequently contain strong simplifications: isotropic and homogeneous tissues, perfectly bonded interfaces, static point loads and elastic materials. These assumptions can be suitable for sensitivity studies but can also conceal the mechanisms that determine fatigue or interface failure. The 2025 dynamic framework study by Sahin Hazir et al. [16] and the hybrid-abutment study by Poovarodom et al. [17] demonstrate how material modulus redistributes stress; the next step is to validate such predictions with measured strain, displacement or component failure.

For ceramics, defect-sensitive FEA can be combined

with Weibull or weakest-link statistics. For thin veneers/crowns, local tensile stress at the cementation surface can be mapped against defect distributions inferred from fractography. For composites and interfaces, cohesive-zone models can represent progressive debonding, while viscoelastic constitutive models can capture time-dependent polymer response. For printed anisotropic materials, orthotropic elastic or fatigue properties should be measured by orientation instead of assuming isotropy. For implants, nonlinear contact and screw preload are essential if the question concerns micromotion, fretting or connection fatigue.

Life prediction should include uncertainty. Manufacturing scatter, flaw size, contact location and patient load variation can be represented through Monte Carlo simulation, Latin hypercube sampling or probabilistic design. Rather than report a single peak stress, a thesis can predict probability of failure versus cycles and validate the distribution experimentally. This moves dental FEA from explanatory color maps toward engineering reliability.

Machine learning can assist once a physically meaningful dataset exists. DOE/response-surface models are often preferable for small experimental datasets because they expose interactions and uncertainty. For larger multi-factor datasets, Gaussian-process regression, random forests or neural networks can serve as surrogate models for expensive FEA/experiments. The important principle is physics-informed feature selection: print orientation, pore fraction, modulus, roughness, contact stress and ageing dose are more interpretable predictors than arbitrary labels. Multi-objective optimization can then seek a Pareto set balancing fatigue life, wear, antagonist loss, stress shielding, manufacturability and cost.

Verification, validation and uncertainty quantification

FEA becomes predictive only when verification and validation are separated. Verification asks whether the numerical equations are being solved correctly: mesh refinement, element quality, contact stabilization, time increment and solver tolerances should not materially change the target output. Validation asks whether the model represents the physical system: predicted strain, displacement, contact area, failure location or load should be compared with independent experiments. A model may be numerically converged but physically wrong if the cement layer, boundary restraint, screw preload, support modulus or friction coefficient is unrealistic.

The most efficient validation experiment is not always a full anatomical fatigue test. A hierarchy can be used. Level 1 validates material constitutive data on coupons. Level 2 validates a simplified contact or bonded geometry with DIC/strain gauge/displacement. Level 3 validates the anatomical crown, veneer, abutment or implant component under the same load path used in the model. Level 4 validates durability by comparing failure location and life distribution. Sahin Hazir et al. [16], Poovarodom et al. [17] and Padullés-Roig et al. [42] provide a contemporary basis for moving implant modelling toward such multi-level validation.

Uncertainty quantification is particularly important for brittle ceramics and patient-specific geometry. A deterministic maximum stress does not express variation in flaw size, thickness, contact position, modulus, cement thickness or load. Monte Carlo or Latin-hypercube sampling can propagate these uncertainties, while Gaussian-process surrogates can reduce the computational cost of repeated nonlinear simulations. The final output should be a confidence or failure-probability band rather than a single stress value whenever scatter is intrinsic to the material or process.

Model calibration should avoid circularity. If the same failure data are used to fit and validate the model, agreement is expected and does not establish predictive capability. A doctoral project should reserve an independent material orientation, thickness, surface treatment, geometry or load case as a validation set. This is particularly valuable in additive manufacturing, where a process model may be calibrated at 0 and 90 degree orientations and challenged at 45 degrees, or calibrated on coupon fatigue and challenged on a crown component.

Evidence synthesis and cross-domain gaps

The selected 50-paper corpus is used as an engineering evidence map rather than a numerical quality ranking. The variable-mechanism-gap synthesis in Table 4 shows that the literature is sufficiently mature to formulate focused research questions while still leaving major

gaps in protocol standardization, long-term fatigue, coupled degradation and experimental validation.

