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A review on total fatigue life models for metallic components

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Summary

The fatigue assessment of metallic structures traditionally relies on a stress-life or strain-life approach that describes the initiation of a short macroscopic crack. The simplifications involved in traditional approaches imply significant conservatism, which is in turn difficult to be quantified. To overcome such limitations, total fatigue life models for metals have been extensively developed in the past decades. Total life models aim to describe the fatigue process from nucleation to fracture and quantify the cumulative damage sustained at any point of the component life.

This report reviews fatigue life models for metallic components. The fatigue assessment methods that are currently part of the ASME BPVC are first presented and their potential towards lifetime predictions is discussed. The literature on total fatigue life models is then surveyed. The models are categorized as two-stage, equivalent initial flaw size (EIFS), and multiscale computational models. Two-stage models consist of separate initiation and propagation life descriptions and the definition of a transition crack length. Traditional EIFS models back-extrapolate a detectable crack to an equivalent initial flaw size corresponding to zero cycles. Computational models predicting fatigue life based on analysis of multiple scales have the potential of a total physics-based treatment of fatigue but are still in an early development stage. Environmental fatigue in the plant environment is summarized, and total life models that include the environmental aspect are analysed. The models reviewed in the report are then discussed.

In the context of fatigue of nuclear components, the report is best read accompanied by the summary report surveying different environmental fatigue models for light water reactor environments [6].

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Contents

Nomenclature

BPVC – Boiler and Pressure Vessel Code
EIFS – Equivalent Initial Flaw Size
EPS – Equivalent Pre-Crack Size
FEA/FEM – Finite Element Analysis/Method
LAM – Life Assessment Methodology
LEFM – Linear Elastic Fracture Mechanics
LWR – Light Water Reactor
RVE – Representative Volume Element
SCC – Stress Corrosion Cracking
SWT – Smith-Watson-Topper strain-life model

1. Introduction

Fatigue is recognized as a major cause for failure of metallic structures. Repeated loading can cause structural failure at a significantly lower load level than at a single application due to progressive damage accumulation. The onset of fatigue failure is typically observed in stress concentrations such as discontinuities, defects, or notches. Generally, the total fatigue process consists of initiation, stable crack propagation and unstable crack propagation until fracture. Fatigue failure studies can be traced back to the mid-1800s and progressive development continues to this date [1]. Due to the phenomenological complexity and stochastic nature, no single comprehensive theory of fatigue exists. Fatigue life prediction models and the influence of numerous parameters are object of continued study.

Traditionally, the fatigue life assessment of metallic structures relies on a strain-life or stress-life approach and damage accumulation rule. In propagation-dominated cases, a reasonable life estimate is obtained by postulating a pre-existing crack and employing established fracture mechanics principles to compute the number of cycles to failure. Comprehensive reviews on traditional and emerging methods for fatigue life prediction, including material, loading and environmental factors, are presented in Refs. [2], [3], [4]. Different philosophies for fatigue design are presently in use [5]. Infinite-life design requires local stresses and strains to be below the fatigue limit. Safe-life design defines a finite fatigue life, after which the component is repaired or replaced. Fail-safe design recognizes that fatigue failure is possible, and the structure is designed to withstand local failures. Damage-tolerant design refines the fail-safe approach, in which the fatigue process is controlled by analysis and inspection. With improved understanding of the fatigue process and increased availability of test data, the importance of the damage-tolerant philosophy to reduce the conservatism towards cost-efficient structures is increasing. For a reliable damage-tolerant design, methods that can describe the entire fatigue process, providing an estimate for crack size during the service life are needed. Ideally, a comprehensive model for the fatigue process should be able to describe fatigue from microstructural-level effects until the onset of unstable crack propagation.

In this report, existing models that aim to describe the total fatigue life of metals are summarized and discussed. Emphasis is put on semi-empirical models that include separate initiation and propagation phases, but other possible approaches are also described. The report is organized as follows. In Chapter 2, the standardized lifetime prediction approaches included in the ASME Boiler and Pressure Vessel Code (BPVC) are described along with its limitations. Chapter 2 presents several alternative fatigue life approaches found in the literature. The main aspects of each approach are discussed, followed by a discussion on their features, advantages, and shortcomings. Chapter 4 presents a brief evaluation of environmental fatigue and incorporation strategies on the customary lifetime models. Finally, Chapter 6 summarizes the findings and sets directions for future work.

2. Total life models in the ASME BPVC

For the design of metallic NPP primary circuit components subjected to cyclic loading, the ASME Boiler and Pressure Vessel Code Section III provides the so-called design by analysis approach for fatigue assessments. The approach is presented in more detail in Ref. [6]. Here, the methods in the ASME code (2021 edition, specifically) are discussed for their suitability in total fatigue life methodology. The Code also provides the more conservative design-by-rule approach for selected components, but it is not applicable for the total fatigue life approach.

In the traditional stress analysis-based fatigue design of components, the calculated total elastic stress intensity is compared to the design fatigue strength curves provided by the code. The calculation of the stress intensity is based on stress categorization, linearization and calculating the equivalent alternating stress as well as possible plasticity correction, as explained in Section 2.1 of Ref [6]. Because of conservative assumptions made in the stress analysis and the safety factors in the fatigue design curves (see the next paragraph), this provides a conservative estimate for the permissible number of cycles for the component. In case of variable amplitude loading or multiple stress transients, a linear damage accumulation model (i.e. Miner's rule) is mandated by the code.

The fatigue curves that are to be used in the design of metallic nuclear components given by the Appendix I of Section III are based on strain-controlled uniaxial fatigue experiments. The experiments are strain controlled, indicating that at higher strain levels the total strain cycle imposed on the specimen consists of both elastic and plastic strains, but the fatigue curves are given in terms of stress to facilitate their use in stress-based design. As stated in ASME para. (Section III Appendices paragraphs III-1300 and W-2710) and detailed in Ref. [6], the design curves are obtained from a best fit to a large data set after which a safety factor of 2 on stress and 12 or 20 on cycles (depending on the material type), whichever is more conservative, is applied to obtain the design fatigue curve to account for the variation in the data, size effects, surface finish, etc. Moreover, the curves are said to include the maximum effect of mean stress to simplify the analysis and add conservatism.

Considering the design fatigue curves, each point in the underlying uniaxial experimental fatigue data set corresponds to a single specimen where one or more small cracks have initiated and grown such that the load required to cause the predefined strain cycle has reduced e.g. by 25%, or that the specimen has completely failed, depending on the data set (Section 2.3 in Ref. [6]). In the Master's Thesis by Alex Norrgård [7] it is shown that the 25% load drop in a standard specimen corresponds to roughly a 3 mm isolated surface crack and no considerable hardening during the crack growth phase. The crack growth phase at the end of a fatigue experiment is relatively fast and there can be a lot of variation in the final crack size due to difficulties in stopping the experiment accurately. The error in terms of cycles is however small, again due to the rapid growth rate. Moreover, the specimen-to-specimen variation in fatigue life typically exceeds the inaccuracies in stopping the experiment.

In Section III Appendices paragraph XIII-3500, it is stated that it is the designer's responsibility to evaluate if there are detrimental effects on fatigue life that can be caused by a corrosive environment. However, paragraph W-2710 states that the design factors applied on stress and cycles cover the effects of normal primary water environment on the fatigue life. The environmental effects on fatigue initiation life are thoroughly presented in Section 3.2 of Ref [6]. The research remains active and there is not yet a consensus on the most suitable model for capturing the effects and alternative methods also exist (Section 3.3 in Ref. [6]).

