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Published in:
Procedia Structural Integrity

DOI:
[10.1016/j.prostr.2025.11.019](https://doi.org/10.1016/j.prostr.2025.11.019)

Published: 01/01/2025

Document Version
Publisher's PDF, also known as Version of record

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Please cite the original version:
Ono, Y., & Remes, H. (2025). Non-local continuum damage mechanics-based crack growth modelling for high-performing steel structures. *Procedia Structural Integrity*, 75, 176-183.
<https://doi.org/10.1016/j.prostr.2025.11.019>

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Fatigue Design 2025 (FatDes 2025)

Non-local continuum damage mechanics-based crack growth modelling for high-performing steel structures

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Abstract

This study describes a non-local continuum damage mechanics-based model for crack initiation and growth modelling. The focus is on its application in high-performing welded structures, where crack initiation and short crack growth play an important role. The introduced model uses local stress-strain field and microstructure-dependent material units together with continuum damage analysis, allowing the same modelling principle used for initial geometry and following crack growth analysis, i.e. whole fatigue damage process from crack initiation to final failure. This modelling enables an explicit consideration of micro-scale geometry, residual stress conditions, and material mechanical properties to estimate fatigue life accurately. An application case using a mild notch geometry illustrates the evolution of local fatigue response during crack initiation and growth, offering insights into surface integrity effects on fatigue behavior. Also, examples of welded joints are also given to demonstrate the model's capability in estimating total fatigue life and $S-N$ curves.

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Peer-review under the responsibility of Dr Fabien Lefebvre with at least 2 reviewers per paper

Keywords: Continuum damage mechanics; crack growth; welded joint; fatigue life; surface integrity

1. Introduction

Advanced manufacturing technologies are rapidly developing and leading to the evolution towards high-performing welded structures across various industrial sectors, including offshore structures, ships, and bridges. For instance, innovations such as high-quality welding (e.g., advanced laser-arc hybrid welding) and post-weld treatments

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(e.g., peening methods) have gained prominence. The utilization of these technologies alters the fundamental mechanism for the fatigue strength of welded joints. Conventional welds often have crack-like imperfections such as sharp and deep undercuts, which influence the fatigue life predominantly through the propagation of long cracks [Maddox (1991)]. In contrast, in high-performing welds, the smoother weld geometry and the reduction in imperfection size results in higher fatigue strength compared to the conventional welds, as initiation and propagation of short cracks become longer [Weich et al. (2009), Tai and Miki (2014), Lillemäe et al. (2016), and Remes et al. (2020)]. Therefore, theoretical fatigue modelling of the initiation and propagation of short cracks is essential to estimate the beneficial fatigue strength of high-performing steel structures.

Among different methods, the linear elastic fracture mechanics (LEFM) approach is commonly used to model the crack growth process and fatigue life of conventional welds, where the propagation of long cracks predominates [Yamada and Nagatsu (1989) and Hobbacher (2016)]. However, applying LEFM directly to high-performing welds presents challenges [Remes et al. (2020)]. This is because short crack phases are heavily affected by local elastic-plastic response near the crack tip that results from microscale geometrical features, residual stress, and microstructure effects. Furthermore, assuming an initial crack size, which serves as the starting point for fatigue life calculations, is required in high-performing welds with smooth weld notches and small imperfections. Over a few decades, the modelling approach based on non-local continuum damage mechanics to link local stress-strain behaviour and fatigue damage process has been studied by, e.g., Chaboche (1988), Bhattacharya and Ellingwood (1998), Takagaki and Nakamura (2007), and Mikheevskiy et al. (2015). Lately, the basis of this approach has been leveraged to model the crack initiation and growth of high-performing welds, as demonstrated in Remes et al. (2012), Remes (2013), Remes et al. (2017), Al-Karawai (2021), and Ono and Remes (2024). This model relies on local stress and strain fields and the accumulation of fatigue damage within a representative volume element (RVE), depending on grain size statistics for arbitrary-shaped imperfections and various crack sizes. Thus, the method enables explicitly considering the effects of surface roughness, material mechanical properties, and residual stress. This model estimates fatigue life for all short crack initiation and short and long crack propagation, extending beyond fracture mechanics-based methods that require the assumption of initial crack size.

