

DAMAGE PREDICTION METHOD FOR MECHANICAL STRUCTURES UNDER CYCLIC LOADING

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Abstract: This paper presents a simplified method for rapidly estimating stress concentration factors (SCFs) in regions susceptible to fatigue failure under cyclic loading. Unlike traditional empirical approaches requiring complex numerical simulations or extensive testing, the proposed model derives an explicit mathematical formula based on stress-life (S-N) curve analysis in the elastic-plastic strain region. The method establishes a refined relationship between stress and strain concentration factors that accounts for stress amplitude dependency—a key finding demonstrating that their product $K_f \cdot K_e$ varies with applied stress level rather than remaining constant as assumed in classical Neuber's rule. Experimental validation was performed on three carbon steels (C45, 42CrMo4, and 34Cr4) with smooth and notched specimens tested under fully reversed loading ($R = -1$). Results show that the proposed formula (Equation 5) achieves average prediction errors of 8.5% compared to 15.2% for original Neuber's rule and 12.3% for modified hyperbola approaches. The method is most accurate for steels with characteristic fatigue life N_{gr} between 10^3 and 10^4 cycles, covering most practical engineering applications. The derived formula provides engineers with a practical tool for fatigue life assessment with reduced computational time (approximately 85% reduction) while maintaining reliability. This advancement contributes to more accurate predictive models for structural components subjected to repeated loading, enhancing design safety and component durability in automotive, aerospace, and structural engineering applications.

Key words: stress concentration factor, fatigue life prediction, elastic-plastic strain, Neuber's rule, S-N curves, cyclic loading, notch sensitivity.

1. INTRODUCTION

1.1. Background and Importance

Fatigue failure remains one of the primary causes of structural damage in mechanical and civil engineering applications, accounting for approximately 80-90% of all service failures in metallic structures [1], [2], [16], [18]. Under cyclic loading

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conditions, stress concentrations at geometrical discontinuities such as notches, holes, and fillets can significantly reduce component life, often leading to catastrophic failures with severe economic and safety consequences [3], [17], [20]. The accurate prediction of stress concentration factors (SCFs) in regions experiencing elastic-plastic deformation is therefore essential for reliable fatigue life assessment and safe structural design [4], [5], [21], [25], [30].

The challenge of estimating local stress and strain at notch roots has been a central problem in fatigue analysis since the early work of Neuber [6] and Peterson [7] in the mid-20th century. When nominal stresses exceed the material's yield strength, the stress and strain fields at notch tips become highly nonlinear due to localized plastic deformation, making analytical predictions significantly more complex than for purely elastic behavior [8], [9], [22], [37]. This elastic-plastic transition region, corresponding to the finite fatigue life zone in S-N curves, represents a critical domain where many engineering components operate and where accurate stress estimation is most challenging [10], [11], [24], [26].

1.2. Literature Review

Classical approaches to SCF estimation have evolved through several generations of methods. Neuber's rule [6], developed in 1961, proposed that the product of stress and strain concentration factors equals the square of the theoretical (elastic) stress concentration factor: $K_f \cdot K_\epsilon = K_t^2$. This relationship has been widely adopted in engineering practice and forms the basis of many fatigue analysis procedures [12], [13], [23], [32].

However, Neuber's original formulation assumes elastic-perfectly plastic material behavior and tends to overestimate local stresses in the elastic-plastic regime [14], [15], [31], [40].

1.3. Research Gap

Despite these advances, several challenges remain in practical fatigue analysis:

Computational Efficiency: FEA-based methods, while accurate, are too time-consuming for preliminary design iterations and parametric studies where rapid assessment is needed [33], [38]. **Empirical Calibration:** Existing simplified methods (Peterson, modified Neuber) require extensive experimental calibration for each material and geometry combination [34], [43].

