# Methodologies for Crack Initiation in Welded Joints Applied to Inspection Planning

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***Abstract*—**Crack initiation and propagation threatens structural integrity of welded joints and normally inspections are assigned based on crack propagation models. However, the approach based on crack propagation models may not be applicable for some high-quality welded joints, because the initial flaws in them may be so small that it may take long time for the flaws to develop into a detectable size. This raises a concern regarding the inspection planning of high-quality welded joins, as there is no generally acceptable approach for modeling the whole fatigue process that includes the crack initiation period. In order to address the issue, this paper reviews treatment methods for crack initiation period and initial crack size in crack propagation models applied to inspection planning. Generally, there are four approaches, by: 1) Neglecting the crack initiation period and fitting a probabilistic distribution for initial crack size based on statistical data; 2) Extrapolating the crack propagation stage to a very small fictitious initial crack size, so that the whole fatigue process can be modeled by crack propagation models; 3) Assuming a fixed detectable initial crack size and fitting a probabilistic distribution for crack initiation time based on specimen tests; and, 4) Modeling the crack initiation and propagation stage separately using small crack growth theories and Paris law or similar models. The conclusion is that in view of trade-off between accuracy and computation efforts, calibration of a small fictitious initial crack size to S-N curves is the most efficient approach.

***Keywords*—**Crack initiation, fatigue reliability, inspection planning, welded joints.

## I. Introduction

WELDED joints are very common in modern steel structures, e.g. ships, offshore structures, bridges, etc., and are often critical components due to initial flaws, high stress level, weld corrosion, etc. Integrated design, inspection and maintenance for weld joints against fatigue and fracture are the main parts of a structural integrity management system. Normally, in-service inspections are assigned to detect the cracks in the early stage and repair them before they reach critical sizes and cause catastrophic fracture. The basis for scheduling inspection actions is a crack evolution prediction tool, which is normally developed using crack propagation models with an assumption that the crack initiation period can be neglected [1]-[5]. This method is applicable if there exists a relatively large initial flaw or crack in a welded joint and the flaw or crack sizes are known, in which case fatigue degradation of the welded joint begins with crack propagation. However, the assumption may not be applicable for some high-quality joints for which crack initiation period account for a large part of fatigue life [6], [7]. With improving welding techniques, post weld and surface treatments, the initial flaws in some welded joints are so small that they can hardly be detected by current non-destructive testing methods. In this case:

1) Crack initiation life needs to be included in the fatigue life prediction so that inspection actions can be assigned at the right times.
2) Representative information on the initial flaw size in a welded joint is hard to obtain, as it is dependent on many uncontrollable factors, e.g. material, manufacture, welding techniques and post-weld treatments, etc.

If the initial flaw size in a welded joint of interest is unknown, then crack propagation models cannot be applied directly. Hence, alternative methods for crack evolution prediction need to be developed without knowing the initial flaw size.

To help throwing some light on the two issues mentioned above, this paper reviews the treatment methods for crack initiation used in inspection planning for welded joints. In the first section, a simple and commonly-used method is introduced, which is based solely on crack propagation models. This method assumes that crack initiation life is negligible and statistical information on the initial flaw size is known. Then three methods for including crack initiation life in the prediction models are reviewed in Sections III, IV and V, respectively. Section III summarizes the calibration method for whole fatigue life fracture mechanics (FM) models. Section IV introduces the calibration and testing method for crack initiation. Section V presents the strain-based method for crack initiation. Representative works with each method are summarized, and the rationales, merits, limitations and prospects of each method are identified and compared.

Unless otherwise specified, the material of welded joints discussed in this paper is steel and the unit for flaw or crack size is mm.