This paper aims to present a methodology of continuum damage mechanics-based modelling and its application to the analysis of short crack initiation and growth in high-performing structures. The methodology provides a detailed description of the modelling concept, the procedures for calculating the fatigue life, and simulation tools using finite-element methods. The application cases include a notch model and a weld model. The results of the estimated fatigue life for the weld model are compared to experimental data. After that, this study discusses the fatigue damage mechanism of high-performing structures by focusing on the change of local fatigue response during short crack growth.

2. Methods

2.1. Continuum damage mechanics-based modelling

Fig. 1 presents the concepts and methodology for fatigue life calculations grounded in non-local continuum damage mechanics. This process incorporates four computational steps to obtain the fatigue life up to a specific crack length.

Step 1. Fatigue effective stress and strain

This model utilizes the local stress and strain field within the representative volume element (RVE) for arbitrarily shaped small imperfections and various crack lengths. The stress components in front of an imperfection or a crack tip are averaged over the RVE's length. In this framework, these averaged stress components are termed "fatigue-effective stress ($\sigma_{\text{eff},ij}$)". The RVE length is constant, defined by the grain size at a 99% probability level ($d_{99\%}$). This definition follows the Hall-Petch relation for material strength and grain size characteristics, considering its statistical distribution proposed in the previous study [Lehto et al. (2014)], providing a homogenized and averaged representation of material strength and behaviour.

$$\sigma_{\text{eff},ij} = \frac{1}{d_{99\%}} \cdot \int_0^{d_{99\%}} \sigma_{ij} dy \quad (1)$$

Then, the corresponding fatigue-effective strain ($\varepsilon_{\text{eff},ij}$) is deduced using the defined fatigue-effective stress for a cycle k and the elastic-plastic material properties of the material.

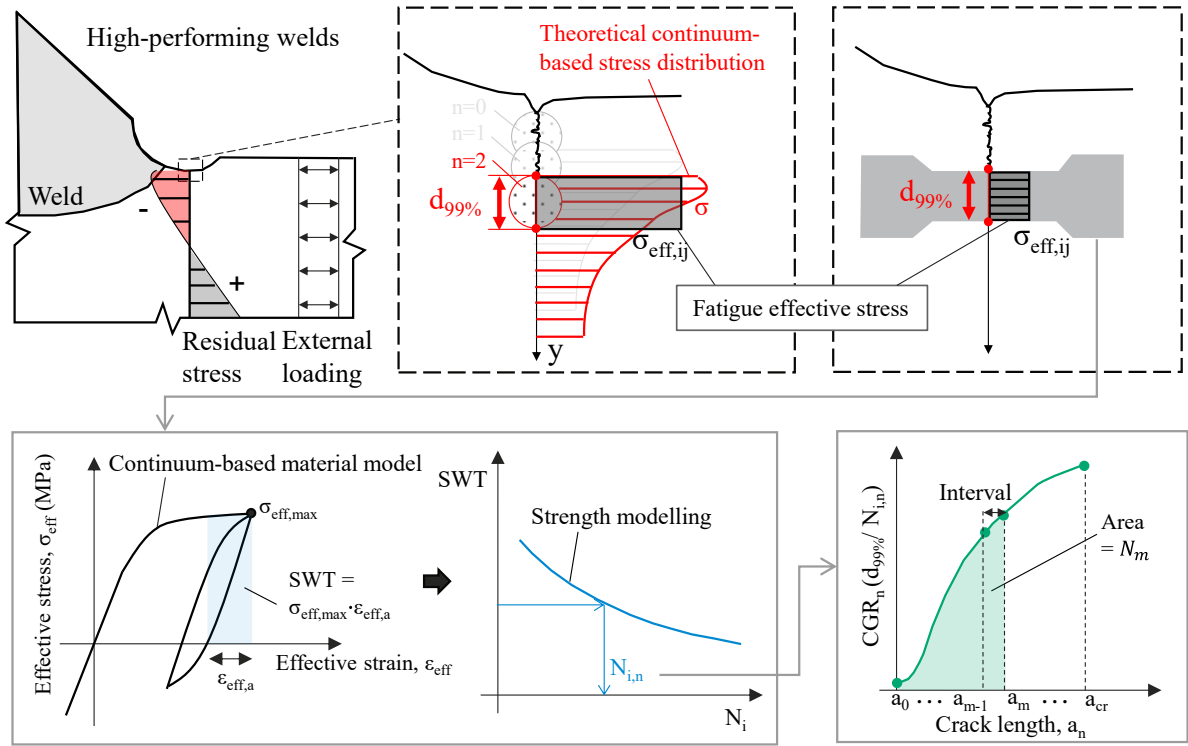


Fig. 1 Non-local continuum modelling of fatigue damage process based on grain-based homogenization of theoretical stress distribution, adapted from Ono and Remes (2024).