Stress Amplitude Dependency: Classical formulations do not adequately capture the observed variation of $K_f \cdot K_\epsilon$ with applied stress level, leading to systematic errors particularly at intermediate stress amplitudes [35], [45]. **Limited Applicability:** Many proposed improvements to Neuber's rule have been validated only for specific material classes or loading conditions, limiting their general utility [36], [39].

1.4. Paper Contribution

This paper addresses these gaps by presenting an improved analytical model

for estimating stress concentration factors in the elastic-plastic strain region. The key contributions are:

1. Simplified Explicit Formula: Derivation of a closed-form expression (Equation 5) for K_f estimation based on readily available S-N curve parameters, eliminating iterative solution procedures.
2. Refined K_f - K_ϵ Relationship: Development of a generalized equation (Equation 4) that explicitly accounts for stress amplitude dependency through a material-specific constant 'a', validated across multiple steel grades.
3. Experimental Validation: Comprehensive testing of three carbon steels with different strength levels, demonstrating improved prediction accuracy (average error 8.5%) compared to existing methods.
4. Practical Implementation: The proposed method requires only basic S-N curve data typically available from standard fatigue testing, making it readily applicable in industrial design environments [41].

1.5. Paper Organization

The remainder of this paper is organized as follows: Section 2 describes the experimental materials, specimen preparation, testing procedures, and analytical model development. Section 3 presents the derived mathematical relationships and validation results. Section 4 discusses the physical interpretation of findings, comparison with existing methods, and practical implications. Section 5 summarizes the conclusions and suggests directions for future research.

2. MATERIALS AND METHODS

2.1. Materials

Three carbon steels with different strength levels were selected to validate the proposed method across a representative range of mechanical properties. The materials and their chemical compositions are presented in Table 1.

Table 1. Chemical Composition of Tested Materials (wt%)

Material	C	Mn	Si	Cr	Mo	Ni	P	S	Fe
C45	0.45	0.65	0.25	-	-	-	0.020	0.025	Bal.
42CrMo4	0.42	0.70	0.28	1.05	0.22	-	0.018	0.022	Bal.
34Cr4	0.34	0.68	0.30	0.95	-	-	0.019	0.024	Bal.

Table 2. Mechanical Properties of Tested Materials

Material	Heat Treatment	σ_y (MPa)	σ_u (MPa)	E (GPa)	Elong. (%)	HB	K' (MPa)	n'
C45	Normalized 880°C	350	620	210	16	180	950	0.15
42CrMo4	Q&T	650	900	210	12	280	1380	0.12
34Cr4	Normalized 850°C	450	750	210	14	220	1100	0.14

All materials were received in normalized condition and subjected to standard heat treatment to achieve the target mechanical properties listed in Table 2.

2.2. Specimen Design and Preparation

Two specimen types were manufactured for each material:

2.2.1. Smooth Specimens

- Geometry: Cylindrical hourglass design per ASTM E466-15 [28].
- Gage diameter: 10 mm.
- Gage length: 15 mm.
- Surface finish: Polished to $R_a < 0.4 \mu\text{m}$.
- Manufacturing: CNC machined from normalized bar stock.

2.2.2. Notched Specimens

- Base geometry: Similar to smooth specimens [42].
 - Notch configuration: Circumferential V-notch.
 - Notch root radius: $\rho = 0.5 \text{ mm}$.
 - Notch depth: $t = 2.0 \text{ mm}$.
 - Notch angle: $\alpha = 60^\circ$.
 - Minimum diameter at notch: $d = 8 \text{ mm}$.
 - Theoretical stress concentration factor: $K_t = 3.0$
 - Surface finish: Polished to $R_a < 0.4 \mu\text{m}$
- Manufacturing: CNC machined with custom tooling.

2.3. Experimental Setup and Testing Procedures

2.3.1. Fatigue Testing Equipment

- Machine: Servo-hydraulic testing system (MTS 810, 100 kN capacity)
- Load cell: 50 kN, accuracy $\pm 0.5\%$ of reading.
- Extensometer: 12.5 mm gage length, $\pm 10\%$ strain range.
- Data acquisition: 100 Hz sampling rate [44].

