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A Review on Impact of Notch Length on Fatigue Life of Metals

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ABSTRACT: Fatigue has become progressively more relevant for technological development in automobiles, aircraft, compressors, pumps, turbines, etc., subject to repeated loading and vibration. Fatigue failure is particularly insidious because it occurs without any obvious warning. The current review discusses the fatigue failure in metals with special emphasis on the impact of notch length on their fatigue life. The effect of stress concentration due to notch on the member is discussed. The scope of the review also includes a detailed discussion on the fatigue life estimation methods of notched members. It is clearly evident from previous literature that notch length has a vital impact on the fatigue life of a structural member and the life decreases drastically even when the length of the notch increases marginally after certain threshold length.

KEYWORDS: Fatigue, Notch length, stress concentration, global methods, local methods

I. INTRODUCTION

Material fatigue is a phenomenon where structures fail when exposed to a repeated load. This type of structural damage might even occur when the applied stress range is lower than the static material strength. Fatigue is one of the most basic sources of the reason for failures of mechanical structures. Fatigue failures inevitably start at some form of geometrical interruption. The most common failure mode of structures and its components subjected to cyclic stresses/strains.

The process is divided into 3 Phases according to where the component finally fails under continuous loading are as follows:

- The crack formed when the load applied might be transformed from microscopic to the macroscopic level. During many cyclic loads.
- The macroscopic crack grows for each cycle of the load until it reaches a critical length.
- The cracked segment breaks since it can no longer sustain the peak load.

The second stage cannot be seen in certain applications. As the Microscopic crack grows quickly, causing sudden breakage of the component.

Fatigue life is a mechanical and scientific term that identifies until what extent the object or material will last before total failing because of concentrated stresses. There are various factors that can impact the fatigue life including the type of materials being utilized, its structure, and its shape and temperature changes.

In general, fatigue is considered as a high cycle when the peak stresses in the material are held within the elastic range while low cycle fatigue occurs when stresses are above the elastic limit. This arbitrary division can be different for material-to-material depending upon tensile properties.

When fatigue occurs higher than 10^3 cycles, which is in the range of 10^3 to 10^6 cycles is called a high-cycle fatigue model while the low-cycle fatigue model is in a range of 10^2 to 10^3 cycles. The stress levels in high-cycle fatigue are in

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elastic range and vary from very low to a tune of 2/3 of yield stress whereas, in low-cycle fatigue model, the stresses applied often fall in the plastic range.

Fatigue analysis isn't continually dependent on a stress response. This branch, in any case, has historically gotten much consideration since the dominant parts of research has been performed in administrations where stress-based models are suitable. The difference between low-cycle fatigue (LCF) and high cycle fatigue (HCF) can be made depending upon the number of load cycles needed to yield a crack. The limit between the two cycles is not discrete. However, it is typically of the order of 10,000 cycles. The physical method of reasoning in the case of HCF, the stresses are low enough that the stress-strain relation can be considered elastic. When working with HCF, the stress range is typically utilized for describing the local state. In the meantime, for LCF the strain range or dissipated energy are the common choices.

II. EFFECT OF NOTCH ON FATIGUE LIFE

The major obstacle in the study of fatigue is the notch effect and notches cannot be avoided in many structures and machines because the notch effect of the details controls largely the fatigue strength of a component. The term Notch effect is explained as a mixture of the stress concentration and strength reduction by notch. To find out the effects of notches one must consider five parameters [1]:

1. Concentrations of stress and of strain.
2. Stress gradients.
3. Mean stress effects and residual stresses.
4. Local yielding.
5. Development and growth of cracks

In a fracture, the notch effect is elucidated by the fact that the critical gross stress of a notched structure is less than the critical net stress which acts on the remaining ligament area under the notch tip. The notch effect in a fracture is highly sensitive to structure geometry, scale effects and loading mode. The stress concentration created by a given notch is not a unique number as it highly depends on the mode of loading. Elastic stress concentration factors depend solely on geometry (which does not depend on type of material) and mode of loading, and that they only come into picture when the notch is under linear elastic deformation condition. Elastic stress concentration factors are obtained from:

- Theory of elasticity
- Numerical solutions
- Experimental measurements

G. Birkbeck, A. E. Inckle(1971) observed that transformation from structure sensitive to structure insensitive Stage II fatigue crack propagation in carbon steels. The crack propagation length is determined by the ratio of plastic zone radius at the crack tip to the grain diameter, Controlling factor for the transition from Stage IIa to Stage IIb plastic zone size at the tip of the advancing crack and its relationship to grain size of the material [2].

