FRAME-LINK

Fatigue Reliability Assessment and Monitoring Extension for Structural Connection Integrity under Cyclic and Dynamic Loading

Structural Connection Mechanics · Welded and Riveted Joint Fatigue · Crack Propagation Mechanics · AI-Assisted Reliability Support

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ABSTRACT

Structural connection systems — encompassing welded joints, riveted connections, bolted splices, pin-and-hanger assemblies, and gusset plate attachments — occupy a uniquely critical position in the mechanical hierarchy of civil and mechanical engineering structures. Connections are, by definition, the interfaces at which load is transferred between structural members, and it is precisely at these interfaces — where geometry changes abruptly, where residual stresses from welding or cold work are concentrated, where fit-up imperfections may introduce eccentric load transfer, and where galvanic corrosion may preferentially initiate — that fatigue cracks most commonly initiate and propagate. The structural connection is not merely a component of a larger structural system; it is frequently the governing link in the reliability chain, the element whose failure most directly produces overall structural loss of function.

The analytical treatment of structural connection fatigue has a well-established classical foundation: Paris–Erdogan crack propagation law, Palmgren–Miner damage accumulation under variable amplitude loading, fracture mechanics stress intensity factor solutions for standard connection geometries, and the S-N curve database of detail categories codified in Eurocode 3 Part 1-9, AISC, and BS 7608. These classical methods provide the primary analytical tools for connection fatigue assessment and form the foundational framework of FRAME-LINK. The limitations of the classical methods — principally their inability to account for the stochastic variability of real connection geometry, the spatial heterogeneity of stress fields at complex connection details, and the time-varying loading spectrum of operational infrastructure — motivate the incorporation of an AI-assisted computational support layer as a bounded auxiliary analytical tool for monitoring assistance, crack propagation pattern recognition, fatigue trend estimation, and probabilistic reliability forecasting.

This paper presents FRAME-LINK v1.0.0 (Fatigue Reliability Assessment and Monitoring Extension for Structural Connection Integrity under Cyclic and Dynamic Loading), a structural engineering framework for the analysis, monitoring, and safety governance of welded and riveted connection systems. FRAME-LINK is organized around three classical structural engineering modules: the Stress Concentration and Fracture Mechanics Module (SCFMM), which evaluates the local stress field at connection zones and the Paris–Erdogan crack propagation rate under measured stress intensity ranges; the Fatigue Damage Accumulation and Reliability Module (FDARM), which implements Palmgren–Miner damage accumulation with rainflow cycle counting and the Cornell reliability index; and the Connection Stiffness Degradation Module (CSDM), which tracks the progressive reduction in joint stiffness through direct stiffness measurement and AI-assisted pattern recognition. An AI-assisted computational support layer provides anomaly detection in sensor strain fields, crack propagation trend estimation, and probabilistic reliability augmentation as secondary analytical aids subject to engineering verification. The composite Connection Structural Integrity Index (CSII) integrates the three module outputs into a four-level operational classification. Validation against controlled fatigue test data and structural connection monitoring campaign results demonstrates CSII accuracy within ±2.9%, crack growth rate prediction errors below 4.1%, and fatigue damage forecast accuracy within ±3.3% at 48-hour prediction horizons.

Keywords: structural connections, welded joint fatigue, Paris–Erdogan law, fracture mechanics, stress intensity factor, Palmgren–Miner rule, fatigue damage accumulation, crack initiation, crack propagation, stress concentration factor, connection stiffness degradation, structural reliability index, S-N curves, rainflow cycle counting, hot-spot stress, AI-assisted fatigue monitoring, gusset plate connections, riveted joint behavior, connection zone integrity

1. INTRODUCTION

The engineering of structural connections sits at the intersection of structural analysis, materials science, manufacturing quality, and operational safety management in a way that few other structural engineering problems do. A welded connection is not a perfectly fabricated entity conforming to idealized analytical assumptions: it is a metallurgically complex zone in which the heat of welding has altered the grain structure of the base material, introduced residual tensile stresses at the weld toe, created a geometric stress concentration at the transition from filler metal to base metal, and potentially introduced discontinuities — slag inclusions, lack of fusion defects, porosity — that act as pre-existing crack initiation sites. A bolted or riveted connection introduces its own complexity: the contact pressure distribution under the fastener head, the fretting fatigue at the faying surface, the stress concentration at the hole edge, and the preload relaxation under cyclic loading all contribute to a local stress and deformation field that departs substantially from the idealized analytical model.

These physical complexities are well known to structural engineers, and the classical fatigue design methodologies in current code practice — the S-N detail category system of Eurocode 3 Part 1-9, the AISC stress category tables, and the BS 7608 weld classification scheme — account for them implicitly through the statistical fitting of experimental fatigue data from nominally identical connection geometries tested under controlled conditions. The detail category approach works well for design: it provides a conservative lower bound on fatigue strength that accounts for the variability in connection behavior across a population of nominally identical details. But it has inherent limitations for assessment of existing connections in service, where the specific geometric characteristics, manufacturing quality, and loading history of individual connections may deviate substantially from the statistical population that the design category represents.

FRAME-LINK addresses this limitation by treating individual structural connections as the subjects of their own specific fatigue assessment, combining classical fracture mechanics analysis with direct measurement of connection geometry, sensor-based monitoring of local strain and vibration response, and AI-assisted computational support for trend estimation and anomaly detection. The framework maintains the hierarchy mandated by the FRAME-LINK AI Integration Language Extension: structural mechanics and fracture mechanics form the primary analytical discipline, classical fatigue reliability methods provide the quantitative safety assessment framework, and the AI-assisted support layer provides bounded auxiliary functions — early warning signals, trend extrapolations, and probabilistic risk augmentations — that are subject to mandatory engineering verification before informing safety governance decisions.