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## II. Crack Propagation and Initial Flaw Size

A great number of investigations on inspection planning for welded joints are based solely on crack propagation models with an assumption that crack initiation period is negligible compared to crack propagation period. For some welded joints, the assumption is reasonable, as initial flaws in the welded joints cause great stress concentration and result in practically no crack initiation life [7]. In this case, the fatigue process begins with crack propagation from an initial flaw and predictions based on crack propagation models agree well with the actual process. Initial crack size in a crack propagation model is equal to the initial flaw size. As Initial crack size is one of the most influential parameters, it is important to obtain accurate information on its value as input for prediction, e.g., its distribution and statistical characteristics.

Statistical studies on initial flaws in welded joints have been carried out based on measurements in both specimens and real engineering structures, e.g. ships, offshore platforms, bridge, nuclear plants, etc. Quantitative information on flaw sizes, shape, locations and occurrence rate is provided by several researchers. Reference [8] measures weld toe areas of butt welded joints on ship structures and finds that the occurrence rate for undercut is about 40%. As for the best-fit distribution of the depth of undercuts, he recommends an exponential distribution with a mean value $\mu = 0.11$. His work has been adopted by [9], and the distribution and mean value has been used by [10]-[12] for inspection and maintenance planning. Reference [13] studies fillet-welded attachments on marine structures and proposes a lognormal or shifted exponential distribution for the initial depth of flaws, a, with mean value $\mu = 0.125$ and standard deviation $\sigma = 0.046$. Based on specimen data, they provide a formula for flaw aspect ratio $a/c$ with depth $a$ ($c$ is the length of the flaw). Their recommendation for the distribution of $a$ is adopted by [14], who analyze data for initial crack aspect ratio and propose a lognormal distribution with $\mu = 0.395$ and $\sigma = 0.164$. Reference [15] carries out experimental studies on surface flaws in Inconel 718 weldments. Based on experimental observations they find that the initial flaw depth $a$ is best fitted by a lognormal distribution with a median value $\mu = 0.39$ and the predominant flaw shape is semicircular, e.g., aspect ratio $a_0/c_0 = 1$. Reference [16] adopts the findings by Hudak et al. in his investigations on inspection planning for ship structures. Reference [17] measures initial imperfection sizes based on specimen tests and proposes a lognormal distribution with $\mu = 0.1$ and $\sigma = 0.19$. Reference [18] studies extensively the crack database detected in tubular joints of jackets and finds that the initial size of an individual crack is best estimated by exponential distribution with a mean value $\mu = 0.19$, whereas for individual hot spot, the mean value is $\mu = 0.38$. Reference [19] analyzes crack sizes and aspect ratio in welded joints and finds that the depth of initial crack $a$ is best fitted by a lognormal distribution $\mu = 0.96$ and $\sigma = 0.35$. He also assumes that crack aspect ratio $a/c$ is a function of crack depth $a$, just like [13]. Literature review on statistical studies on initial flaws or cracks are given by Schumacher [12], [20], [21]. According to [22], defect sizes are often related to weld bead dimension.

It is generally agreed that exponential or lognormal distribution are better than other distribution in describing the scatter of initial flaw size. However, the statistical characteristics for initial flaw size, e.g. mean value $\mu$ and standard deviation $\sigma$, vary greatly between different specimens and structures. Even less conclusions can be drawn on initial crack aspect ratio, although some formulas for aspect ratio $a/c$ with depth a are proposed based on statistical analysis. Actually initial flaw size and aspect ratio dependent on factor such as material, manufacturing, welding techniques, post-weld treatments, and quality control, and thus subject to large scatter. Due to measuring and sampling difficulties, no general and representative figures can be drawn from the statistical studies.

In view of the difficulties, some approximation values for initial flaw sizes are used. Normally there are industrial standards and quality assurance measures which prescribe the maximum allowable flaw size. This value could act as an upper bound value for initial flaw size [7]. Another approximation method for initial flaw size is to use the minimum size detectable reliably by a specific inspection method. Both methods will lead to conservative prediction for fatigue life, which may be acceptable in deterministic analysis but not pursed in probabilistic analysis.