Smith and Miller (1977) Elucidating the cracks in notched and un-notched specimens are identical When they have the same growth rate under the similar bulk stress conditions, a subscription to crack length is determined as the cracks growth in notch stress-strain area. Experimentally procure values of the notch subscriptions were in unexpected agreement with theoretical prophecy. A optimization of the notch contribution is made to catalyze the prediction of the fatigue crack propagation rates on any of notch length, the estimated extent of the notch stress-strain area is given by $0.13\sqrt{(Dp)}$, where D and P are notch depth and the root radius respectively. The easier to understand the design rule which was used to estimate fatigue crack propagation being for various notched specimens from data obtained by an un-notched specimen. The total lifetime is the sum of the life spent with the crack growing first in the notch area and then in the bulk area. Effective correlations with experimental data were obtained.[3].

Guy Pluvinage&Gjonaj(2001) they had concluded that this notch effect in fatigue is typified by the fact that the notched specimen Wohler curve is below the smooth specimen curve. For high cycle fatigue, the theory of efficacious stress range is able to represent the notch impact. For low cycle fatigue, the explanation is done in terms of effective strain energy density. The effect of the notch will depend on the specimen geometry and loading mode for same

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maximum stress/stress range value. The position of maximum stress is not at the notch tip and not connected with the point of fracture or fatigue inception[4].

Notch effects in fatigue are distinguish by the fatigue life duration for the same stress amplitude being less, for a notched member than for a similar plain un-notched specimen, Notch effects in fatigue can be quantified by the fatigue strength reduction factor K_f , The fatigue strength reduction factor it isa function of the notch radius[5].

The effect of the notch in the stress-life approach is taken into account by modifying the un-notched S-N curve through the use of the fatigue notch factor, K_f . Notched fatigue strength not only depends on the stress concentration factor, but also on other factors such as the notch radius, material strength, and mean and alternating stress levels. The ratio of un-notched fatigue strength to net notched fatigue strengths on the alternating stresses is called K_f [6].

$$K_f = (\text{Un-Notched fatigue strength}) / (\text{Notched fatigue strength})$$

Majzoobi&Daemi(2010) investigated on three types of notch geometries V-shape, U-shape and -shape notches notch sensitivity is influenced by many parameters one of it was notch geometry. The results showed that the notch geometry has intense effect on fatigue life of materials. The investigated on HS steel and also on LS-steel alloy reduction depends on fatigue life and varies from 20% for low cycle fatigue tests up to 75% for high cycles fatigue tests. They observed that the maximum and minimum fatigue life reduction occurs for the V-shape and U-shape notches, respectively[7].

Chapetti & Guerrero (2013) they had unified fracture mechanics approach which is proposed to evaluate the fatigue notch sensitivity by incorporating the effect of both dull and sharp notches. Depending on the stress concentration k_t , the notch length D and the material threshold to crack initiation, to short crack propagation and too long crack propagation. It opens the way to a new simple method for prophesying fatigue notch sensitivity and fatigue strength of components with geometric concentrator by using parameters that can be easily measured or evaluated, without the necessity of any fitting parameter[8].

III. NOTCHED MEMBER FATIGUE LIFE ESTIMATION METHODS

The popular fatigue life assessment methods can be classified as follows[9];

- Global Methods
 - Nominal stress method.
- Local Methods
 - Local strain method
 - Local stress method
 - Fracture mechanics method
 - Hot spot method

Nominal stress method

Nominal stress method for the estimation of fatigue strength, is being used for over 150 years. For welded structures, this method is the most popular and simplest method for evaluating fatigue life durability. All kinds of details and a large number of fatigue test results are taken into consideration for the nominal stress method or approach.[10].

“Design of steel structures - Part 1-9: Fatigue,” (2003) A nominal stress multiplied by an appropriate stress concentration factor to allow for a geometric discontinuity that has not been taken into account in the classification of a particular constructional detail[11].

Ye, Su, & Han, (2014) for comparatively complicated structures, they used finite element method to find out nominal stresses and for simple structural components linear elastic structural mechanics can be used. Strain gauges can also be used to obtain nominal stress where the gauges are deployed outside the stress concentration field of the welded joints. The major drawback is that it ignores largely the actual variations in dimensions of a specific structure, so the fatigue life predicted by nominal stress is unreliable for some structural components of steel bridges[12].

