A Review on the Mechanisms and Analysis of Fatigue in Ductile Materials

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ABSTRACT

In civil engineering, fatigue can be referred to as the loss in structural performance of engineering components when subjected to repeated cyclic loads. Fatigue is identified as one of the leading factors that determines the lifespan of an engineering structure. Fatigue develops in the form of small and localized cracks which gradually propagates subcritically until the engineering component is structurally incapable to satisfy the serviceability conditions and ultimately fails. Due to the engineering importance of the phenomenon, fatigue is studied extensively in order to obtain a better understanding of the phenomenon and its manifestation in different engineering components. Over the years a number of mechanisms and models have been developed in order to explain, analyze and predict the effects of the phenomenon on various components. The three key factors that have been identified to have influenced the fatigue life of engineering components include the material properties of the engineering component, the geometry of the engineering component and the load pattern to which the engineering component is subjected. This paper aims to give a brief and consolidated overview of the various mechanisms, the different models and the influence of the various factors on the fatigue performance of components composed of ductile materials.

Keywords: Fatigue, Fatigue Analysis.

1 INTRODUCTION

Fatigue refers to the weakening of materials when subjected to repeated loading cycles which results in progressive and localized structural damage which manifests in the form of small cracks which propagates into larger cracks and ultimately causes structural failure. Fatigue is an important engineering phenomenon as fatigue weakening and the failure of the structural member may occur even when the applied load cycle is significantly lower than the ultimate load the member can carry and permissible failure may occur at lower load levels than the serviceability requirements. Fatigue weakening affects the ultimate lifespan and thus the longevity of a structure.

Engineering has advanced so much over the years and the global infrastructure has been growing at a rate which has never been witnessed before. The rapid growth of the construction sector and the strive towards sustainability has made it a necessity that the structures are build ensuring the maximum possible life for it. Fatigue has been identified as one of the major causes that puts buildings out of commission and fatigue life analysis helps us to understand the probable effects on a structural member due to repeated load cycles and also helps to predict the fatigue life span as well as the probable mode of failure the member may undergo. There are a number of established methods to conduct fatigue analysis and fatigue life predictions and standards set in place in order to ensure minimum life before a structure undergoes failure.

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2 FATIGUE FAILURE

Fatigue failure is a process that manifests slowly and can be divided into three distinct phases including crack initiation, crack propagation and final rupture. Even though fatigue failure is a gradual process that manifests slowly the final rupture often shows brittle characteristics with relatively very little plastic deformation. Brittle failure often means the failure is sudden and has chances of being catastrophic.

2.1 Fatigue Crack Initiation

Crack initiation refers to the nucleation of cracks due to repeated loading and usually occurs at areas of stress concentrations. There are many theories used to explain the crack initiation due to fatigue. Some early theories explaining fatigue cracks include Gough's Postulates which defined crack initiation as a consequence of the local strain hardening limit being exceeded and Orowan's theory which argued that the cause of fatigue crack initiation is the localized exhaustion of ductility which causes and increase in the localized stresses acting at the area which ultimately leads to cracking. The basic cause of fatigue crack has been identified to be the phenomenon of slips and was first proposed by Forsyth whose theory laid down the significance of the material surface, the irreversibility of the cyclic slip and the environmental effects on microcrack initiation (Forsyth, 1953). The modern theories are derivatives of the slip theory and emphasized on the importance of the localized plastic strains that causes the formation of high slip areas called persistent slip bands (PSBs) (Lukas and Kunz, 2004).

The empirical equation derived by Coffin-Manson (1954) can be considered as the first reliable model to explain fatigue crack initiation in materials which can be expressed as:

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f {N_c}^c \tag{1}$$

Where $(\Delta\varepsilon_p/2)$ represents the plain strain amplitude, ε_f is an empirical constant called fatigue ductility coefficient, N_c is the number of stress cycles for crack nucleation and c is an empirical power index called fatigue ductility exponent and falls in the narrow range between -0.45 to -0.65 for most metals and alloys.

In 1981, Tanaka and Mura developed a theoretical fatigue crack nucleation model in terms of continuously distributed dislocation dipole pile-ups which can be expressed as:

$$N_c = \frac{4\pi(1-\upsilon)w_s a^3}{\mu}\Delta\gamma^{-2} \tag{2}$$

$$N_c = \frac{4\mu w_s}{\pi(1-\upsilon)a}(\Delta\tau - 2k)^{-2} \tag{3}$$

where υ is the Poisson's ratio, w_s is the fracture energy for unit area, a is the half grain size, μ is the shear modulus of the material, $\Delta\gamma$ is the range of cyclic plastic strain, $\Delta\tau$ is the range of the cyclic shear stress and k is the friction stress.

Tanaka and Mura (1982) extended the initial model to accommodate the fact that the inclusions and other impurities in a metal or alloy acts as areas of stress concentration in high strength alloys, which caused localized plastic strains and thus initiated fatigue crack initiation. Mura (1994) proposed that the loading cycle causes positive and negative dislocations at the slip points which were then accumulated by a ratcheting mechanism, which increased the elastic strain energy and ultimately causing cracking.

Wu (2017) identified that the original Tanaka-Mura relation (Eqn. 1 and Eqn. 2) is rarely used due to dimensional problems and introduced and validated an extended version of the Tanaka-Mura model which can be expressed as:

$$N_c = \frac{8(1-\upsilon)w_s}{\mu b \Delta\gamma^2} \tag{4}$$

$$N_c = \frac{2\mu w_s}{b(1-\nu)(\Delta\tau - 2k)^2} \tag{5}$$

where b is the Burger's vector. The model proposed by Wu removes the term ba^3 from the Tanaka-Mura model to achieve dimensional unity.