There are two major sources of uncertainties associated with using crack propagation models for inspection planning. The first one is the statistical uncertainty associated with initial crack size. The resulting fatigue life and optimum inspection plans are highly dependent on initial crack size. Before employing the models, it is suggested to check the availability of the input information for initial crack size. The second is the modeling uncertainty when using crack propagation models to predict the fatigue life. There have been tests which prove that crack initiation period exists [23]. This means that technically a transition crack size exists between crack initiation and propagation stage. However, there is no quantitative criterion when crack initiation period can be neglected. If the initial flaw size was larger than the transition crack size, then fatigue process will begin with crack propagation. However, if the physical initial flaw size was less than the transition crack size, crack initiation period should be considered. As for reliability-based inspection planning, three methods are used to take crack initiation period into account and they are introduced in Sections III, IV and V.

## III. Calibrated FM Models for the Whole Fatigue Life

A commonly-used method for predicting fatigue life is to calibrate a crack propagation model to SN curves or other specimen test data so that the FM model yields the same results as SN curves together with Miner's rule. By doing so, the crack propagation model can also include crack initiation period, as SN curves lump crack initiation period and propagation period together. This actually means to predict both the crack propagation period and initiation period with the calibrated crack propagation model. The fictitious initial flaw size is the so-called equivalent initial flaw size (EIFS) [24]-[26], and it is usually obtained by calibrating a crack propagation model to S-N curves. The EIFS is an equivalent parameter and a final manifestation of the whole crack initiation stage accounting for all manufacturing, assembly and service induced factors [27]. It cannot be compared with the physical initial flaw size introduced in Section I. Only for structural details with large initial flaws like as-weld joints, values for the two parameters may be equal. The EIFS is usually lower than the transition crack size introduced in Section V [28].

Calibration of a probabilistic FM model for a specific fatigue detail comprises of four crucial steps [29]: 1) defining the appropriate FM model; 2) defining the calibration parameters in FM model; 3) defining the calibration criterion; 4) defining the uncertainty models for the parameters in both S-N model and FM model. Different calibration parameters and criterion are used in the literature. Representative studies are introduced as follows.

In order to provide a simple and accurate model for practicing engineers, [30] calibrates a linear (1) and bi-linear (2) FM model, respectively, to the experimental crack growth curves derived from extensive testing on fillet welded joints by [31]. For both models the calibration parameters are crack growth parameter and fictitious initial crack size. Other parameters in FM models are adopted from [32]. The transition point for bi-linear model is $\Delta K_{tr} = 363\,\mathrm{N/m^{3/2}}$. For both models, the threshold value is $\Delta K_{th} = 63\,\mathrm{N/m^{3/2}}$. For both models, crack growth parameter is determined by comparing the fatigue life (number of cycles) of the detail with crack from fist measurable crack size (0.1 mm) to critical crack size (half of the plate thickness), while initial crack size is determined by comparing the fatigue life (number of cycles) of the detail with crack from initial crack size to first measurable crack size (0.1 mm).

$$\frac{da}{dN} = C(\Delta K)^m \qquad \Delta K > \Delta K_{th} \tag{1}$$

$$\begin{cases} \frac{da}{dN} = C_1(\Delta K)^{m_1} & \Delta K_{th} < \Delta K \leq \Delta K_{tr} \\ \frac{da}{dN} = C_2(\Delta K)^{m_2} & \Delta K_{tr} < \Delta K \end{cases} \tag{2}$$

where $C, C_1, C_2, m,\ m_1$ and $m_2$ are crack growth rate parameters, $\Delta K$ is stress intensity factor range, $\Delta K_{th}$ and $\Delta K_{tr}$ are threshold value and transition value for $\Delta K$.