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Local strain method

The strain- life method built in the 1960s is mainly focused with the crack initiation stage. It is employed when the strain is no longer totally elastic but has a plastic component. Under these conditions, short fatigue lives in LCF regime. Socie, Morrow and Chen, (1979) they created model to estimate fatigue strength of notched and cracked members by combining strain cycle fatigue and fracture mechanics concepts. It includes both crack initiation and crack propagation concepts. And also they observed that the Crack propagation becomes progressively more important at longer fatigue lives in notched specimens, where as in smooth specimens the opposite effect that is the amount of life spent in crack propagation decreases with decreasing stress level. Crack initiation lengths in various engineering materials appear to be between 0.001 and 0.010 m. The model created by them is integrated with material properties, loading, and geometric parameters which makes crack initiation length hence, the total life spent in crack initiation, vary in suitable manner with these factors [13].

Dowling, (1979) in those years there are two sophisticated methods, they are local strain approach and fracture mechanics approach applicable to crack initiation, and crack propagation respectively. The author used these two approaches in combination to predict total fatigue life. Fatigue life of notched members are considered to be divided into crack initiation and propagation stages. Total fatigue life of notched members are predicted by adding crack initiation and propagation lives, those are determined from the local strain and fracture mechanics approaches, respectively. The procedure for predicting total fatigue life also account for the major source of apparent notch size effect, namely crack propagation by the local notch stress field [14].

Local stress method

Stress-life method is suitable for HCF and primarily used for long fatigue life prediction where stresses and strains are generally elastic. It cannot differentiate between crack initiation and propagation but concerned with total life or the life to failure of a structural component. Stress-life method depicts a relationship between the stress range and fatigue failure in the form of $S-N$ curves, obtained by cycling test specimens at constant amplitude stresses till visible cracking occurs. Those kind of tests are repeated several times at different stress levels to firmly establish the $S-N$ curves. Wohler was the pioneer researcher who tried to quantify the fatigue strength in connection with the experimental results of the metal endurance and also investigated the fatigue failure in railroad axles for German Railway Industry. His work also demonstrated the characterization of fatigue behavior as the applied stress versus the cycles to failure and also the concept of fatigue limit.

Tanaka & Nakai, (1983) they used crack closure measurements for identifying the short fatigue crack near the notch tip. A short fatigue crack first slowdown with increasing crack length, and then it becomes non-propagating near the notch tip depending on the stress applied. They observed that the growth of a fatigue crack in the vicinity of a sharp notch was observed in centre-notched plates of low-carbon steel fatigued under the stress level near the fatigue limit. The growth behaviour was measured based on crack closure. [15].

Lazzarin, Tovo, Meneghetti, & Atzori (1997) Summarizes the results obtained from the experimental work carried out in a deep drawing steel and in a cast aluminium alloy to analyse the initiation and propagation of fatigue cracks on plates. The tested plates were signalized by lateral V and U-shape symmetric notches, They proposed life two new parameters to estimate the crack initiation; they are not based on the peak values of strain and stress, but on the averaged values of such quantities in the vicinity of the notch tip. The proposed two new parameters are in order to estimate fatigue strength notch reduction. The first new parameter is averaged stress-strain values over a depth from the notch tip. second new parameter is stress-strain values calculated at a fixed distance from the notch root, they integrated Paris' law to estimate fatigue lives for notched specimens by adding the determined number of cycles to crack initiation to the number of cycles of crack propagation [16].

Newman (1997) proposed using "small-crack theory" for various materials and loading conditions for the capabilities of a plasticity-induced crack-closure model to predict fatigue lives of metallic materials. The model was calibrated to calculate small- and large crack growth rates and also predict total fatigue lives, by testing notched and un-notched specimens made of two aluminium alloys and a steel under constant-amplitude and spectrum loading. The Calculated and predicted fatigue lives for un-notched and notched specimens made of two aluminium alloys are compared well with tested data under constant-amplitude and spectrum loading [17].

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Fracture mechanics method

The fracture mechanics method is generally applied to forecast the propagation life from an initial crack or a defect. This method of linear elastic fracture mechanics (LEFM) relates the growth. The fatigue crack growth is popularly explained by Paris's rule which is expressed by Paris and Erdogan as an initial crack of size to the number of fatigue cycles.