The ASME code contains tools to address both parts of the total fatigue life, life before crack initiation and life during crack growth. The stress-based fatigue design, coupled with necessary adjustments for the environmental effect, can be used to obtain a conservative estimate on the crack initiation life. The code does not provide a clear guidance on the resulting crack size after the initiation life is reached as the purpose of the safe design is to avoid crack initiation altogether. For the crack growth regime, Appendix L of Section XI can be applied in cases where the fatigue calculations for an operating plant indicate that the cumulative usage factor (i.e. the allowable number of cycles for a given stress amplitude) has been exceeded. For the calculation methods, Appendix L refers to other appendices of Section XI. Appendices A and C provide tools for determining the acceptability of flaws based on linear elastic fracture mechanics for vessels and piping components. A Paris law model and parameters for determining the fatigue crack growth rate is also given for air and light-water reactor environments for carbon and low-alloy steels in Appendix A and for austenitic steels and nickel-based alloys in Appendix C, although some materials and environments and stated to be in preparation. Appendix C also touches on stress corrosion cracking and combined fatigue and SCC. Irradiation effects are also considered. Safety factors or conservatisms in the parameters provided for the models are not quantified. It is mentioned that actual data from representative specimens should be primarily used. For materials not covered by the code, data from other sources can be used but it is emphasized that the data should cover the applicable conditions conservatively.

The assessment methods are meant primarily to determine the growth rate and acceptability of flaws found in inspections and not as a part of normal fatigue design of the components. Hence, the initial crack size required to be used in the methods is no smaller than the inspection acceptance criteria per ASME Section XI, which is approximately 10-15% of the wall thickness for piping components and 3-9% of the wall thickness for vessels. Also, the codified rules in Section XI give limits for the maximum size that the crack can reach within an inspection period. The purpose of the limits is to ensure that the integrity of the component is still maintained during the period and the flaw can be safely repaired if the assessment shows that the crack size would exceed the limits during the next inspection period. Thus, if applying them in a total life-based assessment as such, the ASME code approaches contain a transition from the uncracked component to a component that has a maximum allowable crack in inspections. The period between the crack initiation (with initial crack as inherent to the design fatigue curve data points) and the start of propagation phase is not accounted for, which is conservative. The environmental effects on the crack growth rate are readily considered in the models given in Section XI as different experimental curves are given for air and primary water environments. The growth rates of both SCC and mechanical fatigue cracks are given.

To summarize, methods from the ASME code can be applied with the total fatigue life approach, but with considerable conservatism due to their intended use in normal fatigue design or conservative crack growth rate calculations. The various methods contain differing inherent safety factors making the cumulative safety factor unclear if applying several methods consecutively in a total life assessment. It is advised to seek the original source publications and the underlying actual experimental data sets to perform best-estimate calculations and apply a suitable total safety factor on result.

3. Total fatigue life models

Total fatigue life models describe fatigue damage as process, rather than providing a safety utilization ratio based on extrapolation of experimental data. In this section, recent total fatigue life models available in the literature are surveyed in detail. The models are then contrasted and discussed with focus on their applicability for future research on the nuclear industry.

In this report, total life models available in the literature are split into three categories. Two-stage models provide separate descriptions for initiation and propagation phases. The Equivalent Flaw Size approach back-extrapolates propagation data to obtain an equivalent crack size that matches the total life seen in experiments. Finally, numerical multiscale methods for fatigue life are briefly discussed.

3.1 Two-stage models

Fatigue models accounting for distinct crack initiation and propagation phases have been proposed for over four decades [8], [9] and developments continue to this date. The number of cycles representing the total fatigue life *N* is often described as

$$N = N_i + N_p \tag{1}$$

where N_i and N_p are, respectively, initiation and propagation lives. The main ingredients for two-stage total fatigue life models are often the same. Crack initiation is typically predicted using a stress life or strain life approach and damage accumulation rule, while the propagation usually follows linear elastic fracture mechanics [10], [11]. Separate consideration of the short crack effect [12], [13] yields further decomposition of the total life. Proper treatment of the transition zone between initiation and propagation is a major challenge in defining a total life approach [14], [15]. Next, the development of two-stage models is discussed from the pioneering works up to recent publications.

Socie et al. [9] provided a key contribution in combining strain cycle fatigue and fracture mechanics concepts with a justified transition phase. The crack initiation was evaluated by defining a strain-life curve based on smooth specimen data, evaluating stress and strain ranges of elements along the line defining a potential crack path ahead of the notch root, and obtaining the fatigue life of each element. The reciprocal derivative of the cycle-distance curve defines the rate of crack initiation as function of distance from the notch. The crack propagation phase was determined based on the Paris law, with effective stress intensity factors accounting for crack closure effects and load ratio sequence, defining crack growth rates as function of the crack size. The crack initiation point was related to maximum relative damage between the stages. Initiation and propagation rates were superimposed, with the intersection point defining the initiation point a_I (Figure 1a). The initiation life was then defined based on the strain range at a_I, which also served as the initial crack size in the propagation law. The total fatigue life was obtained by summation of initiation and propagation lives. The approach was validated by comparison with circular notched plate experiments, yielding good results despite inaccuracies in the material data used. The authors indicated that their approach is coherent with physical observations of the stage proportions in relation to stress levels.

Dowling [8] is also an early attempt in predicting the total fatigue life of notched members. Like in Socie et al. [9], the strain life approach along with the Neuber's rule [16] was used for the crack initiation, and the Paris law for the crack propagation phase. It was suggested to increase the crack length by the plastic zone size to account for plasticity outside the notch stress field. The transition crack size was defined based on fracture mechanics considerations, as the point where the behaviour changes from local notch stress- to bulk stress-controlled. An expression to compute this transition length was provided. Generally, this corresponds to a small fraction of the notch radius; for sharp notches, the equation limit is a fifth of the radius. The approach was shown to capture the major trends of selected experimental results, and reasonable accuracy was shown. Differences were attributed to the statistical size effect and the effect of compression on the crack growth.

As evident from the literature that followed, the works of Socie et al. and Dowling formed the basis for conventional two-stage approaches. Their works provided early justification for combining previously established methods that can describe fatigue crack initiation and growth. Later developments built up on their work or proposed new criteria for stress and strain evaluations, transition crack size, small crack growth and others.

The approach in McClung et al. [17] is also recurrently discussed in later literature. In their work, test results for smooth specimens were used to determine the relation between strain or stress and number of cycles to failure. Crack propagation was computed using fracture mechanics principles, with the El Haddad [18] effective stress intensity factor range used for short cracks. The propagation life was estimated for different initial crack sizes and subtracted from the total life to define initiation curves for smooth specimens (Figure 1b). The notch stress at the transition crack length was used to locate the corresponding lives in the initiation curves. The total fatigue life of a notched component is the sum of the initiation lives determined and a fracture mechanics approach for propagation ahead of the notch root. Validation against experimental results was presented to demonstrate the approach and shown its superiority in relation to a conventional stress-life approach for a range of transition cracks. No specific transition length was used, but it was suggested that sensitivity studies can be used to verify its effect on the total life prediction and aid the selection of an appropriate transition length.

