Chapter

Advances in Fatigue Prediction Techniques

Sachin Kumar and Vidit Gaur

Abstract

Fatigue is the prevalent mode of failure in engineering components made from metals. It occurs when the component is undergone fluctuating stresses. It leads to failure in metal structures because of damage accumulation. Therefore fatigue analysis of these structures is vital to ensure service reliability during the real operation. Among various simulation tools available to determine the fatigue life and mechanical behavior of metals and metallic components, the Crystal Plasticity Finite Element Method (CPFEM) has gained wide attention to analyze the microstructural attributes. Owing to the versatility of CPFEM in analyzing the fatigue properties of various metals and alloys, this chapter is aimed to examine and document the state-of-the-art research outcomes linked to fatigue behavior using CPFEM tool. The CPFEM is expected to accelerate the research progress to discover novel metals and alloys with better fatigue properties. For structural welds, estimating fatigue life depends on the material characteristics, object geometry, and applied loads. An in-depth analysis of stress concentrations across the affected areas of welds is vital for calculating fatigue response.

Keywords: crystal plasticity, fatigue life estimation, metallic structures, finite element method, weld sections

1. Introduction

It is well-documented that most of the failures in metallic components are because of fatigue. This makes it vital to analyze and understand the physics behind the fatigue failure and underline a relationship to minimize the chances of failure [1]. Estimation of material fatigue based on multiple experimentation and prediction can have a major role in safe and reliable mechanical design [2]. Several researchers have added their massive effort to devise sound and practical methodologies for fatigue prediction and assess mechanical structures' safety under cyclic mechanical loading [3–5]. It has been affirmed that an accurate forecast of fatigue life is complicated because one must consider several variables to avoid the catastrophic failure of engineering structures while in service [6]. The accuracy of fatigue prediction models is largely based on the capability to predict and model damage under non-zero superimposed mean stresses, range for multi-axiality across the stress regions, and concentration [7]. In case of cyclic and arbitrary loading, it is pretty cumbersome for predicting the fatigue properties because the damage is reliant on major stress components and their deviations while the loading [7].

2. Fatigue of welded sections

When we talk about the welded structure, the analysis of fatigue properties becomes even more critical. Whether solid-state or fusion [8–15], the welding processes can be considered the most widely used joining method to fabricate metallic structures, components, bridges, cranes, low and heavy-duty machines, etc. Several of these are designed and developed to have sustainability for a more extended period under fatigue loading. Typically in a welded component, the fatigue failure occurs either across root or toe of weld. Hence this becomes critical to align the design consideration to avoid premature failure under fatigue loading without incurring any noticeable cost. An initial assessment of the actual fatigue life may facilitate designers for obtaining objectives mentioned above.

Current industries put their massive effort into remote design, analysis, and validation of the structural/welded components, followed by their finite element analysis (FEM) to cater the future requirements [16]. This eliminates the time and cost involved in developing and test expensive pre-fabricated prototypes. The use of FEM also facilitates reducing cycle time and expediting inclusion to production sequence. This does also facilitates quick product development, faster launching into the external market. However, remote design and development of components face many challenges, some of which will be discussed in the forthcoming paragraphs.

As we know, that under fatigue loading, the structure or weld section undergoes permanent failure. The estimation of fatigue can be comprised of initiation of cracks and their propagation until final failure. The fatigue process is often found to originate across the stress concentration region, for example, across the weld toe. Nucleation cum spread of fatigue crack is measured based on the magnitude of stress across the favorable crack planes. Society of Automotive Engineers (SAE) has provided an easy information flow chart to determine and analyze stress and fatigue (**Figure 1**). Herein the structure geometry, material properties, and load profile are the significant variables to identify the fatigue life of a component. Usually, the weld joints are the weakest section in a structure, and fatigue failure is most likely to occur across these regions. Therefore to avoid the material failure under fatigue action, the designer needs to establish a relation to calculate the fatigue of structure and weld sections accurately.