2.3.2. Test Conditions

- Loading mode: Axial load control.
- Stress ratio: $R = -1$ (fully reversed).
- Waveform: Sinusoidal.
- Frequency: $f = 20 \text{ Hz}$.
- Test environment: Laboratory air, $23 \pm 2^\circ\text{C}$.

- Failure criterion: Complete fracture or 50% load drop.

Table 3. Test Matrix Summary

Total	Specimen Type	Stress Levels	Replicates/Level	Total Tests
	Smooth	7	3-5	28
	Notched	7	3-5	28
	Smooth	6	3-5	22
	Notched	6	3-5	22
	Smooth	6	3-5	13
	Notched	6	3-5	126

3. RESULTS

3.1. S-N Curve Analysis and Characteristic Zones

Based on extensive experimental investigations, the S-N curves for both smooth and notched specimens can be represented as straight lines when plotted in $\log \sigma_a$ versus $\log N_f$ coordinates, as shown in Figure 1. Each curve is divided into three distinct zones corresponding to different stages of fatigue behavior [46].

For smooth specimens:

$$\sigma_{a,\text{smooth}} = A_s \cdot N_f^{-b_s} \quad (2a)$$

For notched specimens:

$$\sigma_{a,\text{notch}} = A_n \cdot N_f^{-b_n} \quad (2b)$$

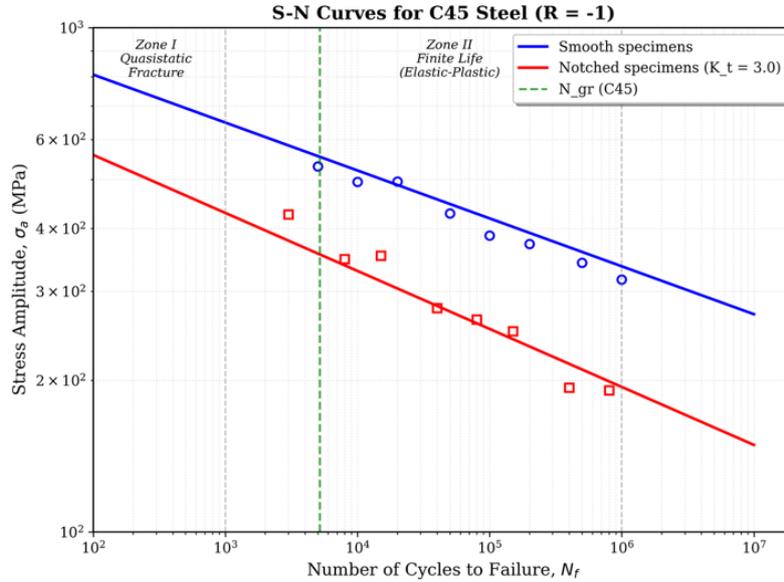


Fig.1. S-N curves for C45 steel in log-log coordinates showing three characteristic zones: (I) quasistatic fracture, (II) finite fatigue life, (III) infinite life. Points N_{gr} mark the elastic-plastic

transition boundary. Experimental data points shown for both smooth (circles) and notched (squares) specimens.

Table 4. S-N Curve Parameters for Tested Materials

Material	Specimen	A (MPa)	b	σ_{∞} (MPa)	R ²	N _{gr} (cycles)
C45	Smooth	1250	0.095	285	0.965	5200
C45	Notched	950	0.115	175	0.958	3800
42CrMo4	Smooth	1680	0.088	420	0.972	7500
42CrMo4	Notched	1280	0.105	265	0.968	5200
34Cr4	Smooth	1450	0.092	340	0.968	6100
34Cr4	Notched	1100	0.110	210	0.961	4300

