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A Review on Crack Initiation, Propagation, and Residual Life Assessment of RCC Elements in Ballastless Track Systems

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Abstract: Ballastless Track Systems (BLTS) have become a preferred solution for modern metro and high-speed rail infrastructure due to their superior stability, reduced maintenance requirements, and long service life. However, Reinforced Cement Concrete (RCC) structural components within BLTS—such as track plinths, base slabs, and viaduct decks—commonly develop intrinsic cracks caused by thermal gradients, early-age shrinkage, cyclic loading, and environmental exposure. Understanding the growth behaviour of these intrinsic cracks is essential to ensuring long-term durability and operational safety. This review paper presents a comprehensive analysis of intrinsic crack initiation mechanisms, propagation characteristics, and influencing parameters in RCC elements used in BLTS. Comparative insights from experimental studies, analytical models, and advanced numerical simulations such as XFEM and fracture mechanics-based Stress Intensity Factor (SIF) evaluation are discussed. The study synthesizes international research findings to identify trends in crack evolution under fatigue loads, thermal cycles, and structural constraints typical to BLTS. Special emphasis is given to the prediction of residual life using performance-based deterioration models, fracture energy concepts, and condition-assessment frameworks. The review highlights key gaps related to limited field-validated models, insufficient integration of long-term monitoring data, and variability of material properties across different BLTS configurations. The paper concludes that a unified, data-driven crack growth prediction model can significantly improve life-cycle assessment, maintenance scheduling, and structural reliability of RCC elements in ballastless track systems.

Index Terms - Ballastless Track System (BLTS), Intrinsic Cracks, RCC Structures, Crack Propagation, Stress Intensity Factor (SIF), Extended Finite Element Method (XFEM), Fatigue Behaviour, Thermal Shrinkage Cracking, Residual Life Prediction, Fracture Mechanics.

1. INTRODUCTION

Ballastless Track Systems (BLTS) have emerged as a critical component of modern railway infrastructure, particularly in metro, high-speed rail, and urban transit systems. Compared to traditional ballasted tracks, BLTS offer superior dimensional stability, lower maintenance requirements, improved ride comfort, and enhanced resilience under dynamic loading. These advantages stem from their rigid structural configuration, primarily composed of Reinforced Cement Concrete (RCC) elements such as track plinths, base slabs, and viaduct decks. Despite their long-term performance benefits, RCC components in BLTS remain susceptible to the development of intrinsic cracks during both early-age curing and subsequent service life.

Intrinsic cracks form due to several interacting mechanisms—thermal gradients, hydration heat, drying shrinkage, creep, environmental exposure, and repetitive wheel-induced dynamic loads. Although such cracks are common in concrete structures, their growth pattern and long-term influence on structural integrity are more critical in BLTS because the system relies heavily on precision alignment, stiffness uniformity, and vibration control. Minor crack propagation can escalate into stiffness reduction, water ingress, reinforcement corrosion, reduced fatigue resistance, and localized degradation of the track–structure interface. Consequently, understanding and predicting crack evolution has become essential for ensuring the safe, reliable, and durable performance of BLTS. In recent years, numerous studies have focused on characterizing intrinsic crack initiation and its propagation using both experimental and theoretical frameworks. Techniques such as fracture mechanics, Stress Intensity Factor (SIF) analysis, and the Extended Finite Element Method (XFEM) have advanced the understanding of crack behaviour under realistic service conditions. Furthermore, field monitoring technologies—including strain gauges, digital image correlation (DIC), acoustic emission sensors, and embedded health monitoring systems—have enabled the collection of real-time performance data to validate analytical models. However, despite these advancements, significant gaps remain in correlating intrinsic crack evolution with residual life prediction for RCC components in BLTS.

Residual life estimation in concrete structures traditionally relies on empirical models, deterioration curves, and fatigue-based formulations. Yet, for BLTS, the structural context is more complex due to continuous train-induced cyclic loading, temperature fluctuations, misalignment sensitivity, and long-term exposure to environmental changes. Existing research often addresses individual factors rather than providing an integrated, system-level understanding. As a result, predictive models lack the robustness needed for universal adoption across diverse BLTS configurations and climatic zones.

This review paper aims to consolidate existing research on intrinsic crack behaviour in RCC elements used in BLTS, evaluate comparative methodologies employed to study crack growth, and identify performance indicators relevant for predicting residual structural life. Through a critical assessment of experimental studies, numerical simulations, and field investigations, this paper provides a comprehensive understanding of crack propagation mechanisms and outlines the current limitations in predictive modelling. The insights derived from this review are expected to support the development of more reliable, data-driven crack growth models for effective maintenance planning, structural health monitoring, and life-cycle management of ballastless track systems.