Step 2. The number of cycles causing fatigue damage of the RVE

The total number of cycles ($N_{i,n}$), developing fatigue damage of RVE length, can be calculated using the strain-life relationship with the mean stress correction, the Smith-Watson-Topper (SWT) equation.

$$\sigma_{eff,max} \cdot \epsilon_{eff,a} = \frac{\sigma_f'^2}{E} (2N_{i,n})^{2b} + \sigma_f' \epsilon_f' (2N_{i,n})^{b+c} \tag{2}$$

where $\sigma_{eff,ij}$ is the 1st principal fatigue effective maximum stress, $\epsilon_{eff,ij}$ is the fatigue-effective strain amplitude, and the parameters of σ_f' , ϵ_f' , b , and c are the Coffin-Manson fatigue strength coefficients and exponents.

Step 3. Crack growth curve

In the continuum damage mechanics, the continuum damage by the load cycle k is expressed as $D_k = 1/N_{i,n}$. The length of crack growth for the load cycle k (Δa_k), within RVE, is assumed to be linearly proportion to the continuum damage, i.e., Δa_k is equal to 0 when D_k takes 0 and Δa_k is equal to $d_{99\%}$ when D_k takes 1.0. Under this concept, the crack growth rate (CGR_n) is expressed in the form of (3).

$$CGR_n = \frac{\Delta a_k}{N=1} = \frac{d_{99\%}}{N_{i,n}} \tag{3}$$

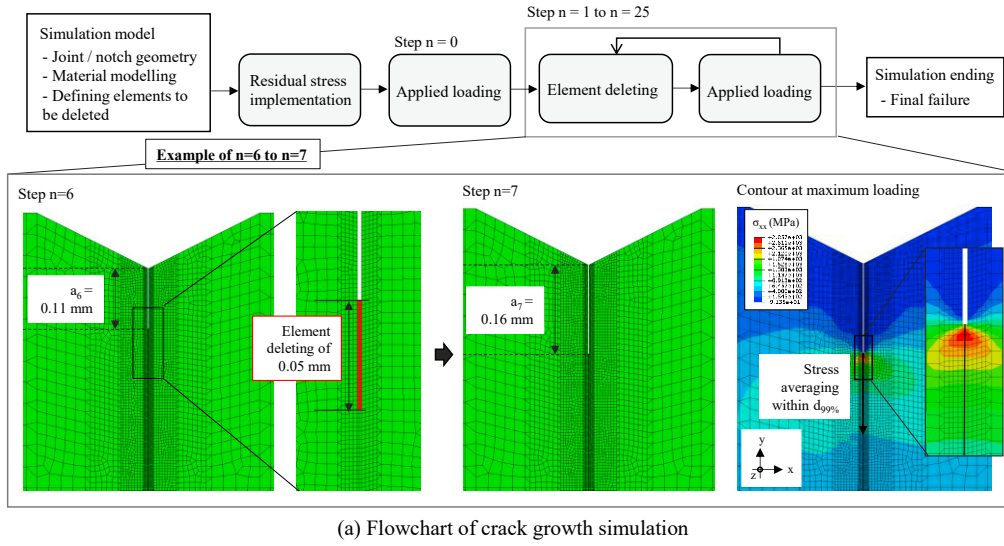
Step 4. Fatigue life calculation

The calculation process, detailed from Step 1 to Step 3, is applied to multiple crack lengths, ranging from a_0 (0 mm) to a_{cr} (critical crack length). The resulting crack growth curve, the relationship between CGR_n and a_n , is utilized to determine the fatigue life at a given crack length (N_m), as expressed in (4). By integrating the crack growth curve from 0 to a_{cr} , the total fatigue life can be computed.