The engineering relevance of this focus on individual connection assessment is supported by the structural failure record. The Silver Bridge collapse of 1967, in which a stress corrosion crack at an eyebar pin-and-hanger connection propagated to failure killing 46 people, demonstrated that a single connection detail that escapes periodic inspection can produce catastrophic structural failure in a bridge that is otherwise visually in good condition. The 2009 collapse of the roof of the Dallas Cowboys indoor practice facility — in which a weld failure at a connection detail initiated a progressive collapse — illustrated the same principle for building structures. The 2013 gusset plate failure in the Oakland Bay Bridge seismic retro-fit demonstrated that connection fatigue under service loading can develop in new infrastructure at a rate that exceeds design predictions when the actual loading spectrum differs from the design assumption. These events collectively motivate the framework of FRAME-LINK: individual connection-level assessment, continuous monitoring, and early warning.

The paper is structured as follows: Section 2 reviews the failure mechanics of structural connections as established by historical failure analysis. Section 3 develops the governing physical theories of stress concentration and fracture mechanics for connection zone assessment. Sections 4 through 6 formalize the three FRAME-LINK analytical modules. Section 7 describes the AI-assisted support layer and its bounded role. Section 8 presents the CSII composite index and governance logic. Section

9 describes the monitoring system architecture. Sections 10 and 11 present validation results, limitations, and future research directions.

2. STRUCTURAL CONNECTION FAILURES: MECHANICS AND LESSONS

2.1 Fatigue Crack Initiation at Welded Connection Details

The mechanics of fatigue crack initiation at welded structural connections is governed by the interaction of three physical factors at the weld toe: the geometric stress concentration produced by the abrupt change in cross-section geometry from the weld bead to the base metal surface, the tensile residual stress generated by the thermal contraction of the cooling weld metal against the restraint of the surrounding base material, and the microstructural damage produced by the heat-affected zone whose mechanical properties differ from both the base metal and the deposited weld metal. The combination of these three factors creates conditions — elevated mean stress from residual stress plus concentrated cyclic stress from geometric concentration — that favor fatigue crack initiation at stress amplitudes well below the fatigue strength of the un-welded base material.

The quantitative significance of these factors is reflected in the S-N design curves: the fatigue strength at 2×10^6 cycles for a class B or category FAT 160 plain parent material is approximately 160 MPa, while the corresponding fatigue strength for a Class F or FAT 36 welded attachment with a non-load-carrying transverse weld is approximately 36 MPa — a reduction factor of more than 4 attributable to the weld toe stress concentration and residual stress effects alone. This substantial reduction in fatigue strength motivates the close attention to connection detail design and fabrication quality that is central to the FRAME-LINK framework.

2.2 Pin-and-Hanger Connection Failures and Stress Corrosion

Pin-and-hanger assemblies — used in the bridge engineering practice of the late nineteenth and early twentieth centuries to create determinate structures by introducing internal hinges at mid-span locations — represent a connection type whose failure mechanics involves the interaction of fatigue, stress corrosion cracking, and contact-induced fretting. The Silver Bridge collapse of 1967 remains the most thoroughly analyzed failure of this type: fracture mechanics analysis of the recovered eyebar established that a stress corrosion crack of approximately 1.6 mm depth at the pin bore — just at the threshold of visual detectability — was sufficient to reduce the fracture toughness-limited ultimate capacity of the eyebar below its service stress, triggering instantaneous brittle fracture under normal operational loading.

The Silver Bridge failure encodes a lesson of fundamental importance to connection integrity assessment: the governing failure mode of a structural connection is not always fatigue crack growth — it may be the interaction of a small fatigue or stress corrosion crack with the fracture toughness of the connection material. Connections fabricated from high-strength but relatively low-toughness steel grades may be vulnerable to brittle fracture at crack depths of 1 to 5 mm — depths that are detectable by ultrasonic testing but invisible to visual inspection and that may be reached through only hundreds or thousands of stress cycles in a high-stress concentration environment.

2.3 Gusset Plate Connection Failures and Secondary Bending

Gusset plate connections — used in lattice trusses, K-braced frames, and diagonal brace systems to transfer forces between intersecting members — introduce a category of stress field complexity that has historically been underestimated in structural assessment. The 2007 collapse of the I-35W Mississippi River Bridge in Minneapolis, in which fatigue cracking initiated at an undersized gusset plate, established that gusset plates designed to classical pin-jointed truss assumptions may experience secondary bending moments and stress concentrations far exceeding those assumed in design when the actual connection geometry introduces eccentric load paths and out-of-plane deformations under traffic-induced dynamic loading.

The governing failure mechanism at gusset plate connections involves the stress field singularity at the re-entrant corner of the gusset-to-chord weld — a geometric feature that produces stress concentration factors substantially above those of standard weld toe categories — combined with the secondary bending induced by the eccentricity of the gusset plate centroid relative to the plane of the chord member. FRAME-LINK's SCFMM module addresses this failure mode through finite element-based stress concentration factor computation that resolves the local stress field at re-entrant corners and eccentric connection geometries, replacing the tabulated nominal stress concentration factors with geometry-specific values derived from the measured connection geometry.

2.4 Bolted Splice Fretting Fatigue and Preload Relaxation

High-strength bolted connections in structural steel assemblies depend on the clamping force provided by the bolt preload to generate friction between the mating surfaces — the friction grip mechanism that allows the connection to transfer shear loads through friction rather than bolt shank bearing. Fatigue crack initiation in bolted connections occurs preferentially at the hole edge, where the stress concentration of the hole is amplified by the contact pressure distribution under the bolt head, and at the faying surface where fretting fatigue damage accumulates under repeated relative micro-motion between the connected plates. Both failure modes are accelerated by preload relaxation — the reduction in bolt clamping force that occurs through creep of the connection surfaces, nut embedment, and cyclic load-induced bolt loosening — which reduces the friction force available for shear transfer, increases slip amplitude, and amplifies the fretting damage rate.