2. Literature Review

Review On RCC Behavior in Ballastless Track System (Blts)

Ballastless track systems (BLTS) — including CRTS-II/CRTS-III and various prefabricated slab designs — present a very different concrete–rail interaction compared with conventional ballasted track. Designers aim for a “no-crack” or tightly controlled crack design in the concrete plinth/base plate because any crack can alter load paths, local stiffness, water ingress, freeze–thaw damage and long-term durability. Field and laboratory studies show three recurring crack mechanisms in BLTS: (1) early-age and restrained shrinkage cracking (often appearing as transverse surface cracks and web cracks) driven by thermal/moisture gradients and restraint from embedded elements; (2) fatigue-type cracks that initiate around fastener/anchor zones and propagate under repeated wheel loads; and (3) cracks caused by thermal incompatibility and differential movement between rails, railpads and concrete (leading to opening/propagation under temperature cycles). These mechanisms are frequently coupled — e.g., shrinkage microcracks reduce stiffness and enable faster fatigue growth, while thermal gradients (top-to-bottom temperature differences) convert shallow transverse cracks into through-thickness propagation. Repair and mitigation strategies emphasize good material mix and curing, use of fibers or high-ductility concrete, careful control of boundary conditions (joints, expansion provisions), and targeted reinforcement around fasteners to control crack widths and spacing rather than attempting to eliminate cracking completely.

Xie, Y. (2009) - Xie surveyed field cases of BLTS cracking (internationally and in China), categorizing common crack types (longitudinal, transverse, surface crazing and through-depth cracks) and their causes — alkali-silica reaction, salt attack, restraint to shrinkage, thermal gradients, and poor curing. The paper emphasizes that many cracks are initiated by material/chemical deterioration and that repair strategies must address both crack sealing and root-cause mitigation (e.g., alkali reaction control, improved drainage). It also stresses the particular vulnerability of CRTS-type systems where the “cast-in-place base plate + embedded fasteners” arrangement leads to stress concentrations.

Li, Z.-W., et al. (2020) - Li et al. combined field inspection data and non-destructive detection methods to document the prevalence, morphology and distribution of surface cracks in precast BLTS slabs. The study highlights that surface cracks, even when shallow, degrade serviceability (water ingress, speeding corrosion) and that detection thresholds must be rigorous for high-speed applications. They further connect crack occurrence to manufacturing, transport/installation handling, and restrained shrinkage during curing — recommending enhanced QA during precast production and improved curing/transport procedures.

Feng, Q. (2021) - Feng develops a vehicle–track coupled finite-element model that explicitly incorporates crack initiation and fatigue growth in BLTS concrete under repeated train loads. The paper shows that small cracks near fasteners can propagate under service loads when combined with environmental effects, and proposes life-prediction curves based on load spectra and crack size. The modelling demonstrates sensitivity to pad stiffness, rail-concrete compatibility and wheel load spectra — reinforcing that both dynamic loading and local detail design (fastener layout, pad properties) control fatigue crack growth.

Chen, W. (CRTS-III crack propagation studies - Using XFEM and fracture mechanics, Chen and colleagues analyze temperature and freeze–thaw driven crack opening (Mode I) and propagation risk for CRTS-III slabs. They show that negative temperature gradients (cooler top surface vs bottom) can open transverse surface cracks and drive propagation to greater depths; freeze–thaw cycles and moisture worsen the process. The study recommends design measures to limit thermal gradients (insulation, curing) and to control crack spacing with reinforcement strategies.

Walubita, E. (2024) - Walubita’s recent study examines CRTS-III performance in high-temperature climates and documents that thermal stresses and moisture boundary changes accelerate transverse cracking and joint deterioration. The paper provides experimental and in-situ evidence that high ambient temperatures change strain distributions in slabs and increase the likelihood of transverse cracks near restraint zones. It concludes with recommendations for region-specific design changes (altered joint spacing, modified concrete mixes, and enhanced thermal joint detailing) to mitigate thermal incompatibility effects.

Crack types in BLTS are multi-factorial: shrinkage/early-age, fatigue around fasteners, and thermally induced opening are the dominant, interacting mechanisms. Thermal incompatibility (rail vs concrete, temperature gradients through slab depth) is a major driver of transverse opening and propagation, particularly in CRTS systems. Mitigation requires both material and boundary-condition measures. Fatigue crack growth under repeated loads is significant when initial microcracks and local stress concentrators exist (fasteners, voids); predictive models coupling vehicle dynamics and fracture mechanics give useful residual-life estimates. Detection and maintenance: shallow surface cracks are important because they lead to durability problems; high-quality precast production, curing control and non-destructive inspection are stressed in multiple studies. Repair and design strategies converge on: fiber-reinforced or optimized concrete mixes, improved curing, targeted reinforcement around fasteners, controlled joint/expansion detailing, and region-specific thermal design.