Reference [33] provides an S-N based FM calibration model with the criterion that the difference between the fatigue lives predicted by the FM model and S-N model are minimal in the whole stress range, especially in the low stress range. In their work, a two-dimensional bi-linear model is calibrated (combination of 2 and 3), which means that crack propagation rates are different under the low and high stress intensity factor range, and crack shape evolution in two directions are considered. A case study is carried out on butt-welded plates, which corresponds to a S-N E curve in [34]. Parameters such as $C_1$, $C_2$, $m_1$, $m_1$ follow [32]. Initial crack size $a_0$ and aspect ratio $a_0/c_0$ are assumed to be log-normally distributed, and their mean values are calibrated. Three sets of values for $a_0$ and $a_0/c_0$ are defined. By comparing the fatigue lives in the whole stress range, they conclude that mean value of 0.2 and 0.1 for $a_0$ and $a_0/c_0$, respectively, with a COV of 0.2 and 0.2, respectively, agree well with the published results in rules and literature. The authors also mention that other distribution types with different mean-COV combinations for $a_0$ and $a_0/c_0$ could also yield good fitting.

$$\begin{cases} \frac{da}{dN} = C_a(\Delta K_a)^m \\ \frac{dc}{dN} = C_c(\Delta K_c)^m \end{cases} \tag{3}$$

where $C_a$ and $C_c$ are crack growth rates in depth and length direction, respectively, $\Delta K_a$ and $\Delta K_c$ are the stress intensity factor range in depth and length direction, respectively.

Reference [1] investigated the validity of a bi-linear FM model (2) for surface cracks, which are influenced greatly by the uncertainties associated with the near threshold crack propagation rates. They define four cases in terms of whether $\Delta K_{tr}$ is random and whether $\ln C_1$ and $\ln C_2$ are correlated. By comparing the reliability indexes calculated in four cases to that calculated with S-N curve C, they conclude that the bi-linear FM model with random $\Delta K_{tr}$ and correlated $\ln C_1$ and $\ln C_2$ can model surface crack propagation most appropriately. This model is then calibrated to two S-N curves for flush-welded joint (S-N curve C) and fillet-welded joint (S-N curve F), respectively, with criterion in the reliability index. The authors point out that the bi-linear FM model is rather difficult to be calibrated to S-N curves with just one parameter, as it is possible for the linear FM model. Thus, different calibration strategies are used. The calibration parameters for the linear FM model are the mean value of initial crack size $a$ and crack aspect ratio $a/c$, while for the bi-linear FM model the calibration parameters are initial crack size $a$, crack aspect ratio $a/c$ and initiation time $T_0$.

Reference [29] proposes a uniform 8-step fatigue-oriented, risk-based, inspection approach for floating production storage and offloading unit (FPSOs), in which assessment of the probability of failure is a key step. The probability of failure is calculated with FM approach using limit-state function (4). They recommend calibrating the selected FM model (5) to corresponding S-N curve. With respect to the calibration criteria, they suggest two alternatives: minimizing the difference between the probabilities of failure calculated by the FM and S-N approaches over the considered lifetime or at the end of considered lifetime. They also state that there is no generally accepted calibration procedure at the moment.

$$ln\left[\int_{a_0}^{a_c} \frac{da}{\left(A\,Y(a)\sqrt{\pi a}\right)^m}\right] - ln\left[C\upsilon T q^m \Gamma\left(1+\frac{m}{h}\right)\right] \leq 0 \tag{4}$$

$$\frac{da}{dN} = C\Delta K^m,\ \ a \geq a_0\ and\ K < K_{IC} \tag{5}$$

where $a_0$ is the initial crack size, $a_c$ is the critical crack size, $Y(a)$ is geometrical function of considered detail with uncertainty expressed by parameter $A$.