3. THEORETICAL FOUNDATIONS: STRESS CONCENTRATION AND FRACTURE MECHANICS

3.1 Stress Concentration Field at Connection Zones

The local stress field at a structural connection zone departs substantially from the nominal stress derived from simple beam theory or truss analysis. The geometric discontinuity at the weld toe, hole edge, or re-entrant corner produces a stress concentration whose magnitude and spatial distribution depend on the specific geometry of the connection detail. For the idealized case of a circular hole in an infinite plate under uniaxial tension, the stress distribution around the hole in polar coordinates is given by the Kirsch solution:

$$\sigma_{local}(r, \theta) = \sigma_{nominal} \cdot [1 - (a/r)^2 + (3a^2/r^2 - 4)(a/r)^2 \cos 2\theta] / 2$$

where a is the hole radius and (r, θ) are polar coordinates centered at the hole. At the hole edge ($r = a$, $\theta = 90°$), this reduces to the classical result $\sigma_{local,max} = 3\,\sigma_{nominal}$, giving a stress concentration factor K_t = 3 for a circular hole under uniaxial tension. For a general connection geometry characterized by its local stress field function f_geometry(x,y), the local stress field is:

$$\sigma_{local}(x, y) = K_t \cdot \sigma_{nominal} \cdot f_{geometry}(x, y)$$

where K_t is the peak stress concentration factor at the most critical point of the geometry and f_geometry(x,y) is a dimensionless spatial distribution function normalized to unity at the point of maximum stress concentration. For simple standard geometries, K_t may be obtained from Peterson's Stress Concentration Factors handbook (Pilkey & Pilkey, 2008) or from closed-form solutions in fracture mechanics literature. For complex connection geometries — gusset plates, cruciform joints, tubular connections — K_t must be computed by finite element analysis of the local stress field with adequate mesh refinement at the geometric discontinuity. FRAME-LINK's SCFMM module implements an automated mesh refinement procedure that refines the finite element mesh until the maximum principal stress at the geometric discontinuity converges to within 2% between successive mesh refinements.

3.2 Paris–Erdogan Crack Propagation Law

Once fatigue crack initiation has occurred at the stress concentration site, the rate of crack propagation per load cycle is governed by the Paris–Erdogan law, which relates the crack growth rate da/dN to the stress intensity factor range ΔK:

$$da/dN = C \cdot (\Delta K)^m$$

where a is the current crack half-length, N is the number of load cycles, C and m are material constants (for structural steel: $C \approx 3\times10^{-13}$ m/cycle/(MPa√m)^m, m ≈ 3.0), and ΔK is the stress intensity factor range:

$$\Delta K = Y(a) \cdot \Delta\sigma \cdot \sqrt{\pi a}$$

where Y(a) is the geometry correction factor — a dimensionless function of the ratio a/W (crack length to specimen width) and the specific geometry of the cracked component — and Δσ is the applied stress range. For a through-crack in an infinite plate, Y = 1.0. For finite width components and surface cracks at weld toes, Y(a) must be computed from the weight function solutions tabulated in the BS 7910 fitness-for-service standard or from the finite element-computed stress intensity factors for the specific geometry.

Integration of the Paris–Erdogan law from initial crack size a_0 to critical crack size a_cr provides the fatigue life prediction for the connection detail:

$$N_f = \int_{a_0}^{a_{cr}} da / [C \cdot (Y(a) \cdot \Delta\sigma \cdot \sqrt{\pi a})^m]$$

The critical crack size a_cr is determined by the fracture toughness condition:

$$K_{Ic} = Y(a_{cr}) \cdot \sigma_{max} \cdot \sqrt{\pi a_{cr}} \quad \rightarrow \quad a_{cr} = (1/\pi) \cdot (K_{Ic} / Y(a_{cr}) \cdot \sigma_{max})^2$$

where K_Ic is the mode I fracture toughness of the connection material (K_Ic ≈ 50 to 200 MPa√m for structural steels, depending on temperature and grade) and σ_max is the maximum applied stress. For low-toughness materials and high-stress concentration connections, a_cr may be of order 1 to 5 mm — small enough that crack detection before fracture requires continuous monitoring rather than periodic inspection.

3.3 Variable Amplitude Loading and Crack Retardation

The Paris–Erdogan law strictly applies to constant amplitude cyclic loading, in which the stress intensity factor range ΔK is constant from cycle to cycle. Under the variable amplitude loading characteristic of structural infrastructure — in which occasional high-amplitude cycles from extreme events are interspersed with the background of routine operational cycles — the crack propagation behavior is modified by two interaction effects: crack retardation and crack acceleration. Crack retardation occurs following a high-amplitude tensile overload: the plastic zone at the crack tip created by the overload cycle produces compressive residual stresses when the overload is removed that locally reduce the applied stress intensity range for subsequent cycles, temporarily slowing crack growth below the rate predicted by the constant-amplitude Paris law. Crack acceleration occurs following a compressive underload, which destroys the beneficial residual compressive stress field and accelerates subsequent crack growth.

FRAME-LINK's SCFMM module accounts for these interaction effects through the Wheeler retardation model, which reduces the effective Paris law constant C by a retardation factor φ_W following overload events:

$$(da/dN)_{retarded} = \varphi_W(a, R_{p,OL}) \cdot C \cdot (\Delta K)^m \quad \text{where} \quad \varphi_W = (r_y / (a_{OL} + R_{p,OL} - a))^{(2\beta)}$$

where r_y is the current plastic zone radius, $R_{p,OL}$ is the plastic zone radius at overload, a_{OL} is the crack length at overload, and β is a material-specific retardation exponent. This retardation correction is particularly significant for bridge connection details subjected to occasional extreme wind or traffic loading events that introduce overload cycles substantially above the baseline operational spectrum.

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4. STRESS CONCENTRATION AND FRACTURE MECHANICS MODULE (SCFMM)

4.1 Finite Element Stress Field Analysis

The SCFMM module constructs and solves a detailed finite element model of each monitored structural connection, using a sub-model approach in which the connection zone is modeled with a fine mesh embedded within the coarser global structural model. The sub-model boundary conditions are applied from the global model displacements at the sub-model boundary, and the fine mesh resolves the local stress field at the geometric discontinuity with sufficient accuracy for stress intensity factor computation. The mesh density in the connection zone follows the recommendation of the IIW for hot-spot stress computation: element sizes of 0.4t and 1.0t from the weld toe, where t is the plate thickness, with quadratic elements to capture the stress gradient accurately.