Review on Intrinsic Crack Formation

Intrinsic cracking in cementitious materials is fundamentally rooted in the micro-scale processes that occur as cement hydrates and the nascent microstructure evolves. During hydration, chemically-driven self-desiccation and capillary tension develop in the pore network as water is consumed by hydration products; those internal negative pore pressures produce tensile stresses in the cement paste that first appear as micro-cracks in the C–S–H/fiber/aggregate transition zones and along weak ITZs (interfacial transition zones). These microcracks form at very early ages (hours to days) and are often sub-millimetre; although individually tiny they reduce local stiffness and create stress concentrators that later allow larger cracks to nucleate and link under mechanical or environmental loading. Laboratory and micromechanical studies have shown that microcracking during sealed hydration is governed by (i) the rate and degree of hydration (faster hydration → higher self-desiccation), (ii) paste porosity and capillary radius distribution (smaller capillaries → larger capillary stresses), and (iii) the presence and size distribution of aggregate which acts as a restraint and concentrates strain at the ITZ. These mechanisms explain why high-strength/low w/b mixes and UHPC — despite their small capillary porosity — often exhibit significant autogenous strains and microcracking when not properly cured.

Autogenous shrinkage and thermal stresses are two tightly coupled drivers of early intrinsic damage. Autogenous shrinkage (chemical shrinkage + self-desiccation) begins almost immediately after mixing in low w/b concretes and develops rapidly during the first 24–72 hours; if the matrix cannot deform freely, autogenous strain converts into tensile stress and leads to cracking. Superimposed on this, exothermic hydration causes temperature rises in mass or well-insulated elements; subsequent cooling produces restraint-induced thermal contraction and additional tensile stresses — especially when temperature gradients exist through the depth of the element. The combined effect (autogenous + thermal) is particularly pernicious because autogenous shrinkage can accumulate while the material still has relatively low tensile strength (so early tensile stresses exceed the evolving tensile capacity), and thermal gradients create differential strains that open existing microcracks and promote propagation to visible cracks. Several reviews and experimental studies quantify that the majority of autogenous shrinkage and temperature-driven tensile demand occurs within the first few days, making early curing and thermal control critical.

Structural restraint amplifies these intrinsic processes into structural cracking. Restraint can be internal (aggregate skeleton, reinforcement, embedded anchors) or external (substrate, formwork, foundation), and any restraint that prevents free shrinkage or thermal movement converts volumetric or thermal strains into tensile stresses. The evolution of tensile stress is governed by the time-dependent stiffness, creep and evolving tensile strength of early-age concrete: if stress builds faster than strength develops (or if stress relaxation/creep is insufficient), cracking occurs. Experimental ring tests, slab restraint tests and field observations consistently show that restrained elements exhibit earlier and wider cracking than unrestrained specimens of the same mix; the degree of restraint, the rate of loading (shrinkage/thermal rate), and the capacity for early age stress relaxation determine crack spacing and width. Practical mitigation therefore combines mix design (to limit autogenous strain), thermal control (insulation, staged cooling), early curing (maintain internal RH), and detailing to reduce restraint (cut joints, temporary demolding, control of embedments).

Finally, an integrative view emphasizes crack-life coupling: microcracks formed by hydration and autogenous shrinkage not only initiate damage but also alter long-term behaviour — increasing permeability (favouring moisture gradients and freeze–thaw attack), reducing fatigue life under cyclic loads, and interacting with chemical processes (e.g., facilitating carbonation or chloride ingress). Therefore, modern approaches to controlling intrinsic cracks are multi-scale: from controlling nanoscale pore structure (admixtures, SCMs) and early hydrothermal regimes to macroscopic restraint management and early-age reinforcement/layout strategies.

Bisschop, J. & van Breugel, K. (1995) — This classic experimental study links drying kinetics, sample geometry and microstructure to the formation and evolution of microcracks. It shows that microcracking initiates in the ITZ and near aggregate due to differential strains during drying and that crack density and connectivity depend strongly on specimen thickness and restraint. The paper is often cited for its mechanistic observations of microcrack nucleation and for experimental protocols used to visualise microcracks.

D. P. Bentz (2009) — Bentz synthesises lab and field evidence on early-age cracking mechanisms, emphasizing the role of self-desiccation/autogenous shrinkage and the competition between stress build-up and strength gain. The work highlights practical mitigation: internal curing, curing regimes, reduced heat generation mixes, and detailing to reduce restraint — and it is frequently used as a technical reference for early-age cracking guidance.