The 2025 evidence establishes the principal process-to-damage variables. Buser et al. [1] showed that loading protocol can alter the apparent reliability of lithium disilicate and 5Y-TZP; Cantelli et al. [2] linked zirconia surface conditioning to bonded fatigue survival; Packaeser et al. [3] demonstrated sensitivity to core material and occlusal contact; and Pilecco et al. [46] showed that milling protocols can shift CAD/CAM fatigue response. For digital materials, Pinelli et al. [10] reported generally higher flexural strength and Weibull reliability for milled than printed zirconia, while Rizzante et al. [6], Mudhaffer et al. [7] and Alhotan et al. [49] demonstrated the roles of polymerization, orientation and thermal cycling in printed resins. Doumit et al. [8] supplied clinically relevant 24-month wear evidence. At the implant scale, Schettini et al. [36], Vegas-Bustamante et al. [37], Sahin Hazir et al. [16] and Poovarodom et al. [17] collectively connect manufacturing route, tribocorrosion and stiffness-dependent stress redistribution to component durability. These studies support a common interpretation: a reported strength or wear value is meaningful only when its process history, contact state and ageing history are defined.

The 2026 studies sharpen the same engineering direction and expose where validation remains immature. Bakitian [18], Zurlo Dellazzana et al. [4], Prott et al. [5] and Spitznagel et al. [43] show that multilayer architecture, thickness and restoration configuration interact with ceramic fatigue. Ruggiero et al. [11], Sabatini et al. [12], Bergler et al. [13] and Wu et al. [45] reinforce the need to report print orientation, layer/firing history and process-induced microstructure when evaluating additive zirconia. For definitive resins, Flottes et al. [14], Dascanio et al. [15], Terán Lozada et al. [25], Alhotan et al. [24], Korkmaz et al. [9] and Benalcázar-Jalkh et al. [26] collectively show material- and process-dependent property envelopes but limited long-term standardization. Watanabe et al. [33], Stape et al. [44], Troha et al. [32] and Osiewicz et al. [30] extend the problem toward reinforcement architecture, interface fatigue, real-time versus accelerated ageing and two-/three-body wear. Hariprasad et al. [39], Boffano et al. [40] and Padullés-Roig et al. [42] further emphasize coupled electrochemical-mechanical implant degradation and validated FEA. Thus, the strongest cross-domain evidence favors mechanism-specific, state-variable-based testing followed by component-level validation rather than direct comparison of isolated property values.

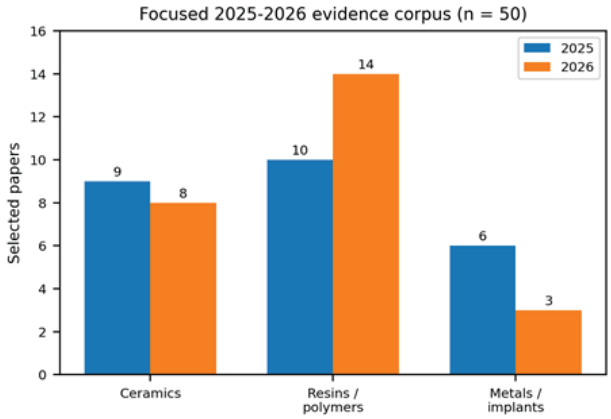


Fig. 4. Distribution of the focused 50-paper evidence corpus: 25 papers from 2025 and 25 from 2026

Table 4. Condensed 2025-2026 evidence synthesis and unresolved gaps

Domain	Representative evidence	Unresolved engineering need
Ceramics / zirconia	Protocol, contact, thickness, milling and surface condition change fatigue [1, 2, 3, 46, 5, 43, 4]	Standardized fatigue + defect-sensitive thickness/reliability models
AM zirconia	Printed-vs-milled differences; orientation, layer and firing effects [13, 10, 11, 12, 45]	Process-defect-life mapping using micro-CT/XRD/fractography + fatigue
Printed resins / composites	Orientation, cure and ageing strongly affect response [49, 24, 23, 26, 22, 15, 14, 9, 7, 6, 25]	Long-term fatigue/clinical validation and standardized print-to-test reporting
PEEK / polymer CAD/CAM	Wear and thermal ageing are material/tribosystem dependent [35, 28]	Coupled wear-fatigue and surface/interface design
Metals / implants	Manufacturing, ion release, corrosion and tribocorrosion interact [40, 39, 41, 38, 42, 36, 37]	Synchronized bio-tribocorrosion-fatigue + validated nonlinear contact FEA

The first cross-domain gap is protocol standardization. Fatigue studies differ in specimen geometry, support stiffness, waveform, frequency, load increment, thermocycling, failure definition and run-out. Wear studies differ in antagonist, lubrication, contact force, sliding path, debris and reported metric. Additive-manufacturing studies vary in orientation, post-cure or sintering and surface finishing. These differences are not merely reporting inconveniences; they change the damage mechanism. Dascanio et al. [15] and Flottes et al. [14] make this particularly clear for 3D-printed

resins, while Pinelli et al. [10] and Ruggiero et al. [11] expose the same challenge for printed zirconia.