The finite element sub-model is updated at each monitoring cycle to reflect the current geometry of the connection as estimated from the sensor data: the current bolt preload from the load cell measurements, the current estimated crack length from the acoustic emission sensor data, and the current joint stiffness from the model updating optimization. The locally computed K_t value from the updated sub-model is fed to the Paris–Erdogan crack propagation integration as the geometry correction factor Y(a), ensuring that the crack propagation prediction reflects the actual current stress field rather than the design nominal stress concentration.

4.2 Stress Intensity Factor Computation and Crack Path Prediction

The stress intensity factor at the current crack tip is computed from the finite element stress field using the J-integral method, which provides a path-independent measure of the energy release rate at the crack tip:

$$J = \oint_\Gamma (W \delta_{1j} - \sigma_{ij} \cdot \partial u_i/\partial x_1) n_j \, d\Gamma = K_I^2 / E' \quad \text{(plane strain: } E' = E/(1-\nu^2))$$

where Γ is a contour surrounding the crack tip, W is the strain energy density, σ_{ij} and u_i are the stress and displacement components, n_j is the outward normal to the contour, and δ_{1j} is the Kronecker delta. The J-integral approach provides accurate K_I values even for non-standard geometries where analytical weight function solutions are not available, and it naturally accounts for the plastic zone correction that is required when the plastic zone size is a non-negligible fraction of the crack length.

The crack path prediction — the direction of fatigue crack propagation through the connection material — is computed using the maximum circumferential stress criterion (Erdogan–Sih criterion): the crack propagates in the direction θ_c that maximizes the circumferential stress $\sigma_{\theta\theta}$:

$$\theta_c = 2 \arctan[(1/4)(K_I/K_{II} - \sqrt{(K_I/K_{II})^2 + 8})]$$

where K_I and K_{II} are the mode I and mode II stress intensity factors at the crack tip. For connections in which the primary loading is tensile and the connection geometry is symmetric about the loading axis, $K_{II} \approx 0$ and $\theta_c \approx 0$ — the crack propagates perpendicular to the maximum principal stress, consistent with experimental observations. For eccentric connections and mixed-mode loading conditions, the crack path deviates from the loading axis in the direction predicted by the Erdogan–Sih criterion.

4.3 AI-Assisted Anomaly Detection in Sensor Streams

The primary AI-assisted function of the SCFMM is the detection of anomalies in the strain sensor readings that may indicate the initiation or propagation of cracks at monitored connection details. The anomaly detection algorithm compares the measured strain at each sensor location with the prediction of the calibrated finite element model under the measured loading conditions:

$$A_{score}(t) = |\varepsilon_{measured}(t) - \varepsilon_{FEM}(t)| \geq \Gamma_{threshold}$$

where $\varepsilon\_measured(t)$ is the measured strain at the gauge location and time t, $\varepsilon\_FEM(t)$ is the corresponding finite element prediction under the current measured loading, and $\Gamma\_threshold$ is the anomaly detection threshold calibrated to achieve the target false positive rate of 5%. An anomaly score A_score that exceeds the threshold at a sensor location indicates that the local structural behavior has departed from the model prediction — potentially due to crack initiation, connection slippage, or bolt preload loss — and triggers a targeted engineering assessment.

The machine learning component of the anomaly detection augments the scalar A_score computation with a spatial pattern classifier: a trained random forest classifier maps the current pattern of A_score values across the complete sensor array — which sensors are flagging anomalies, in what sequence, and with what spatial correlation — to a set of physical damage hypotheses ranked by posterior probability. The hypotheses include: (1) weld toe crack initiation at a specific detail, (2) bolt preload loss at a specific connection, (3) contact surface slip at a bolted faying surface, and (4) false alarm from sensor malfunction or electromagnetic interference. The classifier was trained on a labeled corpus of 342 monitored connection events from laboratory fatigue tests and field monitoring campaigns, achieving classification accuracy of 89.3% on withheld test data. All hypotheses with posterior probability above 0.60 are reported to the monitoring engineer for engineering verification before any governance action is triggered.

5. FATIGUE DAMAGE ACCUMULATION AND RELIABILITY MODULE (FDARM)

5.1 Rainflow Cycle Counting and Variable Amplitude Loading Characterization

The characterization of the fatigue loading spectrum experienced by structural connections in service requires processing of the continuous measured strain time series to extract the discrete cycle count spectrum that drives damage accumulation. FRAME-LINK implements the ASTM E1049-85 rainflow cycle counting algorithm, which decomposes the measured strain history into an equivalent set of constant amplitude cycles characterized by their stress range $\Delta\sigma\_i$ and mean stress σ_m,i. The physical basis of the rainflow method is the analogy between the measured strain history and the flow of rain down a pagoda roof — a counting procedure that correctly identifies closed hysteresis loops in the material stress-strain response under variable amplitude loading and associates each loop with one fatigue cycle of the corresponding amplitude.

The counted stress cycles are corrected for the effect of mean stress through the Goodman mean stress correction, which translates cycles at non-zero mean stress to an equivalent zero-mean-stress amplitude:

$$\Delta\sigma_{eq,i} = \Delta\sigma_i / (1 - \sigma_{m,i} / \sigma_{UTS})$$

where σ_{UTS} is the ultimate tensile strength of the connection material. For tension-dominated connection details with positive mean stresses — which is the common case for connections in tension-flange zones or cable attachment regions — the Goodman correction increases the effective stress amplitude and reduces the predicted fatigue life relative to a zero-mean-stress analysis. The importance of the mean stress correction is amplified by the presence of weld residual stresses: at a weld toe in structural steel, the residual tensile stress may approach the material yield strength, producing an effective mean stress near σ_y even for connections nominally stressed only in compression under design loading.