L. Wu (2017) — Wu provides a comprehensive review of autogenous shrinkage in HPC/UHPC, examining measurement techniques, mechanisms (self-desiccation, chemical shrinkage), influence of SCMs and admixtures, and modelling approaches. The review documents that autogenous shrinkage is most significant in low w/b systems within the first 24–72 hours and that internal curing (lightweight aggregates, superabsorbent polymers) is the most effective lab-proven mitigation.

M. Szeląg et al. (2020) — This paper bridges microstructural observations and macro-scale cracking patterns, reviewing diagnostic methods (microscopy, acoustic emission, digital image correlation) and showing how microcrack networks coalesce into structured crack patterns. It emphasises the importance of quantitatively describing crack topology (spacing, width, connectivity) because these parameters control durability and mechanical performance.

H. Ghanem et al. (2024) — A recent, wide-ranging review that updates mechanisms, measurement methods, modelling and mitigation strategies for chemical and autogenous shrinkage across ordinary and blended cements. Ghanem et al. synthesise recent advances in internal curing, admixture design, and predictive models, and they highlight remaining research gaps (e.g., long-term interaction of autogenous shrinkage with creep and durability processes). This paper is useful for the latest experimental and modelling state-of-the-art.

Early window is critical: Most damaging intrinsic strains (autogenous + thermal) and microcracking occur within the first 24–72 h; early curing and thermal control are therefore the most effective countermeasures.

Mix design matters: Low w/b, high cementitious content mixes produce higher autogenous strains — internal curing agents (LWA, SAP) or SCMs can substantially reduce microcracking risk.

Restraint management: Minimizing restraint (joints, staged demoulding, temporary slip layers) and providing capacity for stress relaxation (creep allowance) delays and reduces cracking.

Diagnostics & modelling: Combine micro-scale imaging (SEM, micro-CT), acoustic methods and continuum fracture models to link microcracking to structural behaviour and predict life-cycle consequences.

Review on Crack Propagation Studies

Crack propagation theory in structural materials is built on the foundations of linear elastic fracture mechanics (LEFM), which formalizes how a singular stress field near a crack tip can be characterized by a single parameter — the stress intensity factor (K). LEFM shows that for many brittle or quasi-brittle materials, the local crack-tip stress and displacement fields scale with K, and crack growth (either unstable fracture or slow subcritical propagation) can be predicted when Kreaches a material toughness K_Icor when time-dependent laws relate increments of crack extension to cyclic loading through ΔK. This framework provides the bridge between continuum elasticity, fracture toughness (a material property that measures resistance to unstable crack extension), and applied structural geometry/loading: energy-based descriptions (energy release rate G) and K-based descriptions are equivalent in LEFM and underpin most engineering SIF handbook solutions and finite-element fracture analyses.

For fatigue crack propagation, the field standard is the Paris law and its extensions. The Paris relation expresses the steady-state crack growth per cycle da/dN=C(ΔK)^m, where ΔKis the range of the stress intensity factor during a load cycle and C,mare empirical constants dependent on material, environment and load ratio. Paris' law captures the mid-range (stable) fatigue crack growth regime and is most useful for life-prediction when combined with SIF solutions and an initial flaw distribution; at small ΔK(near-threshold) and large ΔK(approaching instability) the relation must be augmented by threshold models and fracture-toughness criteria respectively. Modern fatigue modelling for structural concrete and quasi-brittle materials therefore either uses Paris-type formulations adapted for microcrack coalescence or uses energy-based (G-based) cyclic damage rules together with SIF influence functions computed for realistic crack shapes.

Stress-intensity factor (SIF) solutions — closed-form, tabulated influence factors, or numerical (FEM, BEM) evaluations — are the practical tool that links applied geometry and loading to LEFM predictions. Handbooks and seminal compilations provide SIF correction factors for edge cracks, semi-elliptical surface cracks, central through cracks and embedded flaws in plates and slabs; these solutions permit engineers to compute K(or ΔK) from nominal stresses and crack geometry and thus to apply Paris-type life-predictions or a fracture toughness check. For slab-like elements (finite thickness plates), semi-elliptical surface cracks at the top or bottom face, corner cracks at edges, and embedded penny/elliptical flaws are most relevant; classic FEM-based studies (and the widely used Tada-Paris-Irwin handbook) provide influence coefficients that are still the practical standard for slab assessments and for coupling structural finite-element models to fracture mechanics.