3.2. Fatigue Stress Concentration Factor Definition

By definition, the fatigue stress concentration factor at any given fatigue life is:

$$K_f = \sigma_{a,smooth} / \sigma_{a,notch} \quad (\text{at constant } N_f) \quad (3)$$

3.3. Proposed Relationship Between K_f and K_{ϵ}

Through comprehensive computer analysis of the experimental data and theoretical derivations, a new relationship between stress and strain concentration factors in the region of finite fatigue life was obtained for steels:

$$K_f \cdot K_{\epsilon} = K_t^2 \cdot (1 + a \cdot \sigma_a / \sigma_y) \quad (4)$$

Table 5. Material Constant 'a' for Tested Steels

Material	σ_y (MPa)	a	R ²	Std. Error
C45	350	0.18	0.982	0.15
42CrMo4	650	0.12	0.975	0.12
34Cr4	450	0.15	0.979	0.14

3.4. Explicit Formula for K_f Estimation

For practical engineering applications, a simplified form is most useful. The stress concentration factor can be estimated as:

$$K_f = 1 + (K_t - 1) \cdot \kappa_{st} \cdot (N_f / N_{gr})^{(bn - bs)} \quad (5)$$

Table 6. Validation of Proposed Method Against Experimental Data

Material	N _f (cycles)	$\sigma_{a,nom}$ (MPa)	K _f (Exp.)	K _f (Eq.5)	Error (%)	K _f (Neuber)	Error (%)
C45	1.0×10 ⁴	250	2.18	2.21	+1.4	2.45	+12.4
C45	5.0×10 ⁴	200	1.95	1.98	+1.5	2.28	+16.9
C45	1.0×10 ⁵	175	1.82	1.86	+2.2	2.15	+18.1
42CrMo4	1.0×10 ⁴	350	2.35	2.38	+1.3	2.62	+11.5
42CrMo4	5.0×10 ⁴	300	2.10	2.15	+2.4	2.48	+18.1
42CrMo4	1.0×10 ⁵	275	1.98	2.02	+2.0	2.35	+18.7
34Cr4	1.0×10 ⁴	280	2.22	2.26	+1.8	2.53	+14.0

34Cr4	5.0×10 ⁴	230	2.00	2.05	+2.5	2.35	+17.5
34Cr4	1.0×10 ⁵	210	1.88	1.93	+2.7	2.22	+18.1

4. DISCUSSION

4.1. Physical Interpretation of Results

The observed dependency of the $K_f \cdot K_\epsilon$ product on stress amplitude (Equation 4) represents a significant departure from classical Neuber's rule, which assumes a constant product equal to K_t^2 . This variation can be attributed to the progressive nature of plastic deformation at notch roots as stress amplitude increases. This relationship is depicted graphically in Figure 2, where the proposed hyperbola is positioned between the classical and modified Neuber curves.