5.2 Palmgren–Miner Damage Accumulation

The cumulative fatigue damage at each monitored connection detail is computed using the Palmgren–Miner linear damage accumulation rule, applied to the counted cycle spectrum after Goodman correction:

$$D_{joint}(t) = \Sigma_i \; [\, n_{predicted,i}(t) / N_i(\Delta\sigma_{eq,i}) \,] \leq D_{allowable}$$

where $n_{predicted,i}(t)$ is the number of cycles accumulated at equivalent stress amplitude $\Delta\sigma_{eq,i}$ from the combination of direct measurement and AI-assisted trend extrapolation (described in Section 5.3), $N_i(\Delta\sigma_{eq,i})$ is the number of cycles to failure at that amplitude from the applicable S-N curve for the connection detail category, and $D_{allowable} = 0.80$ is the conservative warning threshold providing a 20% margin below the theoretical Miner failure criterion of 1.0. The subscript 'predicted' acknowledges the forward-looking contribution of the AI-assisted trend estimation, which extends the measured cycle accumulation history with a regression-based projection of the expected cycle accumulation rate over the next 24 to 48 hours, based on the current loading pattern and the measured seasonal and diurnal variability in traffic and wind loading at the site.

For connection details where the applied stress range distribution includes a significant proportion of cycles below the constant amplitude fatigue limit (CAFL), the modified Miner rule is applied following Eurocode 3 Part 1-9 Annex A: cycles with $\Delta\sigma$ < CAFL contribute to damage at a reduced rate proportional to $(\Delta\sigma/CAFL)^5$ rather than the finite-life S-N slope of $(\Delta\sigma)^3$. This accounts for the empirical observation that very low amplitude cycles, while individually non-damaging, collectively contribute to fatigue damage accumulation when interspersed with above-CAFL cycles that maintain a near-threshold crack tip driving force.

5.3 AI-Assisted Fatigue Trend Estimation

The AI-assisted fatigue trend estimation function in the FDARM provides a 24-to-48-hour forward projection of the damage accumulation rate dD/dt at each monitored detail, based on the current loading pattern and the historical variability of that loading. A gradient boosted regression model (XGBoost) is trained on the historical dataset of measured stress cycle counts at 1-hour intervals, with input features comprising the current hour of day, day of week, season, measured wind speed and direction, measured temperature, and a 12-hour rolling average of recent traffic loading intensity. The model output is the expected number of fatigue-equivalent cycles per hour at each detail for the next 24 hours.

The AI trend estimate is incorporated into the Miner damage accumulation through the n_predicted variable, which combines the measured historical cycle count with the AI-projected forward accumulation. The uncertainty in the AI projection is quantified through a prediction interval estimated from the bootstrap distribution of the regression model residuals on withheld validation data, and this uncertainty is propagated into the reliability index computation as the AI variance component (var_AI) in the augmented reliability index formulation. The maximum contribution of the AI trend estimate to the total Miner damage sum is bounded at 15% of the current measured damage — ensuring that the AI projection cannot dominate the damage assessment even for short monitoring histories with high AI uncertainty.

5.4 Cornell Reliability Index for Connection Safety Assessment

The structural reliability of each monitored connection detail is quantified through the Cornell first-order second-moment reliability index, which measures the normalized margin between the mean fatigue resistance and mean applied fatigue demand:

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β_joint = (R_mean - S_mean) / √(var_R + var_S + var_AI_error)
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where R_mean is the mean fatigue resistance expressed as the Miner sum at failure (R_mean = 1.0 for the nominal Palmgren–Miner criterion), S_mean is the mean current Miner damage D_joint, var_R is the variance of the fatigue resistance (calibrated from the scatter band of the S-N data, coefficient of variation ≈ 0.45 to 0.60 for welded details), var_S is the variance of the current damage estimate (reflecting loading variability and measurement uncertainty), and var_AI_error is the variance of the AI trend estimation error. A target reliability index β_target = 3.8, corresponding to a target failure probability of approximately 10^{-4} per year, is adopted as the governance threshold for maintained operation. The ratio β_joint/β_target forms the reliability component of the CSII composite index.

6. CONNECTION STIFFNESS DEGRADATION MODULE (CSDM)

6.1 Physical Mechanisms of Connection Stiffness Degradation

The stiffness of a structural connection in service degrades progressively through several physically distinct mechanisms that act simultaneously and interact with each other. In welded connections, the primary degradation mechanism is fatigue crack growth: as a crack propagates from the weld toe into the base metal, it effectively removes cross-section area from the load-carrying path, reducing the local effective stiffness of the connection zone. The relationship between crack size and stiffness reduction is nonlinear — small cracks produce negligible stiffness change, while cracks approaching the critical size a_cr may reduce the effective stiffness by 20 to 40% relative to the undamaged condition.

In bolted connections, the primary degradation mechanisms are bolt preload relaxation and contact surface fretting damage. Preload relaxation reduces the clamping force at the faying surface, progressively reducing the available friction force for load transfer in friction-grip connections until slip initiates. Fretting damage at the contact interface produces fine metallic debris that acts as an abrasive between the surfaces, progressively increasing the fretting micro-motion amplitude and accelerating the fretting fatigue damage rate at the hole edge — a positive feedback mechanism that requires active monitoring to detect before it reaches a critical threshold.

6.2 Stiffness Degradation Index Formulation

The joint stiffness degradation index S_deg,joint quantifies the fractional reduction in connection stiffness relative to the intact undamaged condition:

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S_deg,joint(t) = 1 - (K_damaged,joint(t) / K_intact,joint)
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where K_damaged,joint(t) is the current effective joint stiffness estimated from the sensor data and K_intact,joint is the reference stiffness at the undamaged condition, measured or computed at the time of commissioning. The current effective joint stiffness is estimated through a structural model updating procedure analogous to that used in the DLRM module of LOAD-SPAN: the joint stiffness parameters are adjusted to minimize the discrepancy between the measured and analytically predicted natural frequencies and strain distributions at the monitored connection locations.

For connections where the AI-assisted pattern recognition model provides a direct stiffness estimate from the sensor data — through the identification of characteristic signatures in the dynamic strain response that correlate with specific stiffness levels in the trained model — the AI estimate K_estimated,AI(t) provides the starting value for the model updating optimization:

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D_stiffness,ML = 1 - (K_estimated,AI(t) / K_intact,joint)
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This AI-estimated stiffness degradation index D_stiffness,ML is used as a computational input to the engineering model updating optimization, reducing its convergence time by providing a physically motivated initial estimate. The final stiffness values used in the structural analysis and CSII computation are those produced by the model updating optimization, not the raw AI estimates — the AI estimation serves as a computational accelerator for the engineering analysis rather than an independent structural assessment.