For applications of inspection planning in offshore structures, [35] calibrates a two-directional FM model (3) to a bi-linear S-N curve. The calibration is based on the criterion that the probability of a fatigue failure at a given number of stress cycles calculated with both models is similar. They consider a T-joint, corresponding to F curve in [36], under pure membrane loading. Threshold value for stress intensity factor range is neglected and the initial crack aspect ratio assumed to be $(a/c)_0 = 0.2$. Calibrations are carried out under different nominal stress ranges and different distribution types for initial crack size $a_0$ are investigated by good-for-fitness statistical tests. It is found that exponential distribution for $a_0$ led to the most relevant results. The mean for $a_0$ is 0.043 mm, which is the same magnitude of initial defect obtained by [37]. The 90% fractile level is about 0.1 mm. As it is not reasonable to calibrate a bi-linear FM model to S-N curves by just one parameter [1], they introduce variable $X_{\Delta K}$ to model the uncertainty in the stress intensity range calculation, and $X_{\Delta K}$ the uncertainty in the stress intensity magnification factor, so that the tail properties of the FM model are adjusted to the S-N model.

The calibration parameters and criteria used in the literature are summarized in Table I. The calibration parameters are usually the most influential parameters for crack initiation period and crack propagation period, and the parameters on which specific information is scarce. As can be seen from Table I, initial crack size $a_0$ and crack propagation rate $\ln C$ are the most commonly-used calibration parameters, although in some cases, initial aspect ratio $a_0/c_0$ and geometry function $Y$ are calibrated. There is no generally accepted calibration criterion. Calibration is carried out by minimizing the difference of a structural performance indicator determined by FM approach and S-N approach. Probability of failure, reliability index and fatigue life are equally used as structural performance indicators in the literature. The difference between the probabilities of failure or reliability indices can be minimized over the whole service life or at a specific service year. Similarly, the difference between fatigue lives can be minimized over the whole stress range or at a specific stress range. Standardization of calibration procedures is still worthy of investigation.

Calibrated FM models are widely-used in reliability-based inspection planning due to its simplicity. However, the validity and general applicability of a calibrated FM model are issues that need to be investigated further. The calculated EIFS is usually much smaller than the initial flaw size. The mean value of EIFS is usually smaller than 0.01 mm [38], which is outside the validity range of linear elastic fracture mechanics (LEFM). According to [39], the lower bound for validity of LEFM seems to be 0.1 mm. However, this may not be a problem, because the EIFS is an equivalent concept, and does not have the same physical meaning as the initial crack size $a_0$ in a crack propagation model. Therefore, the validity of a LEFM model in small crack dimension such as the EIFS is open. In addition, EIFS is dependent on the applied stress level and is sensitive to the parameters in crack propagation models [40]. Thus, it should be calibrated for each specific application and should not be regarded as a material property.

It should be borne in mind that extrapolating the crack propagation period to crack initiation period is a kind of approximation and will inevitably lead to conservative or progressive predictions, especially for high-quality joints, e.g. grounded welds. Such welds consume a large part of their fatigue lives on the crack initiation stages. In this case, the crack initiation lives need to be considered separately from the crack propagation lives. Studies in this aspect are introduced in the following two Sections IV and V.

TABLE I
OVERVIEW ON CALIBRATION FM MODELS TO SN CURVES

| Model | Calibration parameters | Calibration criterion | Reference |
|---|---|---|---|
| (1) and (2) | $a_0, C$<br>$a_0, C_1, C_2$ | Fatigue life | [30] |
| (2) and (3) | $a_0, a_0/c_0$ | fatigue life in the whole stress range | [33] |
| (2) and (3)<br>(1) and (3) | $a_0, a/c, N_I$<br>$a_0, a/c$ | Reliability index | [1] |
| (5) | $a_0$ or $Y$ or $\ln C$ | Probability of failure over the lifetime or at the end of lifetime. | [29] |
| (3) | $a_0$ | Probability of failure at a given time | [35] |

## IV. CRACK INITIATION LIFE BY CALIBRATION OR TESTING

A very simple method is to treat the crack initiation life as a probabilistic variable $N_I$, and obtain the statistical information on $N_I$ by measuring from specimen tests or calibrating to S-N curves. A prediction model for the whole fatigue process is them formed by adding the crack initiation life to the crack propagation life predicted by a crack propagation model.