In a review paper, Fricke [18] described various techniques to predict the fatigue life for seam welds. Niemi [19] and Fricke [20] covered various recommendations in context to analyze the fatigue behavior of weld joints. The importance

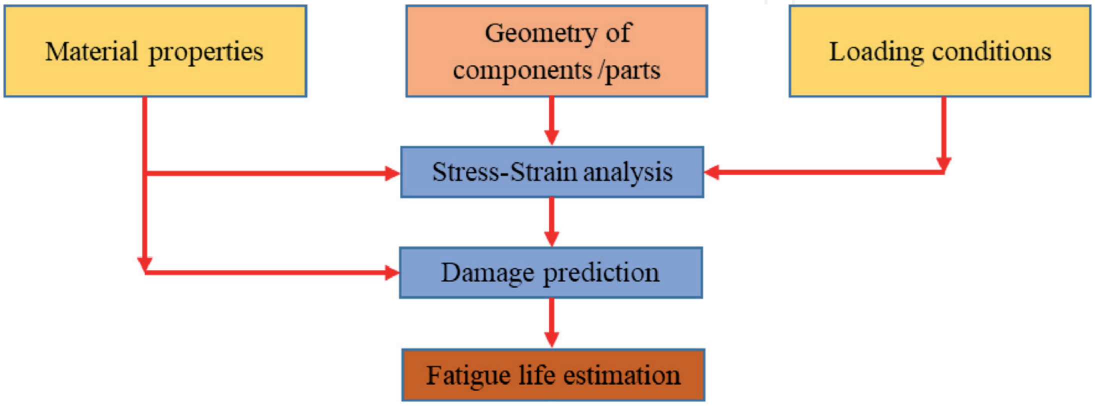


Figure 1.
Stages of stress and fatigue analysis [17].

of analyzing fatigue behavior of structures and weld sections can be understood by the fact that several national and international organizations such as the American Society of Mechanical Engineers (ASME), the International Institute of Welding (IIW), and the Society of Automotive Engineers (SAE), etc. are working round the clock to establish standard procedures and guidelines for determining the fatigue properties of weld joints. Various design guidelines and multiple updates have been proposed by the IIW on "recommendations for the fatigue design of welded components and structures". Various standard procedures are available for determining the fatigue properties of weld sections as per the assessment criterion and requirement of stress –strain data (**Figure 2**).

Previously, several models such as stress and strain-based models [21, 22], Critical plane models [23, 24], Enclosed surface models [25], and Integral type models [26], etc. have been used to predict fatigue properties of structural