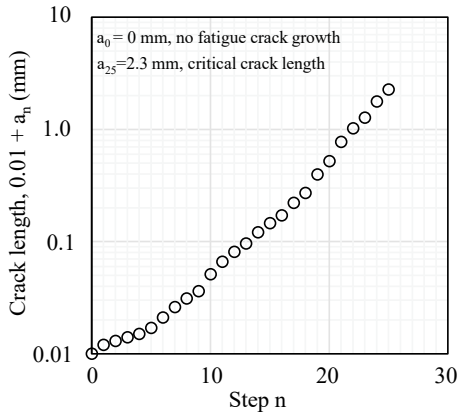
$$N_m = \int_0^{a_m} \left(\frac{1}{CGR_n} \right) da \tag{4}$$

2.2. Numerical simulation example for a notch model

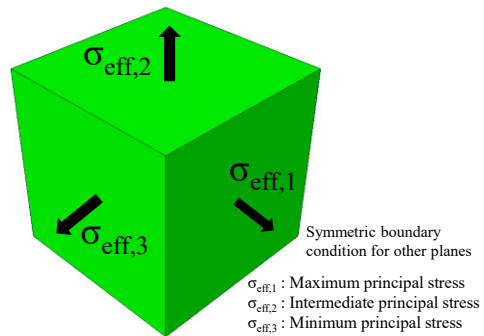
Fig. 2 presents an example of finite element (FE) simulations used to determine fatigue effective stress and strain [Ono and Remes (2024)], referred to as *Step 1* in Section 2.1. The simulation model is a notch model that is a smooth notched plate containing a small imperfection with 40 μm in width and 10 μm in depth. The material under analysis is S690QL, which has a plate thickness of 6 mm and the nominal yield strength of $f_y = 832$ MPa. The model exhibits a compressive residual stress field near the imperfection in loading direction, characterized by stress levels of $-0.5f_y$ up to a depth of 0.5 mm. Beyond this depth, the stresses gradually shift to tensile residual stress side through the plate thickness. The material model is a combined non-linear isotropic-kinematic hardening model, known as Voce-Chaboche’s model. The hardening layer (HL) near the surface is systematically accounted for in the following segments: HL1 ($\sigma_y = 1154$ MPa and $d_{99\%} = 5$ μm) up to 50 μm depth, HL2 ($\sigma_y = 952$ MPa and $d_{99\%} = 6$ μm) from 50 to 100 μm depth, HL3 ($\sigma_y = 811$ MPa and $d_{99\%} = 8$ μm) from 100 to 200 μm depth, and BM ($\sigma_y = 745$ MPa and $d_{99\%} = 10$ μm) beyond 200 μm depth. Here, σ_y refers to the yield strength at zero plastic strain for Voce-Chaboche’s model. A uniaxial cyclic loading ($\Delta S = 0.36f_y$ and $R = 0.23$) is applied at the end of the notch model. To model the crack growth in FE simulation, the element deletion method built in Abaqus is employed, a method previously utilized in some studies, e.g., [Al-Karawai (2021) and Banno et al. (2021)]. Element deletion method allows for the deactivation of specific elements as a step, as similar to loading and boundary conditions. Thus, this approach achieves a continuous,



(a) Flowchart of crack growth simulation



(b) Crack length at each step



(c) Continuum-single element model (CSEM)

Fig. 2 An example of FE simulation procedure and tools to determine fatigue effective stress and strain for a notch model, adapted from Ono and Remes (2024).