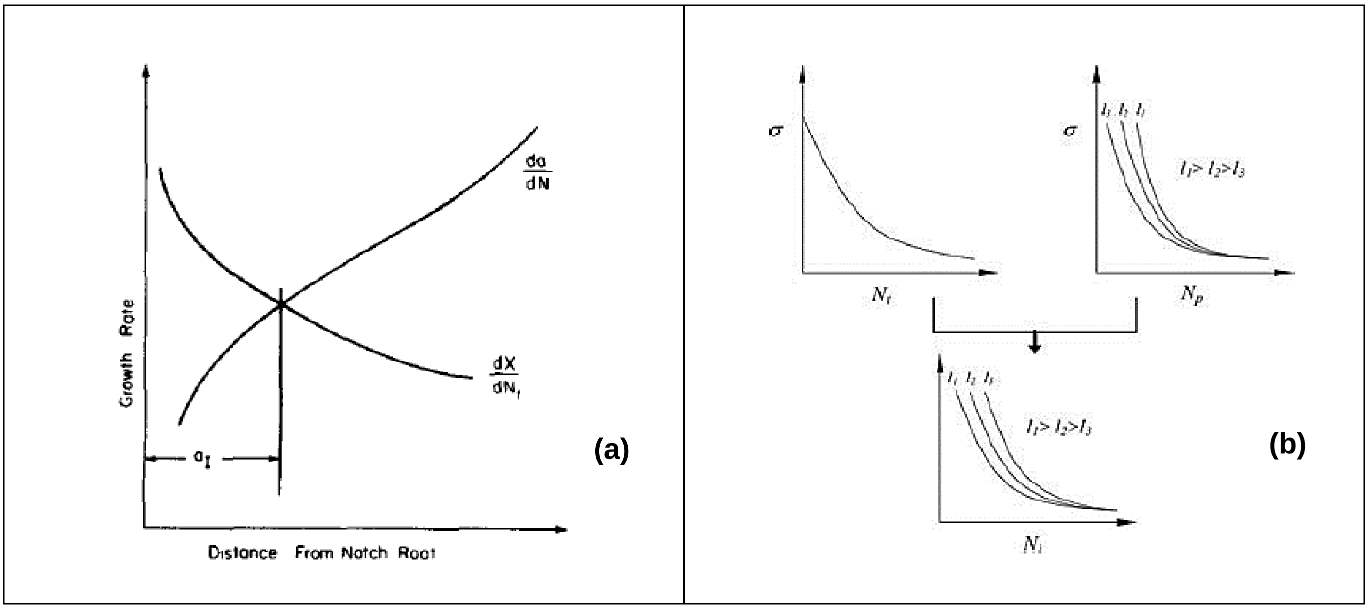

Figure 1 – (a) Definition of transition crack aI in Socie et al. [9] *(reproduced from Ref.* [9]*) (b) Retrieval of initiation lives for different transition crack lengths "l" as defined in McClung et al.* [17] *(reproduced from Ref.* [19]*).*

Mohammadi et al. [20] validated conventional approaches to predict the total fatigue life of a notched shaft. Fatigue initiation is determined based on implementation of the Fatemi-Socie [21] or Smith-

Watson-Topper criterion [22] with FEA-computed stresses and experimental parameters extracted from the literature. Crack propagation was predicted using the Walker equation with commonly assumed values. The transition between initiation and propagation was made using the minimum growth rate law proposed by Socie et al. [9]. The authors compared the fatigue life predictions with experimental results extracted from the literature. It was shown that the Basquin and Smith-Watson-Topper criteria provide good agreement against the set of experimental results. Based on the results, it was argued that the minimum growth rate law [9] leads to superior total life estimates than the El Haddad criterion [23] or a 1-mm fixed initiation crack length.

Zhang et al. [24] studied total fatigue life in a titanium alloy airframe structure. The life prediction model has three stages: crack initiation, short crack growth and long crack growth. The crack initiation was based on the stress-life approach and linear damage accumulation rule [25]; S-N curves were determined from tests, and the crack growth portion deducted from the total life. Short crack growth was predicted using the plasticity-induced crack-closure model [12], which relies on an effective stress intensity factor range with parameters derived in Refs. [13], [26]. Long crack growth was predicted through a Paris-type law [10], [11], with the Willenberg [27] model adopted for growth under variable amplitude loading. The transition between initiation and short crack growth was assumed to occur at a crack size of 0.3 mm, which can be reliably detected by the long-distance microscope used by the authors. It is claimed that fractography analysis indicates 0.3 mm as a lower limit for crack prediction, but no reference or proof to this claim is provided. The transition between short and long crack growth was adopted as 2 mm, with no further justification provided. The total fatigue life model was compared to experimental results obtained for two material grades (average of five specimens), and the predictions for each phase are shown to be consistent. Better accuracy was obtained for constant- than for variable amplitude loading.

Dong et al. [28] proposed an approach to estimate the fatigue life of notched components. A strain-life curve was obtained from fatigue tests of smooth specimens. Strain-life relations were proposed as a modification of the Coffin-Manson law, with the low-cycle fatigue term modified for ductility as in Ref. [29], to determine lives for a given crack size. Local stress and strain histories were determined using the Equivalent Strain Energy Density approach [30] and 3-D linear elastic FEA. Distinct mean stress corrections were employed for plane stress or plane strain cases [31]. The propagation phase was predicted using the “thresholded Paris relation” [32], [33] where the fatigue crack threshold is function of the crack extension as proposed in Ref. [34] to account for physically short crack behaviour. The authors argue that the initiation-propagation transition crack size must be chosen based on the validity bounds of the phases: as small as possible but at least half grain size for initiation (minimizing stress gradient effects and for validity of the strain-life relations), and two to five times the average grain size for propagation (mechanically short crack [17]). The approach was validated by comparison with notched specimen experiments found in the literature. For a proper selection of the dominant crack initiation zone, the approach was shown to provide good predictions except at low load ranges. Selection of two or five times the average grain size as transition crack led to minor prediction differences.

Navarro et al. [35] established a model to estimate fatigue life in notches and fretting fatigue. Initiation lives were determined in similar manner as in Ref. [17]. Plain fatigue tests were conducted and the strain amplitude to total lives relation determined. The propagation phase was computed for different transition crack sizes (LEFM including short crack effects) and subtracted from the total lives to define initiation curves. To evaluate specimens with strain gradients, the average strain between surface and transition crack depth was used based on the results in Ref. [15]. The Fatemi-Socie criterion [21] was used as fatigue criterion, as the multiaxial stress state was identified to be strongly multiaxial in fretting fatigue

[36] and this criterion was found appropriate in previous analogous works [37]. The propagation phase was analysed using a Paris-type law that includes short crack growth [38]. The transition crack length was not defined a priori but chosen by examining initiation and propagation lives computed for different lengths and selecting the length corresponding to the shortest life (Figure 2). The model was validated against experimental results for notched specimens and fretting fatigue and shown to produce consistent predictions for all cases presented. The effect of using different transition crack lengths was investigated; the criterion used in this study naturally leads to the most conservative life predictions.