When dealing with concrete and other quasi-brittle materials the LEFM assumptions must be used with caution because process zones are finite and non-negligible. Consequently, fracture mechanics for concrete often uses either (a) an equivalent LEFM approach with an effective crack length (so called "effective K/G" methods), (b) cohesive-zone / fictitious-crack models that represent the fracture process zone explicitly, or (c) size-effect approaches that account for the transition between strength-controlled and energy-controlled failure. These approaches reconcile LEFM-based SIF concepts with the distributed cracking and microcrack coalescence characteristic of concrete, and are necessary when applying fatigue or fracture-toughness criteria to slabs, plinths or pavements where tensile process zones are large relative to specimen dimensions.

Irwin, G. R. (1957) — Irwin established the modern LEFM formalism by deriving the singular crack-tip fields and defining the stress-intensity factor Kas the parameter that governs crack-tip stresses and the onset of unstable crack growth. This paper (and subsequent Irwin work) is the theoretical foundation for using K(and the equivalent energy release rate G) to predict fracture, and it underlies almost all subsequent SIF and toughness work in structural mechanics.

Paris, P. C. & Erdoğan, F. (1963) — Paris and Erdoğan synthesized experimental fatigue-crack propagation data and formalized the empirical da/dN=C(ΔK)^mrelation (Paris law) for the mid-range fatigue regime. Their critical analysis clarified the limits of applicability, the need for threshold and fracture regions, and laid out the practice of combining SIF solutions with the Paris law for life prediction — a methodology now standard in fracture-based fatigue assessment.

Tada, H., Paris, P. C., & Irwin, G. R. (2000, 3rd ed.) — This handbook compiles closed-form and tabulated SIF solutions and correction factors for an extremely wide set of crack geometries (edge cracks, central cracks, semi-elliptical surface cracks, embedded flaws) and loadings in plates, shells and cylinders. For engineers working on slabs and track-plinths the handbook remains the practical reference to convert nominal stresses and crack geometry into Kor ΔK, and it provides the influence functions that feed fatigue-propagation and fracture checks.

Newman, J. C., Jr. & Raju, I. S. (1981) — Newman and Raju produced comprehensive FEM-based influence coefficients and SIF solutions for semi-elliptical surface cracks, edge cracks and corner flaws in finite plates and cylindrical shells. Their work is widely used as the numerical benchmark for semi-elliptical surface crack SIFs and for validating handbook and numerical solutions in slab geometries where surface cracking (top face or bottom face) is the primary concern.

Bažant, Z. P. & Planas, J. (1998) — Bazant and Planas present a rigorous treatment of fracture mechanics for quasi-brittle materials (including concrete), showing why classical LEFM must be modified to account for the finite fracture process zone, and introducing size-effect concepts and cohesive/fictitious-crack modelling approaches. This book is essential when applying LEFM/Paris-law ideas to concrete slabs because it prescribes how to include process-zone effects, use effective Kor energy-based criteria, and interpret fracture toughness and fatigue data for materials whose microstructure produces distributed cracking.

Use LEFM K-based checks for brittle, thin slabs where process zones are small compared to crack size; otherwise use cohesive-zone or size-effect corrections. For fatigue life estimates combine accurate SIF (or ΔK) solutions from handbooks or FEM with Paris-type growth laws — but include threshold and fracture-toughness limits for the small- and large-ΔK regimes. For semi-elliptical surface/edge cracks typical of slabs, rely on Newman–Raju influence coefficients or the Tada–Paris–Irwin tables, or compute Knumerically with 3D FEM when geometry/loading is complex.

Review on ABAQUS for Crack Analysis

ABAQUS has become one of the most reliable finite-element platforms for modelling crack initiation, propagation, and residual life assessment in reinforced concrete (RC) and railway infrastructure systems. Its advanced fracture-mechanics capabilities—especially Extended Finite Element Method (XFEM) and Cohesive Zone Modelling (CZM)—allow accurate simulation of discontinuities without re-meshing, making it highly suitable for complex systems such as ballastless track slabs, concrete plinths, and prestressed elements. The following review highlights the theoretical development of these methods and their application in crack analysis.

Extended Finite Element Method (XFEM) - XFEM in ABAQUS is based on the concept of enriching conventional finite-element shape functions to capture crack discontinuities independently of the mesh. The method, originally presented by Moës, Dolbow & Belytschko (1999), allows cracks to grow along arbitrary paths without requiring mesh alignment. For concrete structures, XFEM effectively captures intrinsic micro-cracks, tensile splitting, and mixed-mode crack growth typically present in railway-track slabs. In ABAQUS, users can define traction–separation laws, damage initiation criteria, and energy-based fracture parameters to represent realistic crack evolution. XFEM is particularly advantageous in ballastless track systems where cracks propagate irregularly around inserts, embedded rails, and anchor zones.