The second gap is the weak bridge between accelerated laboratory ageing and actual long-term degradation. Thermocycling and water storage are widely used, yet Troha et al. [32] shows that real-time and accelerated ageing can produce different mechanical outcomes. Doumit et al. [8] is valuable because it provides clinical wear data that can calibrate laboratory models, but longer follow-up and matched laboratory conditions are needed. A major research opportunity is to define equivalent-damage metrics instead of converting arbitrary cycle counts into 'years'.

The third gap is coupled degradation. Tribocorrosion studies explicitly couple wear and electrochemistry, but many ceramic/polymer studies still separate fatigue, wear and ageing. In service, a roughened worn surface can raise contact stress; water can accelerate interface fatigue; crack formation can increase debris; and corrosion pits can become fatigue initiators. Future research should deliberately test interaction terms using factorial designs and simultaneous exposure where possible.

The fourth gap is model validation. Dental FEA has progressed beyond simple static comparisons, but predictive life modelling remains limited. Dynamic analyses such as Sahin Hazir et al. [16], hybrid-abutment stress studies such as Poovarodom et al. [17], and fatigue-FEA integration such as Padullés-Roig et al. [42] provide a foundation. The next research generation should report mesh convergence, contact assumptions, material data sources, uncertainty and direct comparison with measured strains/displacements/failure sites.

The fifth gap is translation from material coupon to dental component. Standard flexure or wear specimens are necessary for mechanism identification, but final validation must account for anatomical geometry, cement layer, substrate compliance, connector dimensions and patient-like contact. A two-stage approach-coupon mechanism discovery followed by component validation-is recommended.

RESEARCH ROADMAP AND INTEGRATED METHODOLOGY

A defensible doctoral topic should begin with an engineering failure mode, not with a material brand. The sequence recommended in Fig. 5 starts from an application-level problem (for example premature crown fatigue, printed-resin wear or implant tribocorrosion), selects a material/process system, formulates a mechanistic hypothesis, designs a controlled experiment, characterizes the resulting failure mechanism, builds a physics-based or statistically informed model, validates it and ends with an actionable design/process rule. This sequence prevents the thesis from becoming a catalogue of property tests.

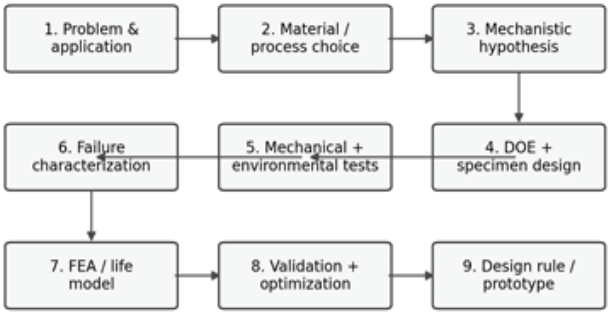


Fig. 5. Proposed translation path from a dental-material failure problem to validated life prediction and an actionable process/design rule

The research scope can be organized into six streams. Stream A-damage-tolerant ceramics-focuses on zirconia/lithium-disilicate thickness, gradient location, surface treatment, AM defects and probabilistic fatigue. Stream B-additively manufactured polymers-focuses on orientation, layer thickness, conversion/post-cure, water/thermal ageing, fatigue and wear. Stream C-composite microstructure-focuses on filler loading, fiber architecture, shrinkage stress, interface ageing and repair. Stream D-PEEK/high-performance polymers-focuses on wear, creep/fatigue, bonding and stress redistribution. Stream E-metallic implants-focuses on fatigue, fretting, corrosion, tribocorrosion and surface/alloy engineering. Stream F-computational durability-focuses on validated dynamic/contact FEA, probabilistic life prediction and multi-objective optimization.