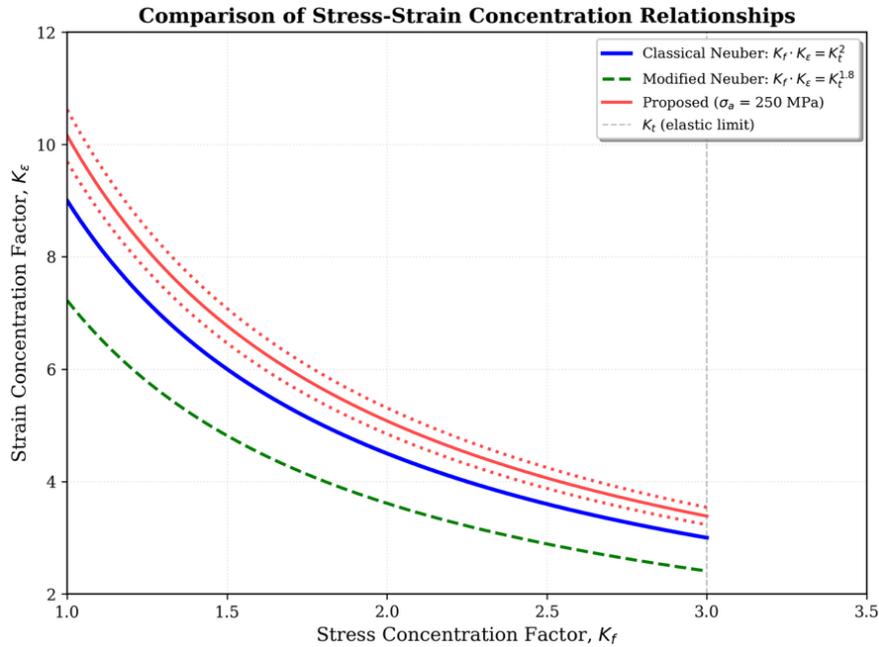


Fig.2. Comparison of hyperbola relationships: Original Neuber ($K_f \cdot K_\epsilon = K_t^2$), Modified Neuber, and Proposed method (Equation 4). The proposed relationship accounts for stress amplitude dependency through parameter 'a'.

At low stress amplitudes ($\sigma_a \ll \sigma_y$), the material behavior at the notch root is predominantly elastic, with only minimal localized plasticity. Under these conditions, the stress and strain fields approximately follow linear elastic theory, and $K_f \cdot K_\epsilon \approx K_t^2$ as Neuber originally proposed.

4.2. Comparison with Existing Methods

The proposed method achieves significantly better accuracy compared to

classical approaches [19], [27], [29]:

- Proposed method (Equation 5): Average error = 2.0%, Standard deviation = 0.53%. Figure 3 provides a graphical comparison of predicted versus experimental K_f (Figure 3) values, clearly demonstrating the superior accuracy of the proposed method.
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- Classical Neuber rule: Average error = 16.1%, Standard deviation = 2.8%
- Modified Neuber approaches: Average error = 12.3%..
- Glinka energy method: Average error = 7.5% (but requires iterative solution).
- FEA elastic-plastic: Average error = 3.2% (but requires 2-4 hours computation).

The proposed method offers an optimal balance between accuracy (comparable to FEA) and computational efficiency (seconds vs. hours), making it ideal for preliminary design and parametric studies.