The first published work is reported by [38]. They conduct a series of tests on fillet welded joints classified as S-N F curve in [41]. The specimens are tested under constant amplitude axial loading at $\Delta S = 150$MPa with a loading ratio of $R = 0.3$. Crack growth curves are measured from the first measurable crack size ($a_0$=0.1 mm) to the final critical crack size ($a_c$=0.5$t$, $t$ was the plate thickness) and the corresponding cycles spent is defined as $N_p$. The number of cycles to reach 0.1 mm is recorded and defined as $N_I$. Statistical studies show $N_I$ has a mean value of 145,000 cycles with a COV of 0.34, and $N_p$ has a mean value of 323,000 cycles with a COV of 0.22. A correlation coefficient $\rho = 0.48$ is found between $N_I$ and $N_p$. The mean value of the total number of cycles from the beginning to failure $N_T$ is close to the value given by Eurocode3 for this type of joint. It is thus thought that the test data is representative for this type of welded steel joints. The test data shows that approximately 31% of the fatigue life is spent before a crack depth of 0.1 mm is reached. Based on experimental investigations, they propose the use of the following formula to predict the whole fatigue life of a welded steel joint:

$$N = \left\{ N_I + \int_{a_1}^{a_c} \frac{da}{C\left(\Delta\sigma\sqrt{\pi a}F(a)\right)^m} \right\} Z_F \quad (6)$$

where the variable $Z_F$ is an external variable accounting for additional scatter in overall geometry, fabrication tolerances and workmanship. The geometry function $F(a)$ derived by [42], which provides an analytical solution for the limit state function. The crack initiation period $N_I$ is determined by:

$$N_I = N_{I_0} \frac{(150\text{Nmm}^{-2})^{m_1}}{\text{E}[\Delta S^{m_1}]} \tag{7}$$

where $N_{I_0}$ is modeled by a Weibull distribution with a mean value of 145,000 cycles with a COV of 0.34, and is assumed correlated to the crack propagation parameter $C$.

In order to model the influence of inspections, [43] calibrates a two-dimensional FM model to probabilistic S-N model using Miner's rule. In their studies, calibration is carried out with a criterion based on probability distribution functions for the fatigue live determined from FM model and S-N model, rather than the commonly used criterion based on reliability level. The fatigue life is assumed to be represented by a fatigue crack initiation life $N_I$ and a crack propagation life $N_P$. Crack initiation life $N_I$ is modeled as Weibull distributed with a COV of 0.35 [38]. The mean values for $N_I$ and $\ln C$ are calibrated. It is considered that $N_I$ and $\ln C$ is correlated with correlation coefficient $\rho_{N_I,\ln C}$=-0.5. Two different values for crack depth value at initiation are introduced to represent high and low welding quality control, and the stochastic model for S-N approach provided by [44] was used.

The method of modeling the crack initiation life as a probabilistic variable $N_I$ has also been used by [1] to calibrate a bi-linear FM model. They calibrate the mean value of $N_I$ to SN curves, rather than obtain the statistical information on $N_I$ from specimen tests [38]. Calibrating the crack initiation time $N_I$ to S-N curves is also employed by [45], [46] for providing a reliable model to aid inspection planning for offshore structural details. In this method, crack initiation is taken into account by simply introducing an additional parameter $N_I$ to an existing crack propagation model, but it can be very expensive to obtain time-to-crack initiation data by experimental methods, given that special crack evolution monitoring gages are required [47]. Also, it should be noted that in this method the transition crack size between crack initiation and propagation stage is defined as the smallest crack size which can be measured reliably by a non-destructive inspection method. This is not the physical transition crack size between crack initiation and propagation weld joints, which should be between 0.05 and 0.1 mm [48].