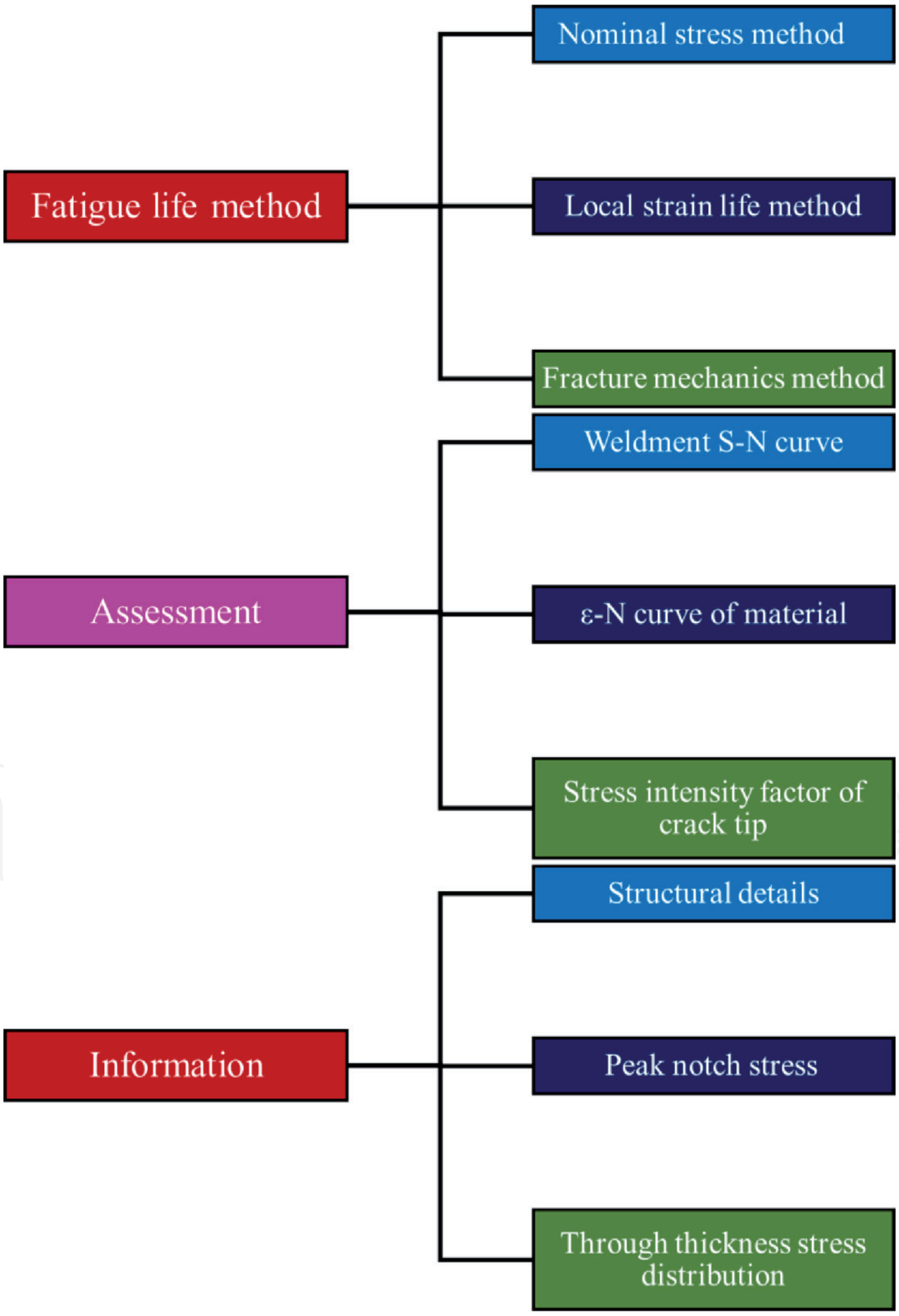


Figure 2.
Variables for fatigue life prediction.

components, however, could not estimate the fatigue properties accurately. The fatigue life predictions based on the application of empirical models (Basquin law, Miner's rule, Goodman diagram) taking into account the macroscopic mechanical fields are structure-oriented methods and therefore material-specific; thus, they do not account for the stochastic fatigue behavior due to the microstructural variabilities. Recently a methodology to predict the fatigue property of metal structures is gaining increasing acceptance and is known as CPFEM. The CPFEM can provide insights, and eventually, predictions of the fatigue behavior and variability of metallic materials become easier. CPFEM is also helpful to accelerate the development of new alloys with improved fatigue performances. While using the CPFEM, the advantage is that the fatigue predictions are much closer to the actual failure phenomenon and thus realistic. On the other hand, they require significant computational time and material intrinsic parameters that are difficult to measure experimentally. The accuracy of such simulations is strongly dependent on the synthetic microstructures generated through mathematical scripts or EBSD data. The CPFEM can provides insights and eventually predictions of the fatigue behavior and variability of metallic materials becomes easier. CPFEM is also helpful to accelerate the development of new alloys with improved fatigue performances.

3. Crystal Plasticity

Crystal plasticity (CP) is known as a fundamentally multi-dimensional approach beginning at the atomic level (dislocation cores) across sub-structural dislocation engagements in a single grain and up to the macroscopic mechanical behavior of the material. The multi-scale specialty and extensive research status of CP allow scientists and engineers to concentrate on different methodological domains. Plastic slip can be regarded as the utmost common plastic deformation mechanism in crystalline solids and metals. Typically, the slip system is found across the pre-established directions and planes in the form of plastic shearing, which is taken care of by the atomic arrangement at a regular crystal structure. The constitutive equations, theories, and mechanisms are derived keeping in mind the deformation characteristics of the materials on meso and micron levels. It derives the significant alteration of crystal plasticity from classical plasticity models for computational analysis. The hypothesis is derived much ahead in context to the continuum mechanics, stress fields, and other essential variables. For single and poly-crystals, the inelastic deformation models are successfully obtained and promoted the researchers to apply the crystal plasticity models for predicting the fatigue fracture and damage analysis. Besides, the freedom to apply various empirical formulas at the scale level permits solicitation of continuum dislocation simulations for determining crack initiation and propagation behavior [27].

4. Mechanism of dislocation slip: physical aspects

Crystals have different structural arrangements of atoms (**Figure 3**). The directions and planes are determined as per the Miller indices with reference to the unit cell edge vectors e_i. The slip plane m_g and direction s_g in FCC crystal are shown in **Figure 4**. Equivalent families of directions and planes for an FCC are depicted in **Figure 4**. For hexagonal crystals, four indices are often noticed to permit permutations when referring to families, one index along each possible edge direction, being the last one the height c direction, **Figure 3**. The FCC arrangement (**Figure 4a**) has