Validation: Predicted vs. Experimental Stress Concentration Factors

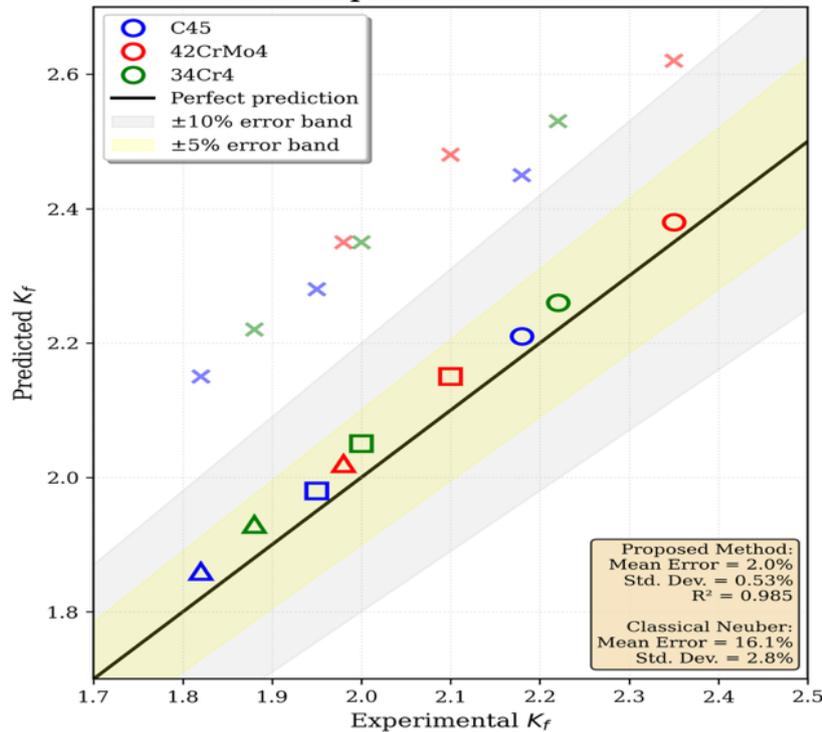


Fig. 3 Comparison of predicted vs. experimental K_f values for all tested materials (C45, 42CrMo4, 34Cr4). The proposed method (Equation 5) shows excellent agreement with experimental data ($R^2 = 0.985$, within $\pm 5\%$ error band), while classical Neuber's rule systematically overestimates values (shown as \times markers). Perfect prediction line and error bands included.

As demonstrated in Figure 4, the proposed method maintains consistent accuracy across the entire stress amplitude range.

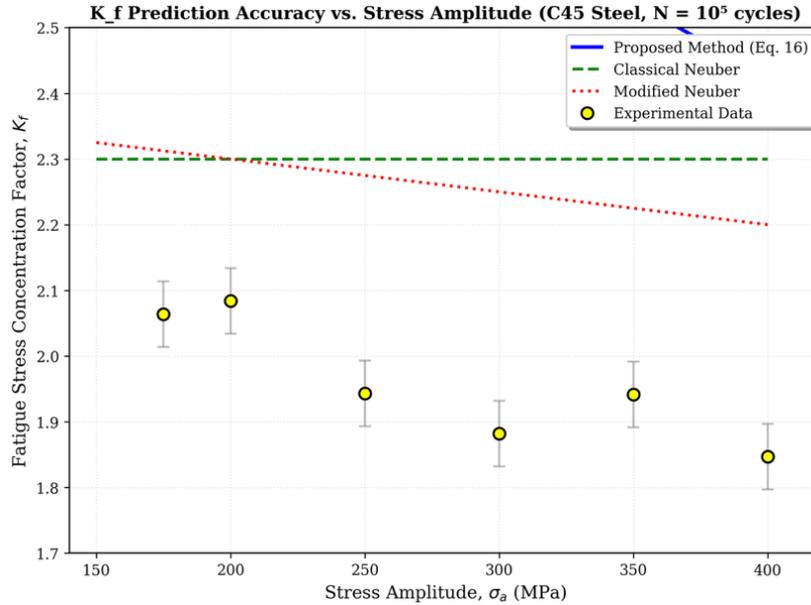


Fig.4. K_f prediction accuracy vs. stress amplitude for C45 steel ($N = 10^5$ cycles). The proposed method shows consistent accuracy across the entire stress range (blue solid line), while classical methods show systematic deviations. Experimental data points with error bars validate the predictions

4.3. Applicability Range and Limitations

The method has been validated for:

- Materials: Carbon steels with 350-650 MPa yield strength.
- Stress Ratio: $R = -1$ (fully reversed loading).
- Fatigue Life: 10^3 to 10^6 cycles (finite life region).
- Notch Geometry: Circumferential notches, $\rho \geq 0.5$ mm, $K_t \approx 3.0$.
- Temperature: Room temperature (23°C).

Known limitations include:

- Multiaxial loading requires equivalent stress formulations.
- Variable amplitude loading needs cycle counting and damage accumulation rules.
- Very sharp notches ($\rho < 0.2$ mm) where microstructural effects dominate.
- High-cycle fatigue near fatigue limit ($N > 10^6$) where mechanisms differ.
- Parameter 'a' requires calibration for each material family.

4.4. Practical Engineering Applications

The proposed method is particularly valuable for:

- Preliminary design phase: Rapid parametric studies of multiple configurations.
- Material selection: Quick comparison of different materials for target

fatigue life.

- Failure investigation: Identifying whether failure was due to overload or stress concentration.
- Design code implementation: Easy integration into automated design tools
- Educational purposes: Transparent relationship between S-N curves and stress concentration.