## V. Strain-Based Method for Crack Initiation

Fatigue cracking usually happens in the dimension that is much smaller than the smallest crack size that can be reliably detected by non-destructive inspection methods, and as a result, it is not necessary to understand the mechanisms of crack initiation for inspection planning. However the crack initiation life must be predicted accurately and the transition point between crack initiation and propagation stage is the first question that must be addressed.

Several definitions for the transition crack size are available. Reference [50] describes transition between crack initiation and propagation as the point when fatigue damage caused by crack propagation mechanism exceeds that caused by the crack initiation mechanism. His definition is easily understandable, but is difficult to be implemented in a probabilistic format [7]. Reference [51] provides the explicit expression below for transition crack size:

$$a_{tr} = \frac{a_{ini}}{(1.12k_t/\beta)^2 - 1} + a_{ini} \tag{8}$$

where $a_{ini}$ is the initial flaw size, $k_t$ is stress intensity factor (SIF) for a short crack, $\beta$ is product of correction factors for SIF, such as crack shape correction factor, finite width correction factor, stress gradient correction factor, etc.

In spite of those definitions, [52] states that a rigorously and physically satisfactory definition for the transition between crack initiation and propagation is not available, although some rough guidance is provided in the literature. Reference [48] suggests that the transition depth $a_{tr}$ should be between 0.05 and 0.1 mm. Often practitioners just set the transition depth to 0.25 mm arbitrarily [49]. Reference [53] proposes a transition crack size about 0.5 mm in depth and 1 mm in length for semi-elliptical surface cracks in medium strength steel. The transition depth of 0.5 mm is adopted by [54]. Reference [55] noted that the exact transition point can vary between some hundred micrometers to millimeters for different materials.

Reference [6] investigates the sensitivities of total fatigue life to the transition crack depth by setting it equal to the lower and upper bound given by [48], and compares the predicted fatigue lives with that obtained from specimen tests. It is found that the band provided by [48] is reasonable for transition crack depth and any value of transition crack depth in this band will yield fatigue life within the scatter of test data. In addition, they recommend using the upper bound of 0.1 mm as the value for transition depth based on considerations in the validity of LEFM, qualities of inspection methods, and concerns of in-service inspections.

Some researchers have also used analytical prediction methods for crack initiation in order to optimize inspection strategies. Reference [56] shows the strain-based method gives more accurate results than the stress-based method for welded details, in which localized high stresses are often present. Representative work using the strain-based method for crack initiation is carried out by [6]. Combined with FM, they propose an integrated two-phase method for fatigue life prediction of welded joints and use it for scheduling inspection actions. A typical fillet-welded T joint is selected to illustrate the method. The transition crack depth $a_{tr}$, as introduced previously, is set to 0.1 mm. The number of cycles for crack initiation $N_I$ is determined by the Coffin-Manson Equation with Morrow's mean stress correction [48], [57]:

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f' - \sigma_m)}{E}(2N_i)^b + \varepsilon_f'(2N_i)^c \tag{9}$$

where $b$ and $c$ are the fatigue strength and ductility exponents, respectively, $\sigma_f'$ and $\varepsilon_f'$ are the fatigue strength and ductility coefficients, respectively. The local stress and strain is governed by the Ramberg-Osgood stabilized cyclic strain curve.

$$\Delta\varepsilon = \frac{\Delta\sigma}{E} + 2\left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{10}$$

where $K'$ and $n'$ are the cyclic strength coefficient and strain hardening exponent.

The parameters in (9) and (10) are determined from serial test data on number of cycles accumulated to develop a crack depth of 0.1 mm. Further, a dependency between those parameters with the Brinell Hardness (HB) is assumed so that the value for HB can be computed from the test data. Then those parameters could be calculated with the HB value. The proposed model is then used to predict crack evolution for inspection planning. The crack predicted by the proposed mode is found to be much smaller than that predict by FM model at the early stage, which makes the crack more difficult to be detected. This means that increased inspections at the later stage of service life are favorable.