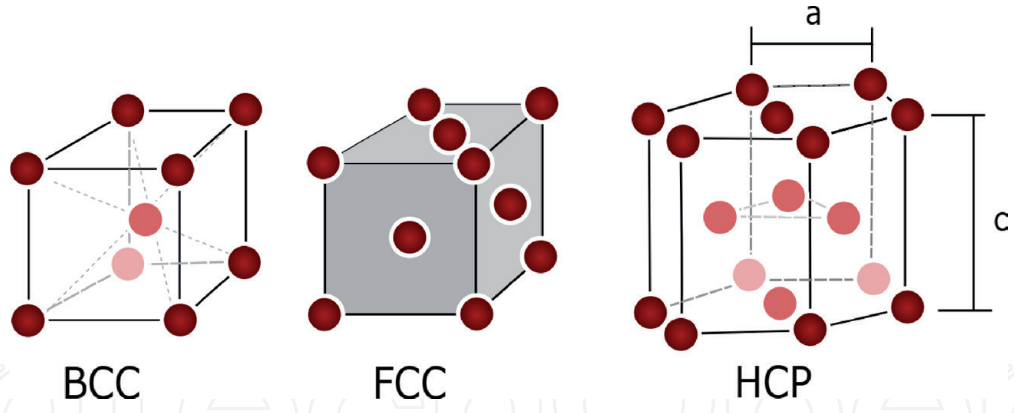


Figure 3.
BCC = body-Centered cubic. FCC = face-Centered cubic. HCP = hexagonal close-packed. The form ratio for HCP is c/a, ideally c/a = 1.632, but for example, cadmium has c/a = 1.886 and berilium has c/a = 1.586 [28, 29].

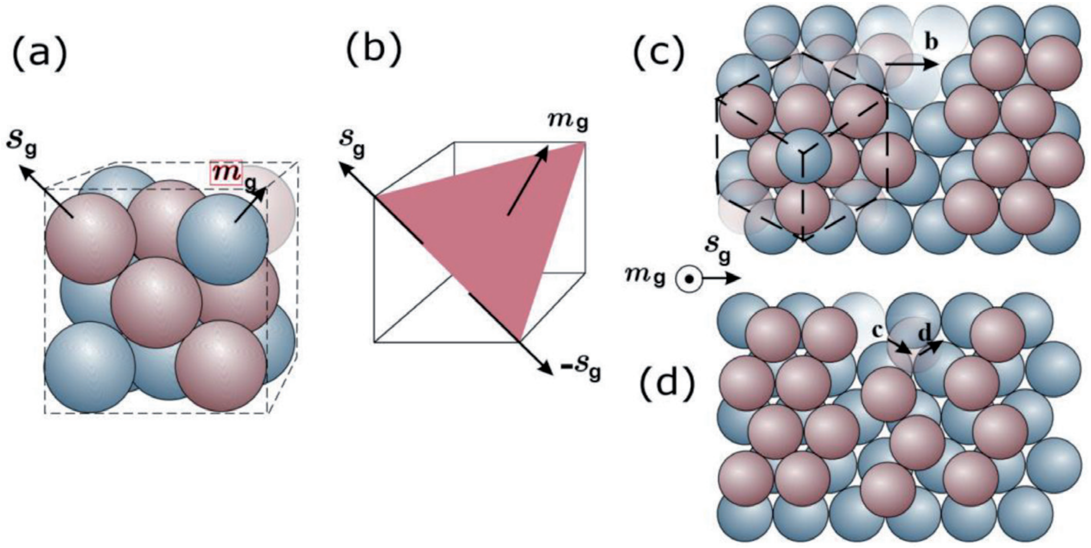


Figure 4.
(a, b) Slip plane m_g and direction s_g in a FCC crystal. (c) Total dislocation in a FCC. (d) Partial dislocation in a FCC lattice, where the dissociation is given as $b = c + d = 1/6[\bar{1}\,2\,\bar{1}] + 1/6\,[\bar{2}\,11]$. Adapted from [28–30].

atoms at the vertices and center of the faces of an ideal hexahedron, resulting in a dense arrangement, and typical of especially ductile materials (e.g., Al, Cu, Au, Ag). FCC crystals have four {111} planes with three <110> directions in each plane, therefore in total have 12 slip systems, referred to as {111} <110>. Body-centered cubic crystals (BCC), (Cr, Fe, W) have atoms in the vertices and in the center of the hexahedron, and usual slip planes in the {110} family and direction < $\bar{1}11$> (secondary slip systems may become active for some materials and temperatures).