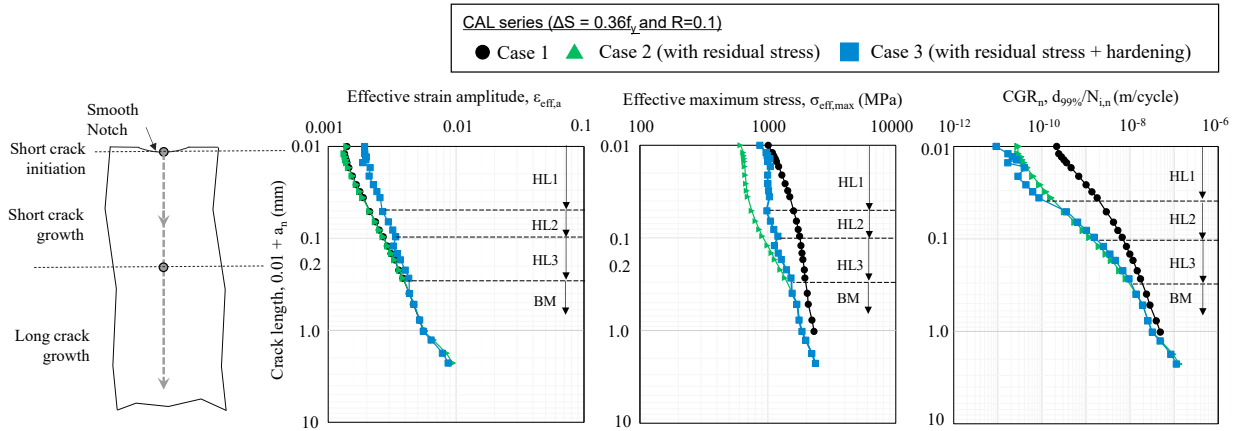


Fig. 3 Estimated local fatigue response and crack growth rate, modified from Ono and Remes (2024).

step-by-step crack growth simulation from short crack initiation to final failure within a single FE model. The single model incorporates multiple sets of element deletion and loading steps. For instance, as shown in Figs. 2 (a) and (b), certain elements along the known crack path are manually pre-defined prior to the crack growth simulation. The example defines 26 steps, ranging from steps $n = 0$ to $n = 25$. At step $n = 0$, the model exists without fatigue crack growth, and a crack length is defined as $a_0 = 0 \mu\text{m}$. At step $n = 25$, the crack reaches a critical crack length of $a_{cr} = 2.3 \text{ mm}$, which corresponds to nearly full cross-sectional yielding at maximum loading. It should be noted that the y -axis in Fig. 2 (b) is adjusted to start at 0.01 mm for visualization purposes in the logarithmic scale graph, thereby avoiding $a_0 = 0 \text{ mm}$. For simplicity, the increment intervals of crack length do not remain constant but vary relative to the crack length. In this example, intervals start at 1 to 2 μm in the beginning of crack growth, then expand from 5 to 25 μm up to a 0.1 mm crack size, and gradually increase further from 25 to 250 μm until reaching the critical crack length. Using finer intervals at several short crack lengths aims to accurately capture local stress and strain states and their changes, which significantly affect the fatigue life estimation for high-performing welds. During each step, the loading history is always applied to average the stress components over the RVE length for calculating fatigue effective stress. Strain amplitudes for these averaged stresses are determined using a separate model known as the continuum-based single element model (CSEM) [Garcia (2020) and Niraula et al. (2024)], shown in Fig. 2 (c). The input load for CSEM consists of the history of averaged principal stresses. The primary objective for CSEM is to derive the fatigue effective strain corresponding to the fatigue effective stress based on the defined elastic-plastic material model. Therefore, this approach ensures to follow the stress-strain behavior and Hooke’s law.

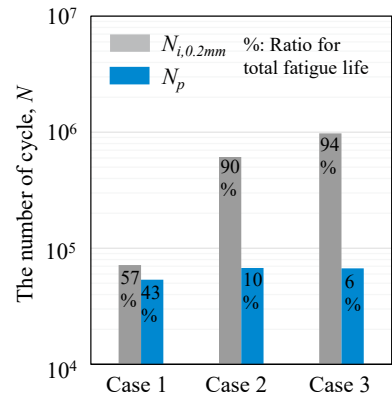


Fig. 4 Estimated fatigue life, adapted from Ono and Remes (2024).

3. Results

3.1 Numerical simulation result example for a notch model

Fig. 3 displays the simulation outcomes for the notch model, highlighting how different surface conditions affect the fatigue damage process during short cracks [Ono and Remes (2024)]. The cases incorporate factors like residual stress and hardening layer sequentially. The results are broken down into effective strain amplitude, effective maximum stress, and crack growth rate as functions of crack length. The plots correspond to the results calculated after each modelling step in Fig. 2 (b). In Fig. 3 (a), Cases 1 and 2 show that the residual stress field does not alter the effective strain amplitude. In contrast, Case 3 reveals an increase in the effective strain amplitude due to the hardening

zones compared to Case 2, as the stress-strain behavior remains nearly elastic during short crack periods. Fig. 3 (b) presents a reduction in the effective maximum stress due to compressive residual stress, with a smaller reduction observed in hardening zones. The decrease of crack growth rate is noticeable only up to a crack length of 0.3 mm, as shown in Fig. 3 (c), despite the introduction of high compressive residual stress until a depth of 0.5 mm. For short cracks, the hardening zones increase the effective strain amplitude and maximum stress compared to non-hardening cases, but enhanced crack initiation time resulting from higher hardness (smaller grain size, higher yield strength) ultimately reduces the crack growth rate.