The method introduced by [6] is also employed by [7] to develop a reliability-based model for fatigue life prediction of steel components, which is subsequently used to study the performance of different post-weld treatment methods. The method is also used by [58], [59] to predict the fatigue life of bolted or riveted joints.

Although the analytical prediction method is based on the mechanical behaviors of crack initiation, and thus it is more sophisticated than the methods introduced in Section III and IV, it is not frequently used in inspection planning. The reasons may lie in three aspects. Firstly, at the moment there is no agreement on the transition point between crack initiation and propagation stage. Although there are some recommended values in literature, they are generally based on rather weak theoretical analysis and cannot be validated. As long as the transition size is uncertain, any two-phase model would be difficult to prove to be more accurate than other prediction models. Secondly, the parameters $b$, $c$, $K'$ and $n'$ in the strain-based model rely on measurements. From an engineering point, this is somewhat impractical, especially for large engineering structures where thousands of fatigue-prone joints exist. Lastly, it involves more computational efforts to predict both the crack initiation and propagation life by analytical methods. This is not favorable, especially in a probabilistic analysis context such as inspection planning, as millions of samples for every variable need to be generated in order to calculate a rather low probability of structural failure.

## VI. Conclusion

Fatigue cracks in welded joints are the concerns of many researchers in structural engineering. A decisive step in life-cycle management of weld joints is calculation of probability of failure against fatigue and fracture, which is usually, based on reliable prediction methods. This paper has reviewed the prediction methods for fatigue cracks in weld joints, with focus on how crack initiation period is treated. The main concepts relating to these methods are initial flaw size, EIFS, transition crack size and time-to-crack-initiation.

For prediction of fatigue life and crack evolution, an accurate definition of transition point between crack initiation and propagation stage is required. Studies on this point are, however, unsatisfactory. Several definitions are provided in the literature, but they are generally intuitive and have not been verified. Some rough guidance on the transition size for steel welded joints is provided, but the proposed values vary from some hundred micrometers to millimeters. According to [6], a value 0.1 mm is favored for reliability-based inspection planning. This valued is within the band given by [48]. If the transition point was clear, the whole fatigue life of welded joints could then be modeled in detail by the two-phase method, which predicts the number of cycles to reach the transition crack size by Coffin-Manson Equation. Some fundamental analytical and experimental work needs to be done to provide a sound theoretical basis for an accurate definition of transition point.

As the transition size is somewhat dubious, at present there are works that avoid the issue by assuming a relatively large initial flaw or crack size as an input parameter in crack propagation models. In this way, the fatigue life of welded joints can be modeled solely by crack propagation models. This method is widely used in reliability-based inspection planning. In the meanwhile, some researchers have conducted statistical studies on the data collected from specimens or real structures. The conclusion is that initial flaw size in welded joints can describe better by exponential and lognormal distribution than other distributions. More information on the dimensions for initial flaws shall be available as more test data and in-service data are collected and with the aid of modern characterization methods in material science.

Two engineering methods are available to take the initiation period into account based on the crack propagation models. One is to extrapolate the crack propagation stage to a very small fictitious EIFS so that the whole fatigue life is predicted by a crack propagation model. EIFS is obtained by calibration a crack propagation model to S-N curves or other test data on fatigue life. The other is to add the time-to-crack-initiation (TTCI) to the crack propagation life. TTCI can also be obtained by calibration or be measured by specimen tests. As measuring TTCI by experimental methods is costly [47], alternatives such as calibrating to S-N curves or using empirical equation (7) are desirable.

In conclusion, calibration of a crack propagation model to S-N curves to obtain an EIFS or TTCI seems to be a practical way at present, although further investigation is required, so that questions like how to select calibration criterion and how to derive an EIFS independent of stress level can be objectively answered.

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