Dislocations are considered as crystal defects that were originated because of the missing of one or few atoms from the regular atomic hierarchy (**Figure 4c** and **d**). The slip is formed due to the sliding of several dislocations, eased by the stress field developed around them. This glide does not occur simultaneously across all the grain but takes place in a worm-like movement. This gliding emphasizes the movement of dislocation concerning a plane that may have both: Burger vector b and its line (**Figure 4c**). The dislocations and their associated local stress fields interact; blocks or auxiliary ease their movement. A slip band is formed because of the accumulation of these multiple displacements. The slip bands may be visualized across the regions of polished samples that might have undergone severe plastic deformation previously.

5. Crystal plasticity model

Even though multiple models of crystal elasto-plasticity and elasto-visco elastoplasticity have been added in several kinds of research to analyze the plastic distortion and fatigue fracture of various structures; there is an absence of in-depth and systematic documentation of the process mechanism involved and essential outcomes.

Nearly in the mid- 1980s, based on extensive experimentation and analysis, Panin et al. [31, 32] added a hypothesis to analyze a deformed material as a complex arrangement or multi-scale system. It proposed to originate a novel theme based on solid-state physics, also known as physical meso-mechanics. In other studies, Panin et al. [33, 34] documented the concepts involved and typical approaches for physical meso-mechanics. These studies were based on a classical assumption of considering a deformed solid as a multi-scale system where the plastic flow takes place because of a loss in shear stability in stress regions on variable atomic levels. These discussions (based on experimentation and theoretical hypothesis) resulted in a new approach to consider a deformed solid as a multi-scale self-organizing system. It permitted configuring a multi-scale model of a deformed object that may have a complete know-how of structural scales of deformation.

Firstly, Pierce et al. [35] proposed the concept of crystal plasticity finite element method (CPFEM) to study the tensile properties of a single crystal. They analyzed only two symmetric slip systems in their model at the initial stage because of the high computational cost. At later stage, Harren et al. [36] implemented the CPFEM to a polycrystalline material by applying a 2D model. They analyzed the mechanical characteristics for a polycrystalline Cu under tensile, compressive, and shear loading. The modeling of channel die compression in an FCC Al material under twelve slip systems is taken by Becker [37]. At a later stage, several other researchers used the CPFEM tool for various purposes due to its increased computational power. For nickel-base super-alloy, Manonukul and Dunne [38] added the CPFEM concept to analyze the crack formation characteristic in LCF and HCF. For the same material, Guan et al. [39] incorporated CPFEM and high-resolution digital image correlation technique to analyze the strain localization under fatigue. It is reported that for a wide range of parameters, the CPFEM can predict the material behavior very accurately.

Kysar [40, 41] analyzed the crack formation behavior across the copper/sapphire interface developed by diffusion welding by multiple experimentation and theoretical studies. They noticed that the propagation velocity of brittle crack was much higher compared to that of ductile one. The behavior of both the cracks was different, which may be due to the variation in slip system orientation in the case of single crystalline copper with respect to the direction of crack growth. In simple words, it can be said that variation in ductility may be due to the differences in dislocation substructure evolution that may promote variable stress properties at the fracture or crack tip. Van der Giessen et al. [42] reported an analysis of discrete dislocation simulation for material response at the crack tip. In their work, they took into account only the edge dislocations having dislocation lines that were perpendicular to the modeled plane. They observed that the stress values across the crack zone were significantly higher compared to those obtained in a direct elasto-plastic model. Flouriot et al. [43] proposed theoretical cum experimental analysis of stress rate in the close region of fatigue crack for FCC crystal. Their theoretical investigations were based on the crystal elasto-viscoplastic model [44] with power-law for shear rate. Across the crack region, strain localization bands, kink bands, and lattice rotation, the theoretical and experimental outcomes showed good agreement. To analyze the damage and fracture, Clayton [45] proposed two-level direct elasto-viscoplastic model. He detailed about the kinematic, dynamic, and thermodynamic properties as well as their relations at each level. In his analysis, an assumption to have internal discontinuities and displacement field discontinuities were made for kinematic equations. He incorporated crystal plasticity model added with anisotropic hardening law to take into account the effect of temperature field. Boudifa et al. [46] incorporated a self-consistent crystal plasticity model to investigate the fracture behavior and strain localization. To determine the damage in mesoscale, averaging of the required parameters over a representative macro volume was done.