A Mechanical Engineering researcher does not need every possible instrument in one laboratory. A practical program can place UTM/fatigue/tribology/FEA/DOE

in the engineering department, use a dental collaborator for clinically realistic geometry and specimen preparation, and use shared facilities for SEM, XRD, uCT, electrochemistry or spectroscopy. The novelty should come from the integration of measurements into a mechanistic model, not from owning the equipment.

Table 5. Research-gap-to-method roadmap for Mechanical Engineering doctoral work

Research gap	Minimum strong experiment	Model / deliverable
Service-representative fatigue	Constant/step-stress + ageing + fractography	S-N/Weibull/survival life curve
AM anisotropy / defects	Multi-orientation specimens + micro-CT/SEM	Orthotropic/defect-informed FEA + process-life map
Accelerated ageing calibration	Matched real-time and accelerated cohorts	Equivalent-damage kinetics with uncertainty
Wear-fatigue interaction	Sequential and simultaneous wear-fatigue	Contact + remaining-life model
Tribocorrosion-fatigue	Potentiostat-tribology plus cyclic load	Synergy coefficient / coupled damage law
Interface fatigue	Aged cyclic bonded specimens	Cohesive-zone fatigue parameters
Patient-specific validation	Anatomical component test + DIC/strain	Validated nonlinear dynamic FEA
Multi-objective design	DOE across material/process/surface variables	Surrogate/RSM + Pareto process/design window

Recommended thesis architecture and practical scope

A four-work-package thesis architecture can accommodate most topics. WP1 establishes baseline material/process characterization and identifies dominant defects. WP2 performs service-representative fatigue, wear, ageing or tribocorrosion experiments using DOE. WP3 develops the computational/reliability model and calibrates it using WP1-WP2 data. WP4 validates the model on an anatomical or component-level prototype and performs multi-objective optimization. The thesis contribution is then a validated process/design rule rather than a collection of independent experiments.

WP1 - Process and structure: establish material chemistry, processing window, surface state, defect statistics and baseline mechanical properties.

WP2 - Damage and durability: apply fatigue/wear/ageing/tribocorrosion under controlled oral analogues and identify crack/wear/corrosion mechanisms.

WP3 - Model and reliability: develop FEA, cohesive, contact, fatigue, Weibull or degradation model with uncertainty quantification.

WP4 - Validation and optimization: test crown/veneer/abutment/implant prototypes, quantify model error, and derive a Pareto-optimal design/process window.

Practical scope selection

If access is limited to UTM, tribometer, optical microscopy and ANSYS/Abaqus, a strong thesis can still be built around printed/milled polymer wear-fatigue or ceramic thickness/contact mechanics with outsourced SEM. If a fatigue machine and chewing simulator are available, crown/veneer/abutment life becomes feasible. If an electrochemical workstation is available, titanium tribocorrosion is a high-value extension. If uCT or XRD is available through collaboration, additive zirconia process-defect research becomes especially strong. The equipment should follow the hypothesis; it should not determine the hypothesis.

For collaboration, the dental partner should define clinically meaningful geometry, preparation, cementation, antagonist and failure criteria, while the Mechanical Engineering team should own the load spectrum, metrology, mechanics, statistics and modelling. This division preserves clinical relevance without shifting the doctorate away from engineering. A materials/metallurgy partner can support SEM/XRD/uCT and an electrochemistry laboratory can support corrosion/tribocorrosion. The resulting interdisciplinary structure supports clinically relevant specimen design while retaining the thesis emphasis on Mechanical Engineering.

Research-topic selection and translational closure

Topic selection should balance scientific gap, equipment access, specimen complexity and the ability to produce a mechanistic contribution. A researcher with a UTM and access to a dental 3D printer can already investigate orientation/post-cure/ageing effects, but the PhD becomes substantially stronger if the study measures fatigue or residual strength and validates anisotropic FEA. Access to a tribometer opens wear-fatigue projects in PEEK, composites and printed resins; access to an electrochemical workstation enables titanium tribocorrosion; access to uCT enables defect-sensitive additive-zirconia reliability; and access to DIC strengthens validation of patient-specific models. The decision should therefore be made from

the required mechanism backward to the equipment, not from available equipment forward to a convenient but weak question.