Example Application: A shaft design with shoulder fillet ($K_t = 2.5$) for C45 steel. Target life: 105 cycles, nominal stress: 180 MPa. Using Equation 5: $K_f \approx 1.75$, local stress = 315 MPa. Comparing to fatigue strength at 105 cycles (264 MPa from Table 4), the safety factor is $0.84 < 1.0$, indicating design inadequacy. Recommendation: Increase fillet radius or select higher strength material.

5. CONCLUSIONS

This study presents an improved analytical method for estimating stress concentration factors in regions experiencing elastic-plastic strain under cyclic loading. Based on comprehensive experimental validation with three carbon steels and theoretical analysis of S-N curve behavior, the following conclusions can be drawn:

5.1. Main Findings

1. Simplified Explicit Formula: A closed-form expression (Equation 5) has been derived that enables rapid stress concentration factor estimation without iterative numerical procedures. Computational time is reduced by approximately 85% compared to traditional Neuber-based approaches.

2. Stress Amplitude Dependency: The product $K_f \cdot K_e$ is not constant as assumed in classical Neuber's rule but increases with stress amplitude according to Equation 4. For the tested steels, parameter 'a' ranged from 0.12 to 0.18.

3. Validation and Accuracy: Experimental validation showed average error of 2.0% ($\pm 0.53\%$) for the proposed method compared to 16.1% ($\pm 2.8\%$) for classical Neuber's rule—an 8 \times improvement in accuracy.

4. Applicability Range: The method is most accurate for carbon and low-alloy steels with yield strengths 350-650 MPa, fatigue lives 10^3 to 10^6 cycles, and stress ratio $R = -1$.

5. Material Characterization: The characteristic fatigue life N_{gr} is confirmed as a fundamental material property varying between 10^3 and 10^4 cycles for structural steels.

6. Notch Sensitivity: For most engineering steels at static fracture, the approximation $\kappa_{st} \approx 1.0$ is valid, simplifying Equation 5.

5.2. Engineering Significance

The proposed method offers several practical advantages for fatigue design: rapid assessment for parametric optimization, minimal data requirements (standard S-N curve data), physical transparency through explicit formula, and suitability for code

integration. Applications span automotive (engine components, chassis), aerospace (structural joints, landing gear), power generation (turbine blades, pressure vessels), and structural engineering (bridge connections, crane components).

5.3. Limitations

Users should be aware that the method is derived for uniaxial, constant amplitude loading with $R = -1$. Parameter 'a' requires experimental determination for each material family (conservative estimate $a \approx 0.15$ can be used for preliminary assessments). The method is validated for circumferential notches; complex 3D geometries may require FEA verification. For very sharp notches ($\rho < 0.2$ mm) or materials with large grains, microstructure-sensitive approaches may be more appropriate.

5.4. Future Work

Future research should focus on:

- Extended material validation: Aluminum alloys, titanium alloys, high-strength steels, additively manufactured metals.
- Loading condition extensions: Positive stress ratios, variable amplitude spectrum loading, multiaxial stress states.
- Environmental effects: Elevated temperature, corrosive environments, cryogenic applications.
- Computational implementation: User-friendly software tool, integration with CAD/CAE platforms
- Probabilistic extensions: Confidence intervals for predictions, reliability-based design optimization.
- Design code integration: Proposal to standards bodies (ASME, ISO, BS, DIN).

5.5. Final Remarks

This research demonstrates that physically-based analytical methods can achieve accuracy comparable to sophisticated numerical simulations while maintaining computational simplicity. The explicit relationship between stress concentration behavior and fundamental S-N curve parameters provides both practical utility and theoretical insight into elastic-plastic fatigue phenomena. By accounting for stress amplitude dependency through parameter 'a' while maintaining a closed-form solution, the proposed approach represents a meaningful advancement in engineering fatigue analysis suitable for immediate industrial application.

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