Fig. 4 summarizes how variations in the damage process zone influence fatigue life estimation. $N_{i,0.2mm}$ represents the fatigue life for short crack initiation and propagation up to a crack length of 0.2 mm [Ono and Remes (2024)]. N_p denotes the long crack propagation life from 0.2 mm to final failure, typically applicable range of linear elastic fracture mechanics for conventional welded joints. Fig. 4 illustrates the notable improvement in fatigue life from Case 1 to Case 3, primarily due to the significant extension of $N_{i,0.2mm}$, and a minor extension of N_p . This shows that compressive residual stress greatly enhances crack initiation and propagation life, particularly in the short crack regime, by reducing mean stress and delaying the crack growth rate. The work hardening layer significantly boosts $N_{i,0.2mm}$ from Case 2 to Case 3, linked to crack growth retardation through beneficial mean stress effects and high material strength, despite increased notch sensitivity leading to higher effective maximum stress and strain amplitude.

3.2 Applications to estimating fatigue life of high-performing welded joints

Fig. 5 provides examples of applying the method to high-performing welds in both as-welded and high-frequency mechanical impact (HFMI)-treated conditions [Remes et al. (2020) and Ono and Remes (2024)]. The estimated fatigue life results are compared with experimental total fatigue life and the design FAT values recommended by the International Institute of Welding (IIW) [Hobbacher (2016) and Marquis and Barsoum (2016)]. Fig. 5 (a) exhibits different cases of weld geometry models with the high-performing butt welds (Case 1 and Case 2) and the conventional butt-weld (Case 3). These models apply the HAZ material property of weld notch for the whole fusion zone to model the fatigue life of short crack initiation and growth, and the base plate property for the other zones. The results indicate that the estimated $S-N$ curves for Case 1 and Case 2 are significantly higher than for Case 3, aligning closely with the experimental $S-N$ data points. Additionally, the estimated $S-N$ slope from the method corresponds well with experimental data, showing shallower slope values compared to Case 3 and the design $S-N$ slope for the conventional weld. For HFMI-treated joints, the model considers not only the geometry effect but also the residual stress and work hardening effects. The IIW shows an improved FAT class, with FAT160 suggested for non-load carrying cruciform joints made of S690QL at $R = 0.23$, resulting from as-welded FAT80 plus 6 class. As shown in Fig. 5 (b), the estimated fatigue life aligns well with the FAT class, serving as the lower bound for large experimental datasets from various studies. Consequently, the method utilizing non-local continuum mechanics theory and microstructure-dependent

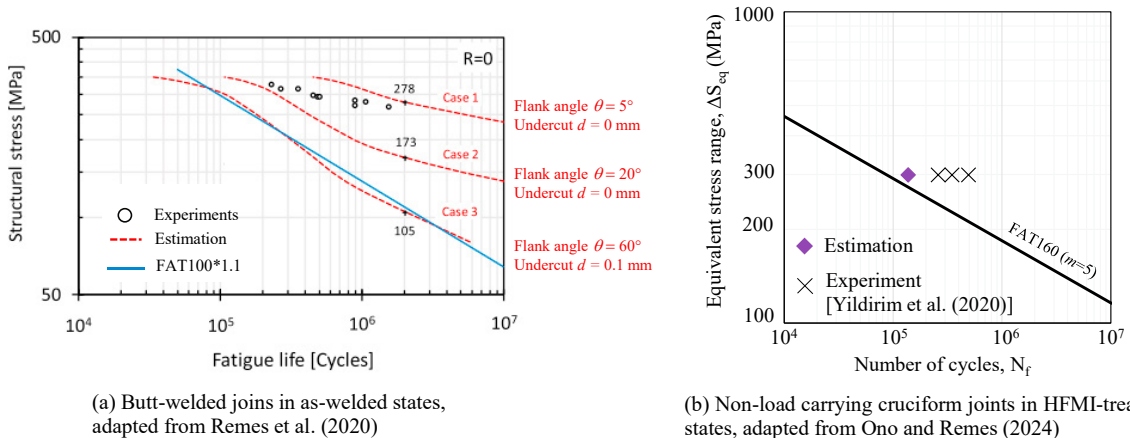


Fig. 5 Fatigue life estimation for high-performing welded joints.