In Ref. [39], Navarro et al. investigated the effect of considering the 3-D crack geometry in total fatigue life predictions. The life estimation model used is generally the same as in Ref. [35]. For the 3-D crack, the stress intensity factor was determined based on Refs. [40], [41]. By assuming that the crack grows at each point according to the SIF value, the evolution of the crack aspect ratio was also determined as a model parameter. The total fatigue life model including 3-D effects was validated against notched specimen experiments and compared with the 2-D model predictions. It was shown that the initiation life prediction in 3-D depends on the crack aspect ratio and notch depth at which stresses are extracted for the initiation life. The authors show that evaluating stresses at mid-depth and considering the variable aspect ratio according to the SIF as proposed, leads to a significantly more accurate prediction of fatigue life in relation to the 2-D model for the experiments under consideration.

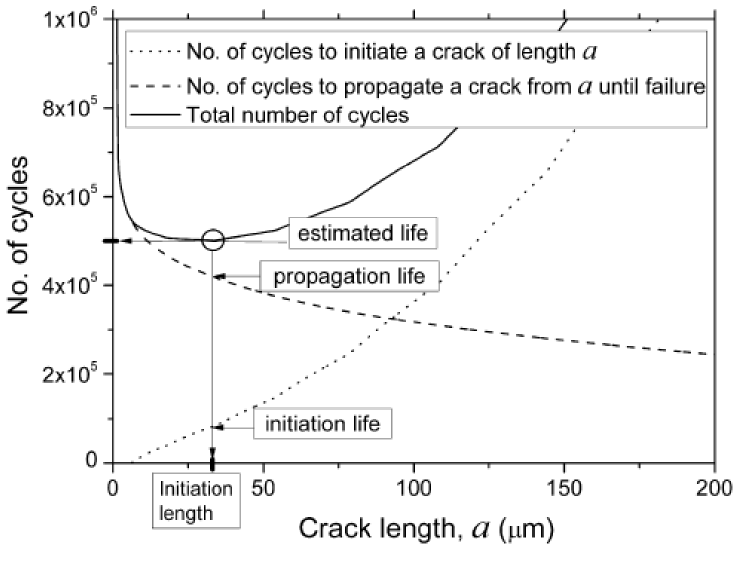

Figure 2 – Example of transition crack evaluation for a fretting fatigue test. Reproduced from Ref. [35].

Fajdiga and Straml [42] employed a two-stage model to predict fatigue crack initiation and propagation under cyclic contact loading, with application to surface pitting in gears. An equivalent contact model to determine cyclic stresses and strains was formulated and built using the FEM. Crack initiation was estimated using different strain-life equations and the Neuber's rule [16]. Fatigue crack propagation is estimated differently for short or long cracks. A model based on the crack tip plastic displacement [43], [44] was used to predict crack growth in the grain scale. The short crack model requires additional parameters to be defined based on experiments. For long cracks, propagation follows the Paris law [10], [11]. A numerical procedure based on Ref. [45] was implemented to simulate crack propagation and estimate the variation of stress intensity factor with the crack length. The total life model was used to simulate crack initiation and growth of a spur gear pair. The package MSC/FATIGUE [46] and its internal material database were used to estimate initiation at different material points based on the stress-state. The transition surface crack length was taken as 15 µm, justified on experimental observations [47]. For micro-pitting, an initial crack of 7.5 µm was assumed. Stress intensity factors were computed using a VCE method-based software [48]. The pits predicted with this model were compared with experimental results for shape and size. No validation on the prediction of cycles to failure was provided.

Makkonen [49] proposed a semi-probabilistic method to predict the total fatigue life of metallic components. The initiation phase was defined by subtracting the propagation phase from the total experimental lives. The transition crack size was computed based on Ref. [50] as function of the stress intensity threshold, stress range and geometry factor [51]. Crack propagation lives were estimated using the Paris law [10], [11]. A best-fit Weibull distribution was fitted to the initiation lives for a probabilistic treatment. Statistic of extremes were used to predict the initiation lives of specimens of different sizes, using estimated crack density and experimentally fitted parameters. The method was used to predict size effect in steel wires with good accuracy in comparison to experimental results. The method can be used to create design fatigue initiation curves for any set of S-N curves based on a limited set of initial data.

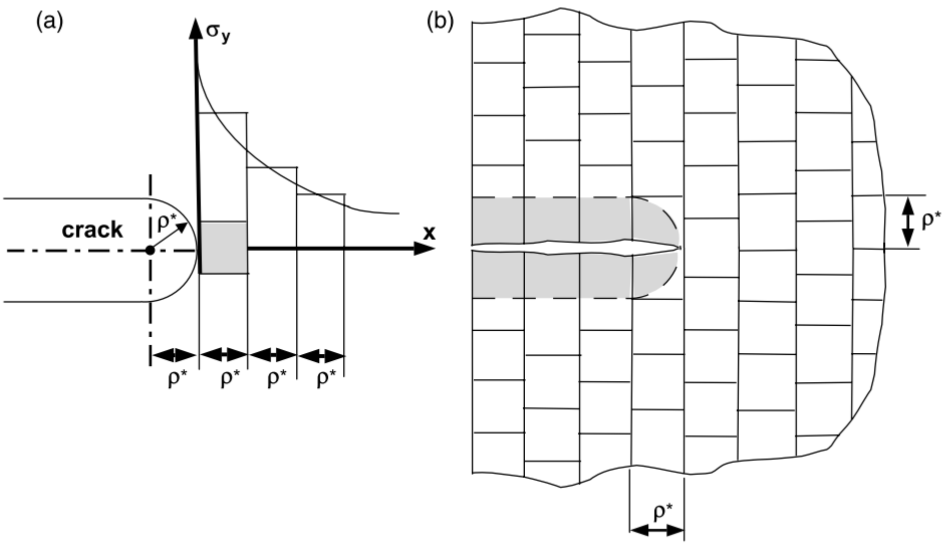

Figure 3 – The idealized crack tip geometry and idealization of elementary material blocks in the Unigrow method. Reproduced from Ref. [52].

Correia et al. [53] proposed a local unified probabilistic model for total fatigue life with application to notched specimens. Crack initiation and propagation are based on probabilistic fatigue models based on the Weibull distribution: the *p-ε-N* field based on strain amplitude [54] or a modification *p-SWT-N* that uses the Smith-Watson-Topper criterion [22] to quantify damage. A procedure to determine probabilistic parameters based on fatigue data from smooth specimens was outlined. Fatigue crack propagation relied on the Unigrow [52], [55] model, which represents the material as an assembly of elementary material blocks of finite dimension ρ^*. The dimension ρ^* constitutes the continuum transition length scale and defines the notch radius representing the crack tip. An iterative approach to define ρ^* based on propagation data from cracked specimens and FEA was presented. Crack initiation implies the development of an initial crack of length ρ^*; initiation lives were determined by conducting elastoplastic FEA for the stress and strain history in the material block ahead of the notch root and employing the *p-ε-*

N or *p-SWT-N* curves. For crack propagation, elastoplastic FEA was conducted to determine residual stresses. Elastic FEA was conducted to determine stress intensity factors and weight functions of the residual stress intensity factors [56]. The stress intensity and range were corrected for residual stresses yielding corrected stresses and strain ranges in *ρ**, and *p-ε-N* or *p-SWT-N* models were used to compute cycles to failure of an elementary material block. The total life is the sum of initiation and propagation cycles of blocks from the notch root until component failure. The model was validated for a notched detail, and good agreement with the experimental data was noted for different stress ratios. As the model is probabilistic, number of cycles to failure were described as probability bands. Almost all experimental points were located within the 1-99% bands predicted by the model.