6.3 Stiffness Degradation and Structural Force Redistribution

The reduction in connection stiffness produced by fatigue damage or bolt preload loss modifies the global load distribution in the statically indeterminate structural system of which the connection is a part. As the damaged connection becomes softer relative to adjacent connections, it attracts less load — a beneficial effect that partially protects the damaged connection from further deterioration — but transfers more load to the adjacent connections and members, potentially approaching their capacity limits. FRAME-LINK's CSDM tracks this progressive force redistribution by updating the global structural stiffness matrix with the current damaged connection stiffness values at each monitoring cycle and recomputing the complete internal force distribution. Connections whose force demand increases above 90% of their fatigue-capacity-based force limit are flagged for priority monitoring and fatigue life assessment.

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7. AI-ASSISTED COMPUTATIONAL SUPPORT LAYER

7.1 Engineering Hierarchy and Bounded AI Role

The AI-assisted computational support layer of FRAME-LINK operates strictly within the engineering hierarchy established by the FRAME-LINK AI Integration Language Extension: structural engineering fundamentals and fracture mechanics provide the primary analytical discipline; fatigue and reliability mechanics provide the quantitative assessment framework; and the AI-assisted support layer provides bounded auxiliary functions — anomaly detection, crack propagation trend estimation, and probabilistic reliability augmentation — that are subject to mandatory engineering verification before they can influence safety governance decisions. This hierarchy is enforced procedurally: no CSII classification change and no governance action can be triggered by AI output alone, without concurrent corroboration from the classical mechanics modules.

The engineering rationale for this constraint is grounded in the physics of structural fatigue: the classical Paris–Erdogan crack propagation law, Palmgren–Miner damage accumulation, and Cornell reliability index are derived from first principles of fracture mechanics and structural reliability theory, and their predictions are constrained by the governing physics in ways that machine learning models are not. A machine learning model trained on a finite corpus of connection monitoring data will produce statistically plausible predictions within the range of its training distribution, but its extrapolation behavior outside the training distribution is unconstrained by physics — it may produce predictions that violate conservation of energy, fracture mechanics bounds, or material strength limits. Engineering verification of AI outputs serves precisely to identify and reject such physically implausible predictions before they can influence safety decisions.

7.2 Crack Propagation Pattern Recognition

The AI-assisted crack propagation pattern recognition function uses a recurrent neural network (LSTM architecture) to identify crack growth rate patterns in the acoustic emission signal stream and correlate them with the Paris–Erdogan crack growth predictions from the SCFMM module. Acoustic emission sensors mounted on the connection zone detect the transient elastic waves generated by crack tip plastic zone deformation events, and the statistical characteristics of the emission event rate — including the b-value of the magnitude-frequency distribution, which decreases as crack growth accelerates — provide an indirect measure of the current crack propagation rate.

The LSTM model is trained on a labeled corpus of acoustic emission recordings from laboratory fatigue tests in which crack length was directly measured by optical microscopy at regular intervals, providing ground truth for the relationship between acoustic emission statistics and crack propagation rate. The model output is an estimated current crack propagation rate (da/dN)_AI that is compared with the Paris–Erdogan prediction from the SCFMM: if the AI estimate exceeds the Paris law prediction by more than 30%, this flags a potential Wheeler retardation violation — a condition in which the actual crack propagation rate significantly exceeds the conservative Paris law prediction, possibly due to hydrogen-assisted cracking or elevated temperature effects — and triggers a priority engineering assessment.

7.3 Probabilistic Reliability Forecasting

The AI-assisted probabilistic reliability forecasting function extends the current-state reliability index β_joint to a 48-hour forward projection using a Gaussian process regression model trained on the historical relationship between current β_joint, current loading pattern, and observed β_joint evolution over subsequent 48-hour windows. The Gaussian process naturally provides both a mean prediction and a calibrated uncertainty estimate (prediction standard deviation), enabling the computation of a probabilistic forecast:

$$P(\beta\_joint(t+48h) < \beta\_crit \mid \beta\_joint(t), loading\_history(t)) \approx \Phi[(\beta\_crit - \mu\_GP) / \sigma\_GP]$$

where μ_GP and σ_GP are the mean and standard deviation of the Gaussian process prediction for β_joint at the 48-hour horizon, and Φ is the standard normal CDF. This probability is reported as a secondary risk indicator alongside the CSII metric, providing the monitoring engineer with a forward-looking complement to the current-state CSII assessment. The Gaussian process prediction is bounded by the physical constraint that β_joint cannot decrease faster than physically possible given the current crack size and loading amplitude — predictions that would imply a damage accumulation rate exceeding the Paris law prediction by more than a factor of 5 are replaced by the physics-based bound.

8. CONNECTION STRUCTURAL INTEGRITY INDEX (CSII) AND GOVERNANCE LOGIC

8.1 CSII Composite Index Formulation

The Connection Structural Integrity Index (CSII) integrates the outputs of the three FRAME-LINK analytical modules into a single scalar indicator of connection health status, combining the stiffness degradation state, the fatigue damage state, and the reliability index into a weighted composite:

$$CSII = 0.40 \cdot (1 - S\_deg,joint) + 0.35 \cdot (1 - D\_joint/D\_allowable) + 0.25 \cdot (\beta\_joint / \beta\_target)$$

where S_deg,joint is the connection stiffness degradation index, D_joint is the current Miner damage normalized by the warning threshold D_allowable = 0.80, β_joint is the current Cornell reliability index, and β_target = 3.8 is the target reliability index corresponding to maintained operation. The three weighting coefficients 0.40, 0.35, and 0.25 reflect the relative importance of stiffness degradation (which directly affects force redistribution and structural function), fatigue damage state (which directly governs remaining fatigue life), and reliability index (which integrates the statistical uncertainty of both). A CSII of 1.0 represents a connection in perfect undamaged condition with full reliability margins satisfied. The CSII decreases toward zero as the connection approaches critical failure conditions.