For friction stir welding (FSW) [47–49] process, mechanical properties of joints are widely governed by microstructure patterns [50–52] and crystal structure characteristics. Across the stirred zone (SZ) in Al alloys, the strain field is not continuous for every texture band joint and contains high angle grain boundaries at most [53]. Some models have been employed to determine the influence of microstructure on the mechanical performance for the FSW joint. Dhondt et al. [53] used CPFEM to document the impact of texture on strain rate across the SZ of FSW joints. Romanova et al. [54] employed 3D microstructure-based model of FSW steel joints using a mesoscale deformation process. The effects of polycrystalline microstructure on the material flow process and fracture failure of FSW joints for Al alloy were studied by Balokhonov et al. [55]. In the case of FSW joints of Mg alloys, the texture analysis on deformation characteristics was modeled using a plastic finite element method by He et al. [56].

For laser-weld joints, Tu et al. [57] employed the Rousselier model for analyzing the fracture properties of Al alloys. Gaur et al. [58] added CPFEM technique to analyze the role of mean stress and weld defects to the fatigue life for Al alloys. They employed a two-dimensional model to simulate the fatigue loading, which replicated the microstructure pattern of the respective metal also. They added an anisotropic tessellation algorithm, as used by Briffod et al. [59] in their work for analyzing the grain shape and size taken by EBSD data. The orientation of crystals for each grain is governed by the algorithm proposed by Melchior and Delannay [60] and was relied on the orientation distribution function (ODF) of EBSD.

The R-ratio ($\sigma_{yy,\min}/\sigma_{yy,\max}$) distribution as an aggregate for the last loading cycle at the lowest applied stress ranges at the respective R-ratios is shown in **Figure 5**.

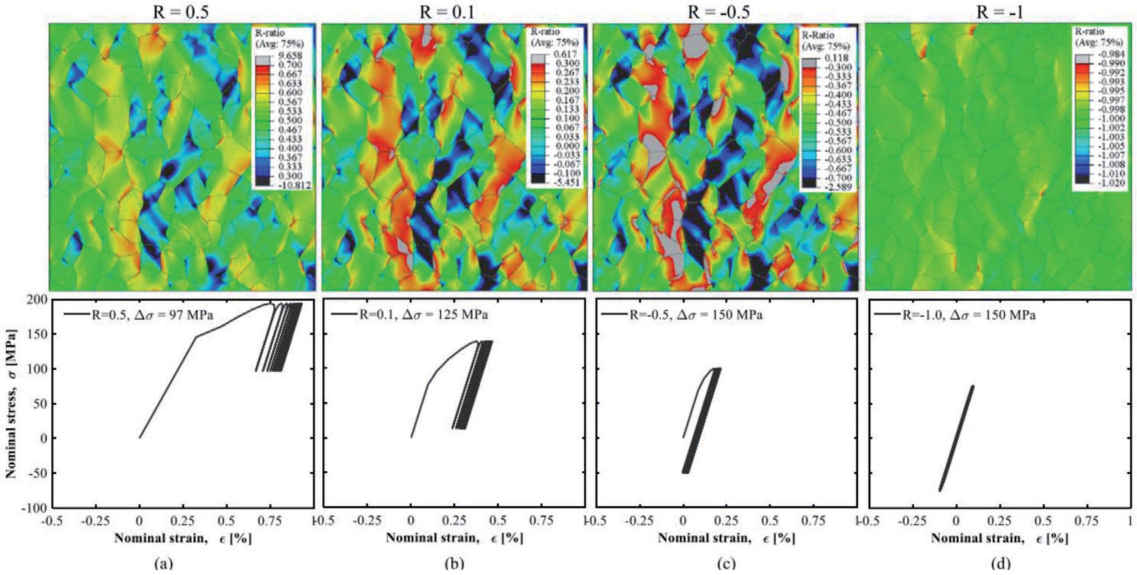


Figure 5.
Inhomogeneities in R- ratio distribution and macroscopic stress strain hysteresis curve at (a) Δσ = 97 MPa, R = 0.5 (b) Δσ = 125 MPa, R = 0.1 (c) Δσ = 150 MPa, R = -0.5 (d) Δσ = 150 MPa, R = -1 [58].