In Vazquez et al. [19], a two-stage model to estimate the fatigue life of notches was proposed. The authors also provided a critical review and further validation for the approaches of Socie et al. [9] and McClung et al. [17]. In their model, an initiation length was defined equal to the El Haddad parameter [23], and the *SWT-N* curve of the material employed to define initiation lives, with the average Smith-Watson-Topper parameter [22] between the notch and initiation length used as reference. The crack propagation phase was based on the Unigrow [52], [55] model. The elementary material block *ρ** was defined as in the original model, with an additional condition that *ρ** must be at maximum 15% of the initiation length in the short crack regime. Elastoplastic stresses were also calculated away from the notch, providing an initial damage state along the crack path. The number of cycles needed for failure of an elementary block was defined as in Glinka [57]. The proposed and reference models [9], [17] were validated against tests of three notch component subjected to different constant amplitude load levels. FEA was used to compute stress and strain fields in all models. It was shown that the three models produce acceptable results, with the model by Socie et al. [9] providing the smallest errors.

Two-stage models have also been proposed to predict total fatigue life in welded joints. Due to the complex geometries and importance of imperfections, total life models for welds require special treatment of some of the aspects.

As a relatively conventional study, Brandt et al. [58] used a two-stage approach to predict the total fatigue life of aluminium alloy butt weldments under constant amplitude loading. Experiments were conducted for full and partial penetration welds. The initiation life was estimated using strain-controlled fatigue properties and the Basquin-Morrow equation. Stress input is function of the nominal stress and fatigue notch factor computed for the worst-case notch. The propagation life was estimated using the Paris law. The transition crack length of the full penetration welds was taken as 0.25 mm as justified as an “engineering crack size” based on previous work by the authors [59]. For the partial penetration welds, the weld penetration length was taken as initial crack size. Comparison between predictions and experiments showed correspondence within a factor of 2 for most cases. It was verified that partial penetration welds have significantly lower fatigue life due to the larger stress concentration that is associated.

Mikulski and Lassen [60] employed a two-stage approach to predict fatigue crack initiation and growth in fillet welded steel joints. Fatigue crack initiation was predicted using the model by Lassen and Recho [61], which is a strain life approach with experimentally established material parameters for welds. The local strain was determined using the Ramberg-Osgood model [62] and Massing’s hypothesis. The propagation phase was tentatively modelled with different Paris-type expressions: the DNV-GL model [63], the BS 7910 model [64], and the model by Huang et al. [65]. The tentative propagation models were implemented with or without the threshold intensity range correction term, and with original or fitted parameters. Stress intensity factors were determined using the DNV-GL equations [63] based on Refs.

[66], [67]. The transition crack length was adopted as 0.1 mm and justified as a practical value within the measurement tolerance of the equipment used in the work. Based on verification against test results, the model by Huang et al. [65] with fitted parameters and no stress intensity range threshold was selected for total life predictions. The two-stage model was compared with the F-class S-N curve [68] that describes the fatigue life of the experimental setup. Good correspondence with the median S-N curve was found. Differently from Ref. [68], the two-scale model does not predict infinite life for low stress range, which was claimed by the authors as a more realistic representation of the fatigue behaviour.

Recently, two-stage models have emerged in the nuclear field with the goal of harmonizing standardized procedures for fatigue crack initiation and propagation. Models for nuclear piping and vessels require careful consideration of environmental effects that are known to affect the fatigue life of metallic components. Further discussion on aspects of fatigue in the plant environment is presented in Section 4.

Simonen et al. [69] proposed a probabilistic fatigue life methodology for nuclear piping. Crack initiation was predicted using the ANL model [70], which describes the probability of initiating a 3 mm deep fatigue crack based on strain-life data for different nuclear component steels. The ANL model considers environmental effects such as sulphur content, temperature, dissolved oxygen, and strain rate in the initiation lives, as well as a correction for differences between test specimens and full-scale components. The evaluation of initiation locations and computations were made with a probabilistic fracture mechanics code [71]. Fatigue crack growth was predicted with a probabilistic Paris-type law based on the ASME Section XI equations that includes mean stress effects [71]. Cyclic stress levels were computed as in the INEL report [72]. The approach was used to compute failure probabilities of a surge line elbow. Conditional probabilities of different leak rates and core damage were computed for different initial data. Probability of crack initiation and through-wall cracks were presented for selected components of seven plants. No validation of the approach was presented.

In Batten et al. [73], the “Life Assessment Methodology” (LAM) incorporates statistical distributions to established methods towards a total fatigue life model. The general procedure is to sample material parameters based on statistical analysis, generate fatigue initiation and crack growth lives for each parameter set and use a Monte Carlo simulation and Empirical Cumulative Distribution Function to determine the reliability of each simulated life. In the case study presented, strain amplitudes computed from elastic-plastic FEA were fed to a ANL fatigue curve [74] to determine initiation lives in air. Two strain measures were used: the Effective Strain Range [75] or the Maximum Strain Range in the Plane of Maximum Stress [76]. A procedure to incorporate environmental fatigue based on the computation of scaled F_{en} factors [74] was outlined. The procedure was applied for each sampled assessment point. Crack propagation was estimated based on elastic FEA and a LEFM approach, with stress intensity factors extracted from the API 579-1 [77] and including an environmental factor C_{ENV} [78]. The concept of transition crack size was discussed, but no general procedure for its determination was proposed. The LAM was compared to conventional approaches to predict the total fatigue life of a Bettis Bechtel Stepped Pipe. A transition depth of 254 µm was adopted, but no justification was given. For the problem studied with parameters proposed, it was shown that the LAM produces results that are significantly less conservative than the current standardized methods for a target reliability of 10^{-5}. The LAM is a practice-oriented approach, as it incorporates methodologies and experimental data currently used in the industry in determining total life predictions.