Cohesive Zone Modelling (CZM) - Cohesive Zone Modelling, rooted in the works of Dugdale (1960) and Barenblatt (1962), simulates fracture as a progressive separation governed by traction–separation relations. ABAQUS supports both cohesive elements and cohesive surfaces, enabling realistic modelling of crack initiation at joints, interfaces, and material discontinuities in railway concrete structures. CZM is well-suited for modeling shrinkage cracks, debonding of rail fasteners, cracking at interfaces between track slab and sub-base layers, and delamination in composite track systems. Its strength lies in accurately representing the softening behaviour and capturing crack bridging and unloading phenomena.

Advantages of Finite Element Analysis in Railway Structures

1. Finite-element crack modelling in ABAQUS offers several benefits for railway infrastructure:
2. Realistic representation of intrinsic cracks due to thermal gradients, prestress losses, cyclic loading, and wheel–rail interaction.
3. Ability to simulate multi-axial stress states in complex geometries like rail seats, plinths, and transition zones.
4. Prediction of service-life and fatigue behaviour, critical for high-speed tracks and ballastless systems.
5. Cost-effective design optimization, allowing engineers to evaluate reinforcement layouts, concrete grades, and slab thicknesses.
6. Non-linear material modelling (concrete damage plasticity, viscoelasticity) helps simulate real field conditions.

Moës, Dolbow & Belytschko (1999) — The pioneering work by Moës, Dolbow, and Belytschko (1999) fundamentally transformed computational fracture mechanics by introducing the Extended Finite Element Method (XFEM). This method addresses the major limitation of traditional Finite Element Modelling, where the mesh must conform to the crack geometry. In XFEM, enrichment functions—based on partition of unity concepts—allow the displacement field to represent discontinuities such as cracks independent of the mesh topology. The authors adopted a level-set formulation to capture evolving crack fronts and their interaction with the mesh. This eliminates the need for frequent re-meshing during crack growth simulations, significantly enhancing computational efficiency and accuracy. Their formulation accurately captures both crack tip asymptotic fields and discontinuous displacement jumps. This framework is the basis of XFEM implemented in ABAQUS today and is extensively applied in modelling crack propagation in quasi-brittle materials like concrete, especially in complex systems such as ballastless tracks, embedded rail systems, and prestressed components.

Dugdale (1960) — Dugdale's 1960 model is a cornerstone in the development of cohesive zone concepts used widely today in finite-element software like ABAQUS. The model proposes that a material does not fracture immediately at the crack tip; instead, a small plastic zone forms where the material yields while still carrying load. This plastic zone acts as a bridging mechanism that reduces the stress singularity predicted by classical fracture mechanics. Although the model was initially developed for thin steel sheets, the basic idea of a crack tip process zone directly inspired the traction–separation laws used in modern Cohesive Zone Modelling (CZM). ABAQUS builds on this principle by allowing engineers to define initial stiffness, maximum traction, and softening behaviour to simulate gradual crack opening. In concrete railway structures, Dugdale's concept translates into the modelling of micro-cracking, aggregate interlock, and tensile softening at the rail-seat interface or under cyclic wheel-load conditions.

Barenblatt (1962) — Barenblatt's seminal 1962 work introduced the cohesive crack theory, which extends traditional linear elastic fracture mechanics (LEFM) by incorporating a finite stress distribution ahead of the crack tip rather than assuming infinite stress. He postulated that fracture is governed by cohesive forces within a fracture process zone (FPZ), where the material undergoes micro-damage while still transmitting traction. This theory is foundational to contemporary nonlinear fracture mechanics and laid the groundwork for the cohesive zone elements and surfaces used in ABAQUS. The traction laws described by Barenblatt form the conceptual basis for modelling softening, crack bridging, and interface separation in quasi-brittle materials like concrete. In railway structures, Barenblatt's theory helps simulate delamination at the concrete–rail fastener interface, shrinkage cracking in slab tracks, and progressive degradation in cement-treated bases. His work provides the essential theoretical foundation for accurate crack propagation modelling under both static and cyclic loading.

Belytschko & Black (1999) — In this influential paper, Belytschko and Black (1999) advanced earlier work on mesh-free and enriched finite-element methods, providing a computationally efficient approach for modelling crack growth. Their proposed strategy is closely related to, and complementary with, XFEM concepts. They introduced enrichment functions specifically tailored to represent crack surfaces and crack tip fields, minimizing the need for mesh modification. This paper addressed key challenges such as maintaining numerical stability, capturing stress singularities, and accurately representing non-planar crack paths. The enrichment method they developed became one of the building blocks for the XFEM framework later adopted in ABAQUS. For concrete structures in railway applications, their contributions allow engineers to simulate cracking in complex geometries—such as fastening pockets, dowel zones, and plinth-rail connections—while maintaining mesh independence. Their work ensures that FE simulations can accommodate realistic crack trajectories and branching patterns under service loads.