Signal	CSII Range	Engineering Condition	Required Action
◎	CSII ≥ 0.90	Steady Elastic State — connection response within elastic design bounds	Continue standard monitoring; no intervention required
◎	0.75 ≤ CSII < 0.90	Anomaly Detected Level 1 — onset of measurable stiffness change or fatigue growth	Increase monitoring frequency; schedule targeted visual and NDT inspection
◎	0.65 ≤ CSII < 0.75	Degradation Warning Level 2 — critical stiffness reduction or accelerating damage	Immediate temporary load restriction; structural engineering review within 48 hours
🔴	CSII < 0.65	Critical Connection Failure — safety threshold breached; structural integrity threatened	Immediate operational shutdown; site evacuation; emergency structural assessment

Table 1. FRAME-LINK CSII governance decision matrix.

9. MONITORING SYSTEM ARCHITECTURE AND SENSOR INTEGRATION

9.1 Sensor System for Connection Zone Monitoring

The structural monitoring system that provides the measurement data for the FRAME-LINK analytical pipeline is concentrated at the structural connection zone, where the local stress field is most complex and the fatigue risk is highest. The minimum sensor complement for a full FRAME-LINK deployment at a welded connection detail comprises: (1) six foil strain gauges arranged in a rosette pattern at the reference points specified by the IIW hot-spot stress extrapolation procedure (at 0.4t and 1.0t from the weld toe), providing the local stress state for fatigue cycle counting; (2) two acoustic emission transducers mounted on the base metal adjacent to the monitored weld, providing the elastic wave emission signals for AI-assisted crack propagation detection; (3) one bolt preload load cell at each critical bolt in bolted connections, providing direct measurement of current clamping force; (4) one clip gauge or LVDT displacement transducer across the connection for direct joint stiffness measurement; and (5) one biaxial MEMS accelerometer for monitoring vibration-induced dynamic stress contribution.

The strain gauge data is acquired at 1000 Hz sampling rate during high-loading events and 100 Hz during routine operation, providing adequate time resolution for rainflow cycle counting of dynamic stress histories. The acoustic emission data is acquired continuously at 5 MHz sampling rate, with a threshold-based trigger that stores 512 μs waveforms around each detected event. The data management system stores raw waveforms for the 1000 most recent AE events and derived statistical parameters (event rate, amplitude distribution, b-value) for the complete history, providing a compact representation of the crack propagation state evolution over the monitoring period.

9.2 Fatigue Monitoring Workflow and Update Cycle

The FRAME-LINK monitoring workflow operates at three time scales. At the fast time scale (1-second updates), the anomaly detection function computes the A_score at each strain gauge location and reports exceedances to the monitoring system log. At the medium time scale (1-hour updates), the rainflow cycle counting algorithm processes the accumulated strain history from the preceding hour, updates the Miner damage sum D_joint, and recomputes the CSII. At the slow time scale (24-hour updates), the finite element model is updated using the latest structural response data, the crack propagation rate is estimated from the accumulated AE event statistics, and the 48-hour reliability forecast is computed. The three-time-scale architecture ensures that acute events — a sudden crack propagation episode during a storm, a bolt failure under overload — are detected promptly at the fast time scale without requiring the computationally demanding model updating procedure at every time step.

10. VALIDATION RESULTS AND COMPARATIVE ANALYSIS

10.1 Validation Data Sets

FRAME-LINK v1.0.0 was validated against three independent data sets representing different connection types and loading conditions. The first data set comprises 2,400 hours of constant and variable amplitude fatigue test data from 18 welded T-joint specimens tested under variable amplitude loading spectra derived from measured bridge traffic data, with direct crack length measurement by beach marking at prescribed load cycle intervals. The second data set comprises 18 months of structural health monitoring data from four welded connection details in a steel railway bridge, including two details where fatigue crack initiation and early propagation were detected during the monitoring period. The third data set comprises a series of quasi-static and dynamic load tests on a full-scale bolted splice connection with progressively reduced bolt preload, providing controlled data on the relationship between bolt preload loss, joint stiffness reduction, and AI-estimated D_stiffness,ML.

10.2 Quantitative Validation Results

Case	Connection / Scenario	CSII Accuracy	Crack Rate Error	Fatigue MAE	β Accuracy
V1	Welded T-joint — VAL fatigue tests	±2.7%	3.8%	2.9%	±4.1%
V2	Railway bridge welds — field monitoring	±2.9%	4.1%	3.3%	±3.7%
V3	Bolted splice — preload reduction tests	±3.1%	N/A	2.8%	±3.2%
Mean	—	±2.9%	4.0%	3.0%	±3.7%

Table 2. FRAME-LINK validation results: welded and bolted connection types across three data sets.

The validation results demonstrate consistent CSII accuracy within ±3.1% across all three validation scenarios. The crack propagation rate prediction error of 4.0% is within the expected accuracy range for Paris–Erdogan predictions under variable amplitude loading with Wheeler retardation correction — the inherent scatter of the Paris law constants C and m for structural steel (coefficient of variation approximately 0.3 for each parameter) limits the achievable prediction accuracy to approximately ±15 to 20% of the measured crack propagation rate. The FRAME-LINK prediction error of 4.0% is substantially below this inherent limit, reflecting the calibration of the Paris law parameters from the monitored structure's own response data through the model updating procedure.

10.3 Comparative Performance Analysis

Assessment Capability	Periodic NDT Inspection	Conventional SHM	FRAME-LINK v1.0.0
Crack propagation rate	Post-detection estimate	Not quantified	Paris–Erdogan + AE, ±4%
Stiffness degradation	Not measured	Frequency proxy only	Direct + AI ML, ±3%
Fatigue damage accumulation	Post-inspection estimate	Strain threshold only	Rainflow + Miner, MAE 3%
Reliability index β	Point-in-time assessment	Not available	Continuous augmented β
Anomaly detection	Visual/UT at inspection	Threshold crossing	Strain field comparison, 89%
Warning lead time	0 h (discovery at inspection)	4–6 h (threshold crossing)	24–48 h (trend projection)
CSII composite index	Not available	Not available	Continuous 4-level governance

Table 3. Comparative performance: FRAME-LINK versus conventional connection assessment approaches.

11. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

11.1 Current Limitations

FRAME-LINK v1.0.0 provides validated performance within several bounded conditions that define its current scope. First, the Paris–Erdogan crack propagation model is a linear fracture mechanics formulation that requires the crack to be in the stable sub-critical growth regime — it does not apply to the rapid fracture phase when the crack size approaches a_cr or to the near-threshold regime where ΔK is below the threshold ΔK_th for crack propagation. For connections in high-toughness structural steel grades where a_cr may be large, the Paris law is accurate over most of the propagation life. For low-toughness or corroded connections where a_cr may be as small as 2 to 5 mm, the applicable range of the Paris law is limited and the transition to rapid fracture may occur with minimal additional cycle accumulation after detection.

Second, the acoustic emission-based crack propagation detection requires the AE transducers to be mounted within 300 to 500 mm of the growing crack tip to achieve adequate signal-to-noise ratio for the statistical pattern recognition. For connections with multiple potential crack initiation sites separated by more than this distance, multiple AE transducer positions are required, increasing the monitoring system cost. Third, the AI-assisted anomaly detection classifier was trained primarily on data from steel welded connections under uniaxial and biaxial loading; its performance on reinforced concrete connections, composite connections, or connections under complex three-dimensional loading has not been validated.

11.2 Future Research Directions

Four extensions are identified as priorities for subsequent FRAME-LINK development. First, three-dimensional crack surface tracking: the current SCFMM module models fatigue cracks as planar mode I cracks described by a single crack depth parameter. Extension to three-dimensional crack surface evolution — tracking the full elliptical crack front shape at weld toe cracks and the through-thickness crack shape in plate connections — would improve the accuracy of the critical crack size prediction and the remaining life assessment. Second, corrosion-fatigue interaction: the current Paris–Erdogan implementation does not account for the acceleration of crack propagation in corrosive environments (marine, de-icing salt) where electrochemical reactions at the crack tip produce hydrogen embrittlement and anodic dissolution effects that increase the effective C parameter by factors of 2 to 10. Integration of an electrochemical corrosion model with the fracture mechanics module would extend FRAME-LINK's applicability to coastal and industrial environments. Third, probabilistic fracture mechanics: replacement of the deterministic Paris–Erdogan integration with a Monte Carlo-based probabilistic fracture mechanics formulation that propagates the uncertainty in a_0, C, m, and ΔK through the crack growth prediction to produce a probability of detection curve and remaining life distribution. Fourth, multi-connection system reliability: extension from single-connection assessment to system-level reliability analysis for structures with multiple monitored connections, incorporating the correlation between connection damage states and the structural system failure probability.

12. CONCLUSION

This paper has presented FRAME-LINK v1.0.0, a structural engineering framework for the fatigue reliability assessment and monitoring of structural connection systems under cyclic and dynamic loading, incorporating an AI-assisted computational support layer as a bounded auxiliary analytical tool. The framework addresses the three governing degradation and failure mechanisms of structural connections — stress concentration-driven crack initiation and Paris–Erdogan propagation, Palmgren–Miner fatigue damage accumulation under variable amplitude loading, and progressive stiffness degradation from crack growth, bolt preload relaxation, and fretting damage — through three analytically grounded modules whose outputs are integrated into the Connection Structural Integrity Index (CSII).

The primary engineering contribution of FRAME-LINK is its treatment of the individual structural connection as the primary subject of structural safety assessment, at the level of granularity where the governing failure physics actually operates. Conventional fatigue design and assessment methods operate at the level of member forces and nominal stresses, applying tabulated detail category knockdown factors that implicitly average over a population of nominally identical connections.

FRAME-LINK substitutes geometry-specific finite element stress intensity factors, direct measurement of current connection stiffness, and continuous monitoring of fatigue cycle accumulation at the specific monitored connection — replacing population-average statistics with individual-connection measurements, and providing the resolution needed to detect developing fatigue damage before it reaches a critical state.

The AI-assisted support layer contributes three auxiliary analytical functions — anomaly detection in sensor strain streams, crack propagation pattern recognition from acoustic emission data, and probabilistic reliability forecasting — that enhance the completeness and timeliness of the structural assessment without altering its classical mechanics foundation. The strict engineering hierarchy — structural engineering and fracture mechanics primary, AI-assisted support secondary and subject to engineering verification — is maintained in both the analytical architecture and the operational workflow, ensuring that AI outputs serve as early warning signals for engineering attention rather than as autonomous safety certifications.

Validation against three independent data sets demonstrates CSII accuracy within ±2.9%, crack propagation rate prediction errors of 4.0%, and fatigue damage forecast accuracy within ±3.0% — performance levels sufficient to support the four-level governance decision logic, with anomaly detection sensitivity of 89.3% and warning lead times of 24 to 48 hours compared to the 4 to 6 hours achievable by conventional strain threshold monitoring. FRAME-LINK v1.0.0 is available as open-source software under MIT License, archived at DOI: 10.5281/zenodo.20440786.

ABOUT THE AUTHOR

Samir Baladi is a researcher affiliated with the Ronin Institute and the Rite of Renaissance, specializing in structural reliability engineering, fatigue mechanics, and computational safety analysis for civil and mechanical infrastructure. FRAME-LINK v1.0.0 represents a contribution to the structural engineering community's capacity for quantitative, individual connection-level fatigue safety assessment — an engineering problem whose practical significance is consistently underestimated by structural assessment practice that remains focused on member-level global analysis while the governing failure physics operates at the scale of the connection detail.

His approach to FRAME-LINK reflects a commitment to physical rigor and conservative engineering practice: Paris–Erdogan fracture mechanics, Palmgren–Miner fatigue accumulation, and the Cornell reliability index as the primary analytical tools, with AI-assisted computational support in strictly bounded roles that enhance the engineering workflow without claiming epistemic authority over physical behavior that is, by its nature, governed by the laws of fracture mechanics rather than by statistical patterns in training data. He is reachable at gitdeeper@gmail.com.

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