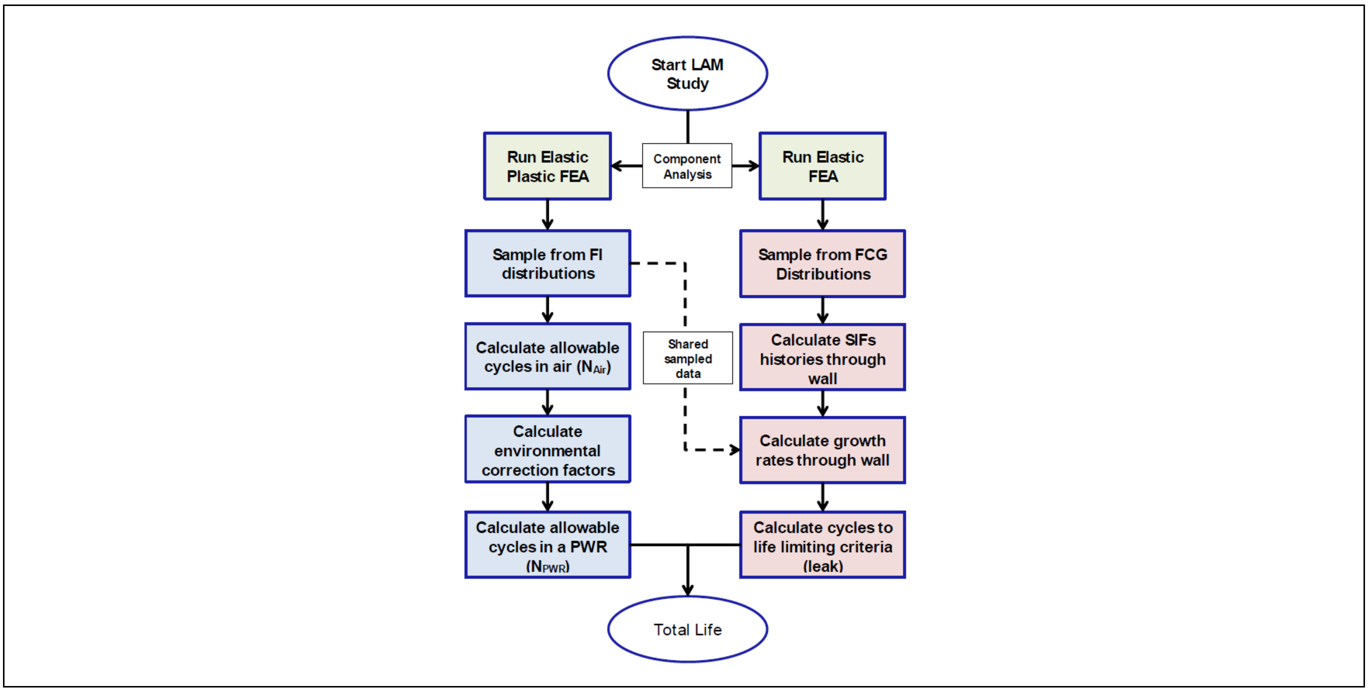

Figure 4 – "Life Assessment Methodology" for total fatigue life assessments including environmental fatigue with applications on the nuclear sector. Reproduced from Ref. [73].

3.2 Equivalent initial flaw size approach

The Equivalent Initial Flaw Size (EIFS) is an alternative estimation approach for total fatigue life prediction that has been used for decades in the aircraft industry [79]. The general idea is to back extrapolate a detectable crack back to an initial flaw distribution representing intrinsic material defects. The EIFS is a fracture mechanics-based approach and, as such, fatigue initiation is treated by selecting a suitable flaw size for good experimental fit – the flaw selection does not necessarily have a physical meaning. The literature on EIFS predictions is vast, as EIFS are problem dependent. Selected contributions are summarized in this section.

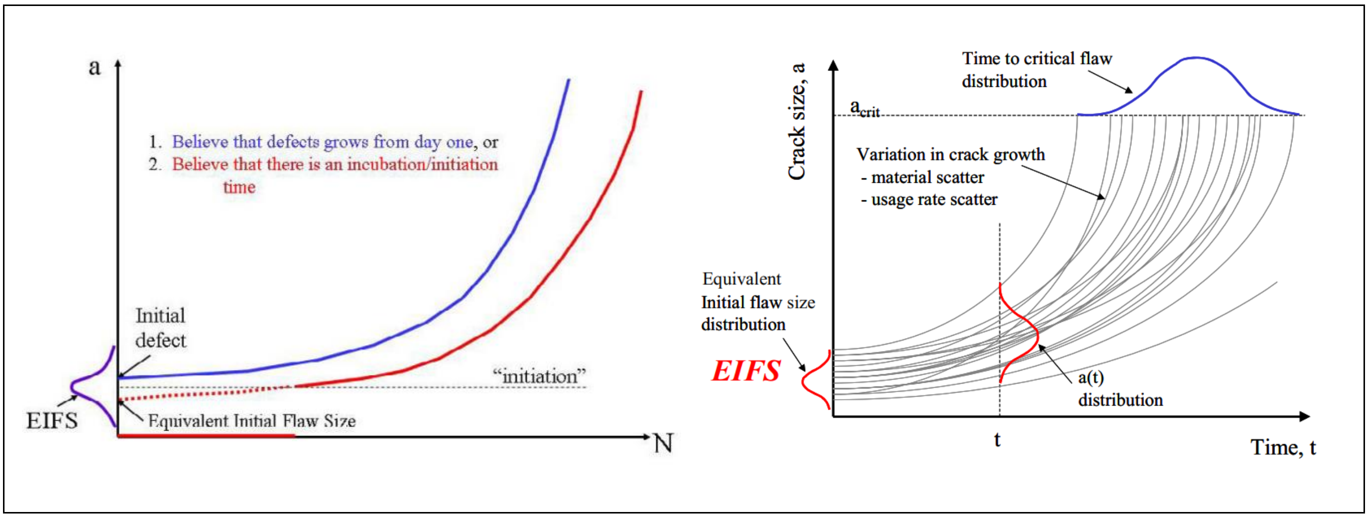

Figure 5 – The Equivalent Initial Flaw Size approach in a nutshell. Reproduced from Ref. [79].

Moreira et al. [80] provided a traditional computation of the EIFS for single-rivet aluminium lap joints specimens. Two crack propagation approaches were used: the conventional Paris law [10], [11] with previously determined parameters [81] and stress intensity factor range [82], and the strain energy density factor model [83], [84]. The crack growth models were back extrapolated to determine EIFS. In both cases, the EIFS were described with two parameters, as a linear function of the stress range. The EIFS proposed are in the order of 30-50 µm.

Fawaz [85] estimated EIFS for flat specimen panels containing a splice joint. Fatigue tests were conducted for different types of joint and load spectra. Crack growth was measured during the tests and later fractographic investigation was conducted using a scanning electron microscope. Fatigue life predictions were made using the software AFGROW [86] and FASTRAN [87], adjusting the EIFS for a good experimental fit. Quarter-circular initial flaw shape was assumed based on experimental observations. It was proposed to compute EIFS only considering small cracks; a 1.27 mm limit was arbitrarily chosen. The mean EIFS obtained by the predictions of the two software was in the order of 5-50 µm.

Correia et al. [88] proposed a fatigue life model for notched details based on fracture mechanics and the EIFS concept. Fatigue crack propagation was predicted by adapting the fatigue crack growth law by Castillo et al. [89] towards an elastoplastic version governed by the J-Integral. Experimental data from CT specimens was used to estimate the propagation model parameters. The EIFS was obtained by an iterative procedure. Elastoplastic FEA was used along with the Ramberg-Osgood model [62] to obtain the J-Integral ranges and number of cycles corresponding to the integration between EIFS and crack size corresponding to the fracture toughness for a given stress range and mean stress. The predictions were compared with experimentally derived S-N curves, and the EIFS modified until a good fit was obtained. For a notched plate made of P355NL1 steel, an EIFS parameter equal to 63.63 µm was estimated.

Liu and Mahadevan [90] proposed a methodology to calculate the EIFS without resorting to back-extrapolation. Probabilistic crack prediction is based on a generalized Paris-type law with parameters fitted from experimental data. The linear Paris coefficient and threshold stress intensity range were considered as random variables described with lognormal distributions. The EIFS was defined based on the threshold stress intensity range expression in El Haddad et al. [23], with a probabilistic version where fatigue limit, threshold stress intensity and, consequently, EIFS as lognormal random variables. An elastic-plastic correction factor based on Refs. [91], [92] was implemented for low-cycle fatigue. The probabilistic total fatigue life was computed using Monte Carlo simulation. The methodology was validated for smooth plate specimens of different materials under constant amplitude loading; good correspondence with the experimental results was obtained. The EIFS obtained in the studies are in the order of 50-400 µm. In Ref. [93], Xiang et al. extended this approach to allow the calculation of EIFS using long crack growth measurement data. The idea is to extrapolate the crack growth curve related to long crack measurements to a rate of 10^{-10} m/cycle; the stress intensity factor obtained is named the "intrinsic threshold stress intensity factor". Such approach was successfully validated against experimental results of smooth and notched specimens. Further extension to multiaxial loading was presented in Ref. [94].