RVE effectively estimates enhanced fatigue strength by modelling short to long crack periods and surface integrity effects on fatigue behavior.

4. Discussions

With the rapid advancement of modern manufacturing technologies, there is a significant need for precise phenomenological modelling of fatigue strength and behavior for high-performing structures. Previous experimental studies indicate that the ratio of crack initiation life at small crack lengths (e.g., 0.2 mm depth) to total life can be as high as 80% for high-performing welds, compared to 40% for conventional welds, e.g., [Weich (2009) and Tai and Miki (2014)]. This shows a fundamental difference in the fatigue physics (i.e., whether short or long cracks are dominated) and the importance of short crack modelling, including surface integrity effects, such as residual stress, microscale geometry, and microstructure effects. This paper presents the methodology and simulation procedure for fatigue life modelling using non-local continuum damage mechanics theory and microstructure-dependent RVE for high-performing welds, along with relevant application examples.

This modelling approach leverages the local stress-strain field and the local damage accumulation within the RVE for various crack lengths. Thus, it explicitly accounts for surface roughness, imperfection, residual stress conditions, and material/microstructure effects. As an example, Section 3.2 provides observations regarding the effects of compressive residual stress and work hardening on the different phases of short cracks and long cracks. The results demonstrate that the compressive residual stress and work hardening significantly extend fatigue life, particularly during short crack phases until a crack length of 0.2 mm. This finding aligns with experimental observations where retardation in CGR is mainly seen in small cracks up to 0.3 mm in HFMI-treated joints made of high-strength steels [Mori et al. (2014)]. Consequently, the model provides a quantitative analysis of surface integrity effects on fatigue behavior and strength in high-performing welds, addressing an area where knowledge is typically limited.

Fatigue test data for high-performing welds have demonstrated greater fatigue strength compared to existing design classes of conventional welds, along with shallower $S-N$ slopes observed as the result of extended short crack periods [Weich et al (2009), Tai and Miki (2014), Lillemae et al. (2016), and Remes et al. (2020)]. Section 3.3 includes comparisons of estimated fatigue life/ $S-N$ curves with experimental $S-N$ data for both as-welded and HFMI-treated conditions. The method encompasses the crack initiation and short crack growth, resulting in estimating the higher fatigue strength and an increase in the $S-N$ curve slope value, as shown in Fig. 5 (a). For HFMI-treated joints, the estimated fatigue life is consistent with the recommended design FAT class, see Fig. 5 (b). This highlights the importance of modelling initiation and growth of short cracks, alongside the surface integrity effects, in determining the total fatigue life. Consequently, the non-local continuum mechanics-based modelling has high potential to define $S-N$ master curves for high-performing welds, accounting for varied engineering conditions such as geometry, residual stress, and material effects as modelling input parameters.

5. Conclusions

This paper outlines the methodology for calculating the fatigue life of high-performing welds, employing the non-local continuum mechanics theory and microstructurally dependent material unit. Some examples of analysis results for a notch model and weld model are presented to showcase the method's capability to clarify the physical role of surface integrity and effectively model total fatigue life and $S-N$ curves. The main summary is written here.

- The crack growth modelling approach, grounded in non-local continuum damage mechanics and microstructure-dependent representative volume element, is well suited for analyzing the fatigue life of high-performing welds, where short crack initiation and propagation periods constitute a significant portion of total fatigue life.
- This approach offers a deeper insight into the influence of surface integrity, such as micro-scale geometry, residual stress, and material microstructure, on the fatigue behavior of high-performing welds.

Acknowledgements

This research was funded by the CaNeLis project from Business Finland with grand No. 3409/31/2022. The financial support is greatly appreciated.

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