Pluvinage (1998) observed that the stress distribution at notch tip behaves like a pseudo-stress singularity characterised by the notch stress intensity factor (NSIF) K_z . The censorious value of K_z can be used to determine the fracture toughness of the brittle materials from notched specimens. This notch effect is related to the physical nature of the fracture process. The stress gradient at notch tip cannot be too critical in order to allow mean stress in this volume to be high enough. The use of this assumption called the hot spot approach but it always leads to an overestimation of fatigue stress. A notch gives more intricate stress distribution than a crack, in this zone a pseudo-stress singularity has been observed. In that case the stress distribution is a negative power of the distance. [18].

Hot spot method

Compared to nominal stress method, hot spot method can be used as a substitute method for fatigue analysis of complicated welded joints which is more accurate and reasonable. For complete calculations of the hot spot stress which involves the complete process of modelling and experiments, the International Institute of Welding (IIW) provides comprehensive rules and explicit recommendations.

G Pluvinage(2001) Notch effects in fatigue and fracture can be construed by a "volumetric approach" which can consider loading mode, and geometric and scale impact. This approach varies from the standard "hot spot" approach since it proposes the presence of a fatigue or fracture process volume. The fracture effective stress is construed as an average stress in this volume. For HCF, the effective stress range is a normal estimation of distance at a relative stress gradient and a weighted stress. For LCF, the similar strategy can be utilized with the strain energy density range[19].

Varvani-Farahani, Kodric, & Ghahramani(2005) they presented means to evaluate the fatigue damage of un-notched and notched segments utilizing a recently created energy-based critical plane fatigue damage parameter. For notched fatigue information, Neuber's analysis has been utilized to ascertain the local stress and strain segments at the notch root. He gave the process for fatigue damage life prediction in view of Varvani's fatigue damage parameter. The stress and strain segments utilized in life prediction of notched and un-notched segments were measured to be localized stress/strain quantities. An energy-based critical plane damage parameter has been effectively utilized to forecast the fatigue life of notched and un-notched segments of several materials. The Varvani damage parameter effectively anticipated the fatigue life information of notched and un-notched segments subjected to tension, torsion, and tension-torsion fatigue loading conditions inside a factor of 1.1–3.2 or better[20].

Sridhar, Kumar, & Gogia(2005) LCF life can be essentially impacted by notches present in segments and the latter isn't accounted by the information depending on smooth specimens. Essentially impacted by notches present in segments and the latter isn't accounted by the information depending on smooth specimens. He analyzed between the smooth and tangential notch specimens deprived of much variety in their surface area or volume. In the current study, the impact of tangential slot notch on LCF life of Alloy 718 has been calculated at 25⁰C and 650⁰C. Fatigue life of slot notch specimen is lower than that of smooth specimens both at ambient and elevated temperature[21].

Steel, Zareze, Trajno, & Trdnost(2007) fatigue strength of spring steels is performed utilizing standard Charpy V-notched specimens with the intention to obtain a suitable contrast with the results of technological tests on real springs. The performed examination could be utilized for quality control and improvements to the properties of the steel springs. The attained S-N curves and the determined notched fatigue strength one can just anticipate the real fatigue strength of the spring steel by the application of the corresponding stress-concentration factor[22].

Joadder, Shit, Acharyya, & Dhar(2011) they determined the outcomes got that the total strain-life curve created from the fatigue test of round specimen could also be utilized for the forecast of life for notched specimens based on actual strain developed at notch tip. The real disappointment might be administered by the over-all stress state in the cross-section.

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At that point, if the life is anticipated based on the average strain in the notched cross section a better match might be attained[23].

Santecchia, E.Hamouda, A. M. S.Musharavati, F.Zalnezhad(2016) Starting from the introduction of the linear damage rule, a huge number of fatigue life prediction models have been proposed, yet none of these can be universally accepted. Authors all over the world put efforts into modifying and extending the already existing theories, in order to account for all the variables playing key roles during cyclic applications of loadings. In the present assessment paper, numerous forecast techniques grew so far are discussed. Specific accentuation will be given to the forecast of the crack instigation and growth stages, having a significant role in the over-all fatigue life forecast. The concepts of damage accretion and continuum damage mechanics are explained, and the forecast techniques based on these two approaches are deliberated in detail. The complexity of the fatigue problem makes this topic actual and interesting theories using new approaches arise continuously[24]

VI. CONCLUSIONS

Fatigue failure in metals is impacted to a large extent by the length of notch. The effect of stress concentration due to notch on the member is profound. It is clearly evident from literature that notch length has a vital impact on the fatigue life of a structural member and the life decreases drastically even when the length of the notch increases marginally after certain threshold length.

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