Medved et al. [95] investigated the applicability of the EIFS technique for fatigue design of an Alclad aluminium alloy structures in presence of corrosion. Single edge notched specimens were pre-corroded, and fatigue tested under constant and variable amplitude loading. All cracks were verified to start from the corrosion pits, and reduction of 40-50% in fatigue life was observed in relation to uncorroded control specimens. The software AFGROW [86] was used with the NASGRO growth model and Paris law constants obtained from experiments to predict a suitable EIFS to describe the test results. EIFS distributions were obtained using Weibull cumulative and probability density functions for constant and variable amplitude life data. The fitted EIFS was shown to predict only moderate error for total life, but less satisfactory intermediate life predictions associated with a given crack size due to the inherent simplifications of the method.

An analogous initial crack concept is the Equivalent Pre-crack Size (EPS), which consists in similar back extrapolation using an empirical crack growth model rather than a LEFM approach [96].

Molent et al. [96] extrapolated EPS for 7050 aluminium alloy based on numerous specimens of different geometries, surface conditions, material batches and loading spectra (variable amplitude loading). Quantitative fractography was used to produce crack growth data. An exponential crack growth model that is linearly dependent on the EPS was fitted to the experimental data as a good fit for the experimental observations and in agreement with previous studies (for instance, Ref. [97]). A log-normal distribution was selected to describe the EPS. It was shown that the EPS is not dependent on load spectra or applied stress levels, but it depends on the surface finish. The log-average of the EPS determined is in the order of 10-30 µm.

Gallagher and Molent [98] compared the EIFS and EPS approaches for the same fatigue test data. Aluminium alloy coupons were tested under different spectra scaled to four reference stress levels. Four fitting approaches were used to determine the Paris law-type material constants. Back extrapolation was conducted using the material constants obtained for each approach to determine the corresponding EIFS. The EPS for each case was determined by an exponential data fit as described in Ref. [96]. The back-extrapolated EIFS and EPS obtained were similarly log-distributed, with a median size in the order of 20 µm. The two approaches were shown to yield virtually equivalent results for the test data under consideration.

Numerous other contributions on EIFS and EPS can be traced in the literature; this review is by no means exhaustively extensive in relation to these methods.

3.3 Multiscale computational models

Recent technological advances led to exponential increase in computational power, increasing the level of detail that can be incorporated to numerical simulations. By implementing established fatigue nucleation procedures to numerical models that include microstructural features, it is possible to predict fatigue life starting from the grain dislocations until unstable fracture. In this section, a survey of selected multiscale models available in the literature is presented.

In Jezernik et al. [99], a numerical model was defined to predict the total fatigue life of martensitic steel specimens. The model was composed of two parts: a macro-model representing the specimen and used for the propagation phase, and a micro-model of the highest stressed region where fatigue crack initiation is expected. The micro-model was modelled with random grains generated with Voronoi tessellation, which were also represented with randomly oriented orthotropic properties. Each grain was equipped with multiple slip bands [100]. Crack coalescence was evaluated by analysing combinations of micro-cracks and comparing their average seam stress with the yield stress of the material. Dislocation pile-up was considered as damage accumulation through cycles. The initiation stage was defined to end when a large, coalesced crack was formed. Crack propagation was calculated with the Paris law, with stress intensity factor ranges and propagation angle computed with Abaqus [101] based on the maximum tangential stress criterion and having the coalesced initiation crack shape as reference. The size of the micro-model was chosen based on observations in Ref. [102] and defined the transition between initiation and propagation. Numerical simulations were performed for the proposed specimens at different stress levels, demonstrating that the method leads to good predictions against experimental results.

Milkota et al. [103] presented a two-scale computational modelling approach to estimate the total fatigue life of a carbon steel specimen. The approach is based on previous publications by the authors [104], [105], which also describe the extraction of material parameters by molecular dynamics simulations. The approach consists of two interacting models: macroscopic for the global stress field and computation of stress intensity factors, and microscopic to assess fatigue crack initiation. The micro-model is a Representative Volume Element (RVE) generated by Voronoi tessellation and discretized with membrane elements. The Tanaka-Mura [106], [107] criterion was used to identify nucleating grains. Progressive nucleation, which affects the local stress field, was tracked until the crack growth rate drops significantly for all segments, defining the completed initiation life. The macro-model representing the specimen was initially discretized with solid elements and used to provide boundary conditions to the micro-model. In a separate effort, the macro-model was discretized with plane-stress elements and equipped with a seam crack (e.g., Ref. [101]) that can open during the analysis. This macro-model was used to compute stress intensity factor ranges. The computational model was used to construct the S-N curve of the specimen under analysis, by conducting computations with two different microstructures for different loading levels. The results have good correspondence with the experimentally determined S-N curve. Minor differences were attributed to uncertainty in the critical resolved shear stress parameter of the Tanaka-Mura model.

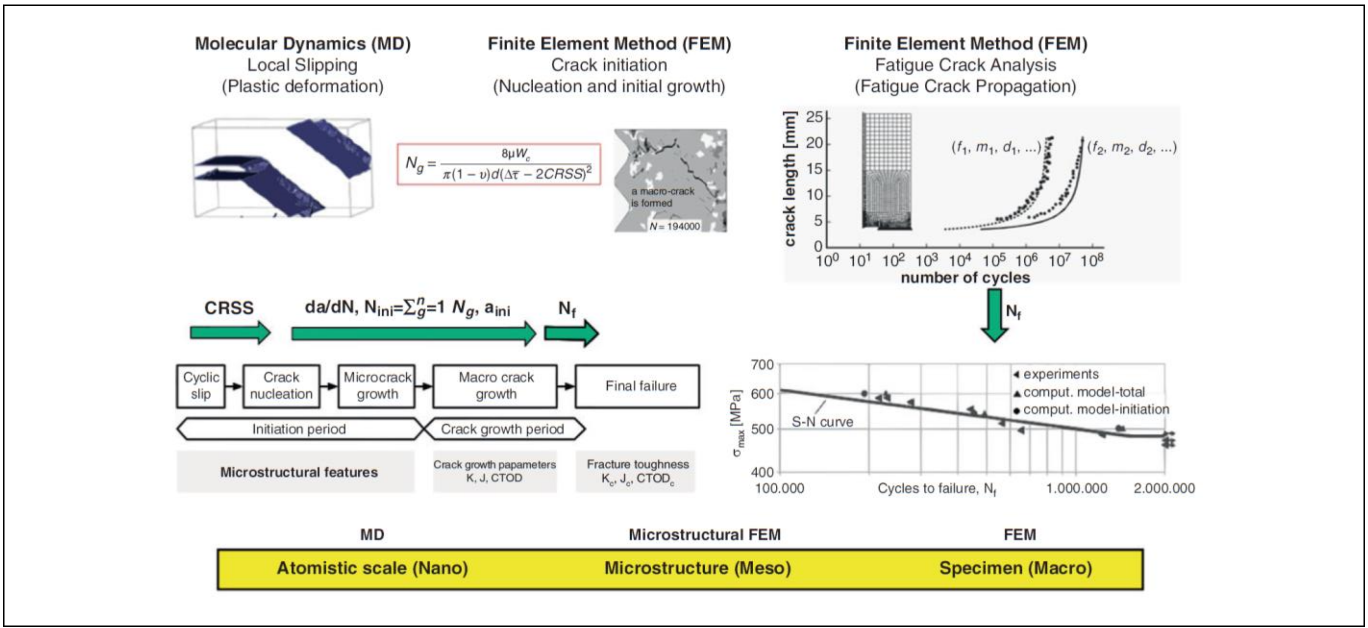

Figure 6 – A multiscale approach for computational fatigue predictions. Reproduced from Ref. [108].