As depicted, a significant amount of heterogeneity for R-ratio distribution with respect to its increasing value is foreseen. When R-ratios are low, macroscopic and local R-ratios are more or less the same in most of the regions. Similarly, when R-ratios are low, their difference is high. A plot depicting the R-ratio distribution at the steady-state condition when $R = 0.5$, i.e., during the last load cycle, and maximum and minimum stress values are shown in **Figure 6**. For a fair interpretation, a plot of stress vs. strain is made across the four randomly chosen elements. In the case of far-field, R-ratio comes out 0.5; however, R-ratio across the four elements are 0.54, −0.61, 5.37 and −4.32. The results emphasized that precise prediction of crack initiation could not be possible by macroscopic parameters. It is because some inhomogeneities may be developed at the microstructural level. This outcome backs the results reported in the previously published literature [61]. While using the MIG technique to join Al-Mg alloy with different filler-wire, Gaur et al. [62, 63] analyzed the fatigue properties of weld joints. It was observed that the damaging action of mean stress was because of a decrease in crack-nucleation time and crack closure effects. Also, at low R-ratios (<0.1), maximum fatigue failures were surface-initiated. However, at high R-ratios ($\geq \mathbf{0.1}$), mostly the defect-induced failures were predominant. A phenomenon of shift in crack development mechanism can be understood because of local cyclic plasticity under stress-concentration factor.

Several researchers [58, 64, 65] have implemented the CPFEM model to predict the material properties and found that the predicted results were in good agreement with the experimental data, of course within some acceptable scatter. For example, Ye et al. [65] analyzed the fatigue crack initiation behavior in an Al beam with a hole under 4-point bending. They employed both in-situ experiments (EBSD and digital image correlation) and CPFEM simulations to investigate the slip bands and crack initiation sites at the microstructure scale. Based on EBSD maps, a realistic microstructure model was developed. They noted that the simulation results had a good agreement with the experimental outcomes in several aspects. Gaur et al. [58] predicted fatigue lives and its comparison with experimental data at different R-ratios without considering any defect (**Figure 7**). The anticipated results are observed to have a good agreement with the experimental outcomes for all the R-ratios. It is also

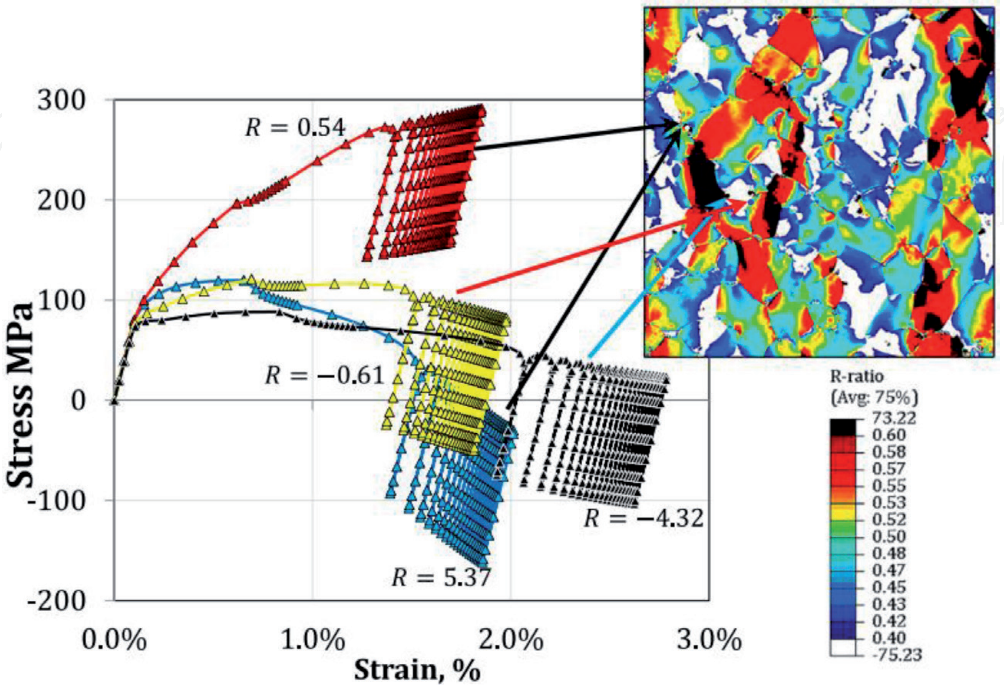
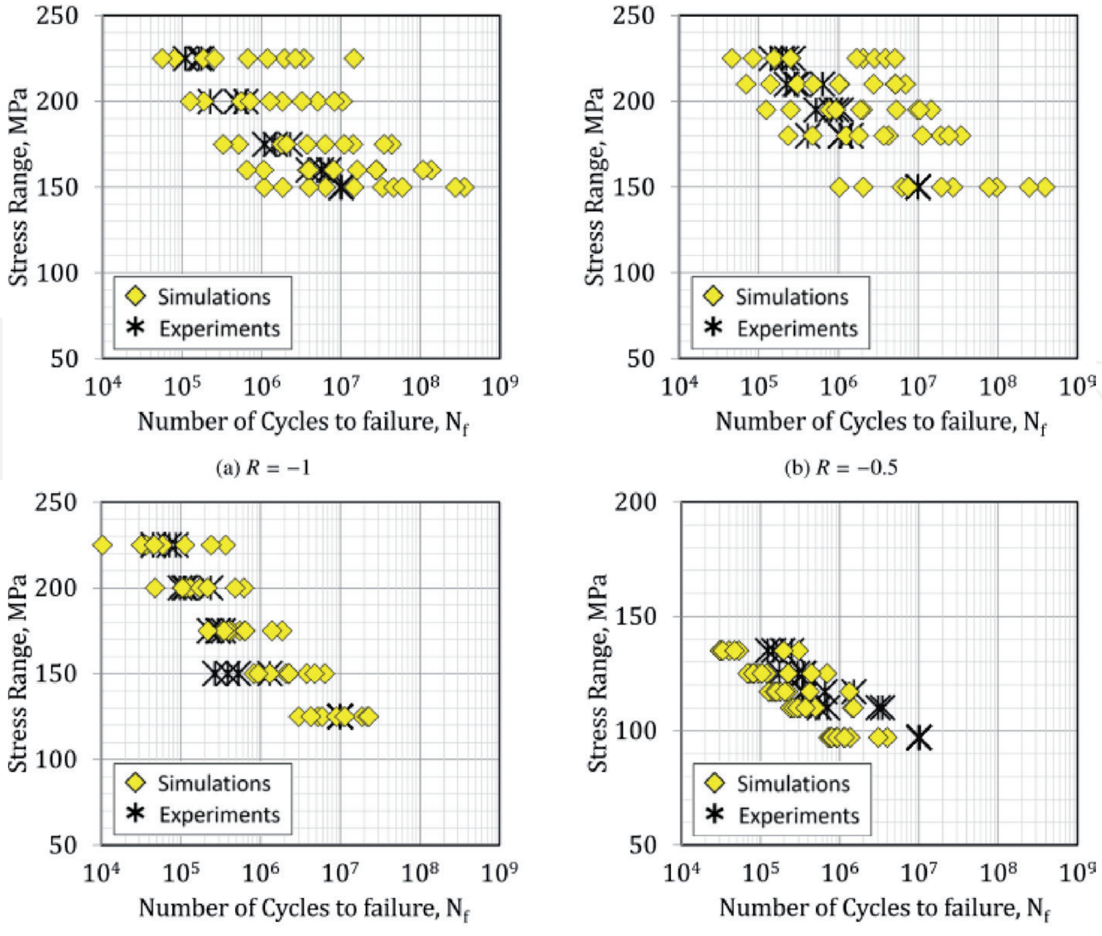