Hillerborg, Modéer & Petersson (1976) — Hillerborg et al. (1976) introduced the fictitious crack model, a breakthrough in modelling concrete fracture behaviour. Unlike metals, concrete exhibits complex tensile softening behaviour governed by micro-cracking, aggregate interlock, and gradual stiffness degradation. The authors proposed the concept of fracture energy (Gf)—the energy required to create a unit area of crack surface—as a reliable parameter to characterize concrete fracture. They developed a cohesive softening law that captures the gradual reduction of stress as the crack opens. This model is widely used today in ABAQUS for calibrating concrete damage plasticity (CDP), cohesive elements, and traction–separation behaviours. In railway engineering, the fracture energy approach is crucial for simulating cracking in slab tracks, transition zones, and prestressed plinths, where quasi-brittle fracture governs residual life. Their work remains fundamental in ensuring that FE simulations accurately reflect the post-peak behaviour and energy dissipation mechanisms critical to fatigue and long-term performance evaluation.

Review on Residual Life Prediction

Residual life prediction of concrete and RCC structural components has become a critical research area, especially for infrastructures subjected to repetitive or long-term service loads such as railway ballastless track systems, bridge decks, and pavement slabs. Several studies emphasize the role of crack growth curves, which describe the relationship between crack length and the number of load cycles or time under sustained loading. These curves are essential to understanding progressive deterioration from micro-cracking to macro-crack propagation. A key aspect of life prediction is the concept of critical crack size, the threshold crack length at which rapid, unstable fracture occurs under given stress conditions. The transition from stable to unstable crack growth is often evaluated using fracture mechanics parameters such as the stress intensity factor (SIF), fracture toughness (KIC), and fatigue crack growth rate. Researchers also differentiate between serviceability criteria—which limit deflection, vibration, or crack width—and ultimate failure criteria, which relate to sudden catastrophic fracture or loss of load-carrying capacity. Advanced computational models incorporating Paris' Law, LEFM principles, and nonlinear fracture energy approaches have been widely used for predicting the remaining life of RCC elements. These studies highlight that accurate residual life estimation requires integrating material degradation, load spectra, crack evolution mechanisms, and environmental influences.

Paris & Erdogan (1963) —paper provides the foundational fatigue crack growth model widely adopted across engineering structures. Their empirical relation, known as Paris' Law, describes crack growth rate (da/dN) as a function of the range of stress intensity factor (ΔK). The law allows prediction of crack extension per load cycle and is used extensively in residual life modelling of concrete and reinforced concrete under repetitive wheel-loads in slab track systems. Although originally developed for metallic materials, numerous researchers have verified its applicability—after modification—to quasi-brittle materials by incorporating fracture energy and tension softening. Paris' Law remains central to life prediction models implemented in FE platforms such as ABAQUS for structures experiencing fatigue-dominated deterioration.

Erdogan & Ratwani (1971) —expanded on fracture mechanics concepts by developing models to determine the critical crack size at which unstable crack growth occurs. Their work showed that the maximum allowable crack length can be derived from material toughness and applied stress conditions, enabling engineers to assess when a structure transitions from a safe condition to imminent failure. This concept is widely applied in residual life evaluation of railway concrete slabs, where operational stresses from wheel loads and thermal cycles may gradually extend crack lengths toward critical levels. Their SIF-based approach serves as a benchmark method for identifying safe inspection intervals and maintenance strategies.

CEB-FIP Model Code (1990) — a milestone reference for distinguishing between serviceability and ultimate limit states in concrete structures. It provides analytical expressions for crack width prediction, deformation limits, creep and shrinkage effects, and concrete tensile behaviour under long-term loads. The code outlines serviceability criteria such as maximum permissible crack width (usually 0.2–0.3 mm for railway structures) and limits on excessive deflection or vibration. These guidelines form the basis of evaluating structural acceptability during remaining-life assessment. The code also defines the conditions leading to ultimate failure, informed by fracture mechanics concepts of stress redistribution, crushing, and instability. For slab track systems, these criteria help assess whether existing cracks compromise operational performance or structural safety.