Božič et al. [108] presented a multiscale fatigue crack modelling approach for welded stiffened panels. Molecular dynamics simulations were conducted with the simulation software IMD [109] to evaluate dislocation nucleation, propagation, and multiplication, and predict the critical resolved shear stress parameter of the Tanaka-Mura [106], [107] model. A microscopic FE model was then used to predict crack nucleation based on the Tanaka-Mura model; it can be implied that the model by Ref. [99] was used, but no explicit explanation was provided. A macroscopic FE model was built in ANSYS 11.0 [110] to compute stress intensity factors. An initial stress state was applied to represent the residual stresses. An effective stress intensity factor range was then computed to account for crack closure [32] and the influence of welding residual stresses [111]. The number of cycles for crack propagation was determined using the Paris law. The initial crack length used in the simulations was not discussed. The authors show that the crack propagation, including the residual stress effect, match a selected experimentally obtained crack growth curve.

4. Environmental fatigue and total life approaches

A total life model for application in the nuclear industry must be able to describe environmental fatigue [112]. Experimental data has suggested that the primary water environment can have a detrimental effect on fatigue life, such that it decreases the cycles to crack initiation or failure and increases the crack growth rate [74]. For fatigue crack initiation and normal fatigue design of nuclear components, models for considering the effect of the primary water environment have been proposed, such as in NUREG/CR-6909 [74]. The models are commonly based on fatigue experiments performed in LWR water environments. Research on the topic remains active and alternative approaches and models have been proposed (Section 3.3 of Ref [6]). Like in normal fatigue design, it is essential to maintain the connection between the underlying experimental data and the model describing the environmental effect (see Section 3.2 of Ref [6]) also in context of the total life approach.

Among the two-stage models reviewed in Section 3.1, only the models by Simonen et al. [69] and Batten et al. [73] put emphasis on environmental aspects that are relevant to the nuclear industry. In Simonen et al. [69], environmental parameters were included in the fatigue initiation curves that relate strain to the number of cycles. The crack growth equations used were based on the ASME Section XI code for water environment. It was mentioned that the equations were yet to be updated to reflect PWR and BWR operating conditions. In Batten et al. [73], environmental fatigue was included though correction factors. An approach was defined to incorporate fatigue initiation penalty factors F_{en} in the probabilistic model. The penalty factors are based on previous studies on LWR coolant environmental effects. In the growth stage, the temperature effect was incorporated by defining suitable fitted model parameters C_{ENV} for the propagation law.

The literature on EIFS is vast, and numerous references deal with environmental aspects, in particular corrosion [95]. Including environmental fatigue in such approach typically implies determining the crack propagation model parameters based on testing of specimens under the intended conditions, hence not directly affecting the procedure itself.

5. Discussion

In this report, total fatigue life models proposed in the last few decades were separately reviewed with focus on the key ingredients needed for a lifetime prediction. The models were categorized as either two-stage initiation-propagation type, propagation-only with the definition of an equivalent initial crack (back-tracked to zero-cycles), or purely numerical based on the analysis of multiple scales. Emphasis was put on describing two-stage models in detail.

Two-stage models are a natural evolution of the traditional S-N curve approach, offering the possibility of a more comprehensive description of fatigue. Two-stage fatigue models usually have the same format: a stress life or, more frequently, strain life approach to predict initiation, and a crack growth law, oftentimes based on the Paris law, to predict propagation. Several models were supplemented with modifications to account for physically short crack growth and plasticity effects.

A major difficulty in the derivation of a consistent two-scale approach is to define the transition between the stages; that is, “when a crack becomes a crack”. The initial macroscopic crack size assumption may significantly affect the predicted propagation life. Prominent approaches to define the transition zone were identified: the growth rate-based approach by Socie et al. [9], the iterative approach by McClung et al. [17], the approach based on the El Haddad parameter [23] and based on the Unigrow block size [52], [53]. Some references rely on “engineering” crack sizes; the generality of such approaches may be questioned, and production of particularly unconservative results for certain problems cannot be ruled out. The capability of incorporating the short crack growth behaviour [113] is another aspect that differentiates the models reviewed. Models that do not consider this crack growth phase are inherently less capable of providing a physics-based description of the fatigue process.

Numerous EIFS models can be found in the literature, as a traditional damage tolerance analysis approach in the aircraft industry [79]. In most cases, the models only differentiate by the method used to fit the crack growth parameters from experimental data. EIFS models based on back-extrapolation are only valid for the strict conditions for which they were derived. As reported in Ref. [80], the EIFS may even depend on the stress level. The comprehensive use of EIFS requires significant amount of experimental data. EIFS models without back-extrapolation have been proposed in the literature based on the El-Haddad expression [23] and gained significant attention in recent years.

A limited number of models with a nuclear industry spirit have been identified [69], [73]. These models can be classified as two-stage, based on standardized tests and the customary LEFM crack growth laws. Both references include probabilistic measures for the governing parameters and include environmental fatigue modification factors. Common shortcomings of both models are the lack of unambiguous definition of transition crack size and no separate consideration of short crack growth. Overall, it is evident from the formulations that considering environmental fatigue on both, two-stage and EIFS-based models is mainly a matter of defining the dependent parameters based on environmentally affected specimens. The same principles described in the models are expected to be valid.

Computational multiscale fatigue models started to emerge in the past ten years. The models can offer a complete description of the fatigue process, from the atomistic-scale dislocations to global specimen rupture. Computational methods may become mainstream with further refinement, validation, and continuing increase in computational power. Currently, such methods are in an early infancy development stage, are resource-intensive and, as such, have limited practical relevance.

6. Conclusions

This work presented a comprehensive literature review on total fatigue life models for metallic components. Three categories of approaches were identified based on their major characteristics:

- Two-stage models accounting for separate initiation, propagation lives and a transition rule.
- Equivalent initial flaw size (or equivalent pre-crack size) approaches that back-extrapolate the predictable crack growth to an initial crack at zero cycles.
- Computational approaches that model different structural scales.

It was shown that all two-stage approaches have similar ingredients. The main differences are in the definition of transition crack length, and whether short crack growth behaviour is separately analysed. Proper treatments are essential for a consistent model with wide applicability. The EIFS and EPS approaches often rely on back-extrapolation and consequently are only valid for the conditions for which the model was derived. Models without back-extrapolation exist, but it is uncertain whether a significant number of cycles may be neglected for cracks smaller than the size adopted. Computational fatigue models with treatment of multiple scales have been recently proposed. While offering a more physics-based description of fatigue, these models are still in early development, their use is overly complex and currently resource-intensive, limiting their practical applicability.

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