The highest-value doctoral questions usually contain one controllable process variable, one service/environment variable and one dominant damage mechanism. Examples are print orientation x ageing -> fatigue of permanent crown resin; milling protocol x surface finish -> ceramic flaw population and fatigue; pH/fluoride x micromotion -> titanium tribocorrosion-fatigue; filler content x ageing -> composite fatigue/wear; or implantoplasty geometry x load spectrum -> implant fatigue. Adding too many materials and too many variables can dilute mechanism resolution. DOE should be used to select a small number of high-information combinations rather than building an unmanageably large material catalogue.

A final criterion is translational closure. The project should end with something an engineer or clinician can use: a minimum thickness curve, allowable process window, fatigue reliability map, post-curing recommendation, surface-treatment Pareto front, equivalent-ageing relation, tribocorrosion damage law, or validated simulation workflow. This deliverable distinguishes doctoral engineering research from comparative material screening.

Ready-to-develop project blueprints

Blueprint A - Additively manufactured permanent crown resin: Hypothesis: print orientation, layer architecture and post-curing create an anisotropic network whose ageing response controls fatigue more strongly than initial flexural strength. Use a compact DOE with orientation and cure as manufacturing factors and water/thermal ageing as the environmental factor. Measure conversion-sensitive properties, modulus, flexure, step-stress or constant-amplitude fatigue, roughness and fracture origin. Fit an orientation-dependent fatigue model and validate it on an anatomical crown. The literature of Mudhaffer et al. [7], Rizzante et al. [6], Alhotan et al. [49], Korkmaz et al. [9], Flottes et al. [14], Dascanio et al. [15] and Benalcázar-Jalkh et al. [26] provides a strong contemporary evidence base.

Blueprint B - Defect-tolerant additive zirconia: Hypothesis: the performance gap between printed and milled zirconia is governed by the orientation, size and location of process-induced flaws rather than by manufacturing route alone. Vary orientation/layer and one firing or sintering parameter; quantify density/porosity and phase/microstructure; measure flexural strength, Weibull reliability and fatigue; locate fracture origins; and develop a defect-informed FEA/probabilistic model. Validate on a thin crown or veneer. Pinelli et al. [10], Ruggiero et al. [11], Sabatini et al. [12], Wu et al. [45] and Bergler et al. [13] directly support this roadmap.

Blueprint C - Minimum-thickness design of minimally invasive ceramics: Hypothesis: a universal minimum thickness is mechanically invalid because contact, support and material-specific crack resistance interact. Compare a tightly selected ceramic pair across clinically meaningful thicknesses and contact configurations; perform thermomechanical fatigue and fractography; calculate intaglio/contact tensile stress; and build a probability-of-failure map. Zurlo Dellazzana et al. [4], Prott et al. [5], Spitznagel et al. [43], Buser et al. [1] and Packaeser et al. [3] provide the foundation.

Blueprint D - Wear-fatigue coupling in PEEK and polymeric CAD/CAM materials: Hypothesis: wear-induced topography and section loss alter subsequent fatigue life, and the effect depends on polymer/filler architecture. Run controlled two-body or chewing-simulator wear under artificial saliva, quantify 3D wear and antagonist loss, then measure residual fatigue life. Model evolving contact geometry and compare predicted stress change with residual life. Li et al. [28], Ateş and Gungormus [35], Osiewicz et al. [30] and Wu et al. [29] motivate this coupled rather than isolated tribology study.

Blueprint E - Resin-dentin interface durability: Hypothesis: long-term adhesive failure is controlled by ageing-induced degradation of interface fracture resistance, not merely initial bond strength. Select a small number of adhesive strategies, conduct real-time/accelerated ageing, cyclic interface tests and failure-mode analysis, and identify cohesive-zone traction-separation/fatigue parameters. Validate the model on a bonded restoration geometry. Stape et al. [44], Larrañaga-Ordaz et al. [50], Chen et al. [48] and Tsujimoto et al. [31] frame the need.

Blueprint F - Titanium bio-tribocorrosion-fatigue: Hypothesis: mechanically assisted passive-film disruption produces a synergistic surface-damage state that reduces residual fatigue life beyond independent corrosion or wear. Use artificial saliva with controlled pH/fluoride, synchronized reciprocating micromotion and electrochemical measurement, quantify synergy, then fatigue pre-damaged specimens or implant components. Correlate pits/scars with crack origins. Vegas-Bustamante et al. [37], Mangal et al. [38], Herbster et al. [41], Hariprasad et al. [39] and Boffano et al. [40] establish the contemporary problem.