Figure 6.
An example of evolution of stress–strain loops at different locations in an aggregate at $\Delta\sigma = 135$, $R = 0.5$ *[58].*



(a) $R = -1$ (b) $R = -0.5$

(c) $R = 0.1$ (d) $R = 0.5$

Figure 7.
Prediction of fatigue lives at different R-ratios without considering any defect [58].

important to note that the scatter in fatigue lives has increased significantly upon considering defects in FE simulations.

6. Conclusions

This chapter has documented a systematic review of previous works on fatigue and fracture analysis by considering the CP approach of weld joints. As per the findings, several models based on the CPFEM methodology have standard features and details the micro-damage initiation and transition to failure. As indicated in numerous articles, the hardening model has a significant role in influencing computational outcomes. It is because hardening law can be directly related to depicting the defect formation mechanism in materials and that “transforms” to the micro-damage structure. The anisotropy of crystal can largely influence the micro-damage formation system to the extent of each grain and by grain lattice rotation adjacent to the crack tip region.

Several new approaches in context to fatigue analysis are reported in the literature duly supported with pertinent details. It is seen that the proposed models have their limitations and certain conditions, i.e., low cycle fatigue or high cycle fatigue, uniaxial and multiaxial loading, and material type (ductile or brittle), etc. Unfortunately, no model is found to fit perfectly under variable loading and material conditions. It leaves a wide gap for further research and development to the precise and reliable prediction of fatigue life under different conditions. The chapter was intended to present a short review to explore novel concepts and techniques, such as, CPFEM, to analyze and predict the fatigue life of weld joints, unlike some classical approaches, which lack to have a generalized algorithm to model the fatigue life. Future research should be oriented to the implementation of optimization models/algorithms in order to explore their full capability for accurately predicting the fatigue properties of metal structures or welded joints.

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