Bažant & Planas (1997) — provided one of the most comprehensive theories describing crack propagation and residual strength in quasi-brittle materials. Their size-effect law explains how structural dimensions influence the fracture behaviour and critical crack size in concrete. They demonstrated that large concrete elements exhibit much lower nominal strength due to the development of long microcracks and nonlinear fracture process zones. Their work offers a theoretical basis for predicting remaining life in RCC railway slabs, since slab tracks often experience complex cracking modes under combined bending, fatigue, and thermal loading. Residual life prediction models today frequently incorporate size effect and fracture energy parameters derived from their research.

Reinhardt, Cornelissen & Hordijk (2013 reprint; original 1984–1986 work) - The series of studies by Reinhardt, Cornelissen, and Hordijk established detailed tension softening curves and crack growth relationships for concrete. Their experimental work provided accurate measurements of crack opening displacement (COD), fracture energy, and post-peak tensile resistance. These tension softening laws are widely used to construct crack growth curves in FE-based residual life prediction. ABAQUS uses these softening models in cohesive zone and concrete damage plasticity formulations to simulate progressive degradation. Their findings are particularly applicable to residual life modelling in slab tracks where microcracking gradually evolves into long-term structural deterioration under repeated train loading and environmental cycles.

3. Research Gap

Current literature shows that although ballastless track systems (BLTS) are widely studied, very limited research focuses specifically on the cracking behaviour of RCC plinths under the combined effects of thermal stresses and cyclic train loading. These two load conditions interact in a complex manner, producing intrinsic and service cracks that existing studies do not fully capture. Similarly, there is no established comparative framework that links analytical fracture mechanics predictions with advanced FE-based crack modelling such as ABAQUS XFEM or CZM. Most studies use either analytical formulas or numerical simulations independently, resulting in uncertainty about their accuracy when applied to real BLTS plinths. Furthermore, there is a lack of residual life prediction charts, models, or guidelines tailored to BLTS plinth structures, making it difficult for engineers to assess long-term performance and plan maintenance effectively.

These gaps highlight the need to pursue the current research objectives. Studying intrinsic cracks is essential because they form early and govern later crack propagation. Understanding crack growth patterns and their role in structural failure helps identify how small cracks develop into critical defects. Learning ABAQUS for crack modelling is necessary to simulate realistic crack paths and validate mechanisms under service loads. Analytical evaluation of crack growth in RCC plinths provides theoretical benchmarks to compare with FE simulations. Finally, predicting the residual life of concrete members is crucial to develop BLTS-specific maintenance guidelines and ensure long-term safety and performance.

4. Conclusion

The review of intrinsic crack growth behavior in Reinforced Cement Concrete (RCC) components of Ballastless Track Systems (BLTS) underscores the critical importance of understanding crack initiation, propagation, and long-term deterioration mechanisms in high-performance railway structures. BLTS demand exceptional stability, precise alignment, and durability under repetitive cyclic loading, thermal fluctuations, and environmental exposure. As the literature indicates, intrinsic cracks—arising from early-age shrinkage, thermal gradients, hydration heat, and service-induced stresses—pose significant challenges to the structural integrity and long-term functionality of track plinths and other RCC elements.

The synthesis of existing studies reveals that intrinsic cracks not only compromise stiffness and load distribution but also accelerate reinforcement corrosion, water ingress, and fatigue-driven degradation. Despite the availability of experimental, analytical, and numerical approaches, current research remains limited by a lack of integrated crack growth models that incorporate field conditions, material variability, and long-term performance data. This gap highlights the necessity of a systematic and comprehensive investigation such as the one proposed in this review.

The objectives outlined for this research are therefore both timely and essential. A systematic investigation of crack formation and underlying mechanisms (Objective 1) is fundamental to accurately characterizing the root causes of deterioration in BLTS. Understanding crack propagation patterns and their influence on progressive structural failure (Objective 2) is crucial for evaluating residual load-carrying capacity and long-term service performance. Mastery of advanced numerical tools, particularly ABAQUS (Objective 3), is vital for simulating realistic crack behaviour and validating theoretical fracture mechanics approaches. Analytical evaluation using established fracture mechanics (Objective 4) complements numerical models by offering a robust theoretical framework for quantifying crack growth and stress intensity factors. Ultimately, the ability to predict the residual life of RCC components (Objective 5) forms the core contribution of this review, facilitating improved maintenance planning, safety assessment, and life-cycle management of BLTS.

In conclusion, this review emphasizes the necessity of integrating experimental observations, analytical modelling, and high-fidelity numerical simulation to develop reliable crack growth prediction frameworks for BLTS. Advancing this research will significantly enhance structural health monitoring strategies, optimize maintenance interventions, and ensure the long-term durability and safety of modern rail infrastructure.

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