Blueprint G - Surface-engineered zirconia with multi-objective durability: Hypothesis: surface treatments that improve bonding or functional coating behavior can simultaneously alter flaw severity and antagonist wear. Compare one baseline and a limited number of surface/coating routes; measure roughness, surface damage, bond-fatigue, crown fatigue and antagonist wear; use Pareto optimization rather than selecting the treatment with the highest single property. Cantelli et al. [2] and da Silva et al. [19] provide direct fatigue/wear motivation.

Blueprint H - Experimentally validated patient-specific implant mechanics: Hypothesis: material stiffness and component geometry interact with preload/contact to redistribute stress and micromotion, and validated dynamic models can identify lower-risk configurations. Build CT/CAD-based geometry, characterize component materials, include contact and preload, perform DIC/strain-gauge or displacement validation, then add fatigue/reliability and uncertainty. Sahin Hazir et al. [16], Poovarodom et al. [17] and Padullés-Roig et al. [42] provide a natural progression from explanatory FEA toward predictive mechanics.

Four-year execution and publication logic

Year 1 should close the literature-to-method gap: finalize the research question, select one primary material system, conduct pilot characterization, establish specimen manufacturing repeatability and complete measurement-system validation. The first publication can be the present critical review or a more focused systematic review. The decision gate at the end of Year 1 is whether the selected process variables produce a measurable and mechanistically interpretable change rather than merely statistical noise.

Year 2 should generate the core experimental mechanics dataset. A DOE should vary only the factors justified by pilot data and the review. Fatigue, wear, ageing or tribocorrosion should be accompanied by surface/microstructural diagnostics and appropriate reliability statistics. The second publication should report a process-structure-damage relationship, not just property ranking. A third publication can focus on coupled degradation or mechanism-specific failure analysis if sufficient depth exists.

Year 3 should translate the experimental data into a computational or reliability model. Material inputs should be measured where possible; contact and boundary conditions should be verified; uncertainty should be propagated; and an independent validation condition should be reserved. The publication target is a validated mechanics/life-prediction paper. At this stage, the project should be able to predict an outcome that was not used during model fitting.

Year 4 should perform component-level validation and optimization. The model can be used to reduce the experimental design space, identify promising material-process-geometry combinations and define a process/design window. Final experiments should challenge the predicted optimum and at least one non-optimal control. The resulting contribution can be expressed as an engineering decision chart, reliability curve, Pareto front, validated digital workflow or component design guideline. This structure gives the thesis a coherent narrative from evidence to mechanism to prediction to design.

CONCLUSIONS

The current 2025-2026 literature shows that dental-material durability is controlled less by a single nominal property than by interactions among manufacturing, microstructure, geometry, surface condition, cyclic load and oral environment. Zirconia and glass-ceramics remain strongly flaw- and thickness-sensitive; additively manufactured zirconia introduces orientation, layer and firing variables that require reliability-based characterization. Printed resin systems are advancing rapidly but remain sensitive to orientation, post-curing and ageing, with long-term fatigue and clinical evidence still less mature than for established milled materials. Direct composites continue to reveal the importance of

matrix-filler-interface design, polymerization stress and ageing. PEEK and related polymers offer distinctive stress-transfer and wear behavior, while titanium/Co-Cr systems shift the durability problem toward fatigue, fretting, corrosion and tribocorrosion.

Five priorities should define the next Mechanical Engineering research phase: (1) service-representative and reproducible fatigue/wear protocols; (2) defect-informed process-structure-life models for additive manufacturing; (3) simultaneous or calibrated ageing rather than arbitrary cycle-to-year conversions; (4) experimentally validated dynamic/contact and probabilistic FEA; and (5) multi-objective optimization that balances strength, fatigue, wear, antagonist response, corrosion, manufacturability and clinical geometry. The most publishable and defensible PhD work will close the loop from controllable process variables to failure mechanism and validated design guidance.

The research roadmap proposed here provides that loop. A researcher can select a material family, identify a process or environmental variable, choose a dominant failure mechanism, design a mechanistic experiment, quantify reliability, build and validate a computational model, and finish with a process/design window. In this way dental materials become not an adjacent biomedical topic but a rigorous Mechanical Engineering research domain integrating materials science, solid mechanics, fracture/fatigue, tribology, manufacturing, surface engineering and computational design.

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