2.2 Fatigue Crack Growth

Crack propagation refers to the growth of cracks under repeated loading cycles and accounts for the majority of the fatigue failure life. Fatigue crack growth is strongly influenced by the applied stress levels and the extend of near tip plasticity (Suresh, 1998). Research have been conducted widely to model crack growth and the breakthrough was by Paris and Erdogan who used linear elastic fracture mechanics to model crack growth (Paris and Erdogan, 1963). The model explains the rate of crack growth as function of the stress intensity and can be expressed as:

$$\frac{da}{dN} = C(\Delta \mathrm{K}\,)^m \tag{6}$$

where da/dN represent the fatigue crack growth for N load cycles, C and m are experimentally obtained material coefficients that depends on a number of environmental parameters and (ΔK) is the stress intensity factor range defined as $\Delta K = K_{max} - K_{min}$, the difference between the maximum and minimum stress intensity factors. In the Paris-Erdogan equation the material constant C was so dependent on the value of the parameter m, that the dimensional parameters of C cannot be determined before the value and dimensions of m is known (Castillo and Fernandez-Canteli, 2009). Most of the modern crack growth models and studies on crack propagation are derivatives of the original Paris-Erdogan equation (Ritchie,1999; Pugno et al., 2006; Frank et al., 2012; Varavka et al., 2016) and the dimensional inconsistencies were persistent.

2.3 Final Rupture

The final rupture of engineering components occurs when the crack propagation has grown to such extends that the remaining cross-section is too small to support the applied load. The final rupture is usually a brittle failure even in tensile materials, thus sudden and might be catastrophic. Many structures have been deemed unfit for service due to the effects fatigue have had on the building over time. Studies on the mechanism of crack initiation and propagation have helped to predict the fatigue life that can be expected out of various structural members.

3 Fatigue Analysis

Fatigue analysis involves the study of the various effects repeated loading may have on engineering components. Fatigue causes a minute decrement in the structural performance of an engineering component with each applied load cycle. Fatigue analysis helps to predict the fatigue life of engineering components which refers to the number of loads cycles the member can withstand before undergoing failure.

3.1 Types of Fatigue

The fatigue life of an engineering component is highly dependent on the type of deformation each loading cycle may have on the engineering component. In order to account for this variation in the fatigue life due to individual deformations, the provisions for fatigue life analysis are often divided as low cycle fatigue, high cycle fatigue and ultra-high cycle fatigue based on the type of deformation each load cycle. Low cycle fatigue is characterized by repeated plastic deformation in each loading cycle whereas high cycle fatigue is characterized by repeated elastic deformations. If the cyclic load applied is so small as compared to the yield strength of the structural member that it is incapable of causing any deformation the member may withstand a large number of loading cycle and this is called ultra-high cycle fatigue. While there is no clear distinction, generally low cycle fatigue refers to when a member is subjected to less than 10^3 loading cycles, while high cycle fatigues is taken to be between 10^3 and 10^6 loading cycles and ultra-high cycle fatigue is when a member can withstand more than 10^6 loading cycles.

3.2 Factors Affecting Fatigue

The major factors found to influence the fatigue life of a structural member are the cyclic material properties, the component geometry and the loading patterns to which the component is subjected. The factors are used to conduct a static stress-strain analysis which is then used to conduct a damage analysis, where the small incremental damage occurring due to each loading cycle is computed, and which helps to predict the approximate fatigue life of engineering components.

3.2.1 Cyclic Material Properties

Material behave differently when subjected to repeated load cycles and there occurs a slight decrement in the performance of the material with each cycle. The cyclic material properties are obtained by physical testing of material under a large number of cyclic loads. The ASTM Manual on Fatigue Testing gives detailed list of more than thirty instrumentation setups used to obtain the cyclic material properties.

The $S-N$ curve (stress curves) and $\varepsilon-N$ curves (strain curves) are examples of cyclic material properties. The $S-N$ curve is a plot having the applied stress range on the vertical axis and the corresponding number of cycles to failure on the horizontal axis. The $S-N$ curve defines the number of cycles a member can undergo before failure (N), when a material is repeatedly cycled through a given stress range. The $\varepsilon-N$ curve is a plot having the applied strain range on the vertical axis and the corresponding number of load cycles to failure on the horizontal axis. The ε-N curve defines the number of cycles a member can undergo before failure (N), when a material is repeatedly cycled through a given strain range. The $S-N$ curves are obtained using stress-controlled fatigue testing and $\varepsilon-N$ curves are obtained by strain-controlled fatigue testing. Both $S-N$ curves and $\varepsilon-N$ curves have a negative slop with the number of cycles to failure decreasing with increase in the applied stress range or applied strain range. If the $S-N$ curve is plotted on a double logarithmic scale, the curve becomes approximately linear, showing a linear relationship called the Basquin relation.

The $S-N$ method is generally used in order to analyze high cycle fatigue and $\varepsilon-N$ method to study low cycle fatigue. While the engineering components are designed such that they are not loaded to the plastic domain on a normal basis, the geometry of the component may induce secondary stresses that may cause plastic strain and hence low cycle fatigue (Pineau and Bathias, 2013). Shen et al. (2009) was able to successfully establish the relationship between the various fatigue curves (i.e., $S-N$ curves, $\varepsilon-N$ curves and $da/dN-\Delta K$ curves). The researchers were able to successfully predict: the $S-N$ curves from the $da/dN-\Delta K$curves, the $S-N$ curves from the $\varepsilon-N$ curves and the $da/dN-\Delta K$ curves from the $\varepsilon-N$ curves.

The fatigue life of materials increases as the applied stress range decreases, and there occurs a lower limiting value beyond which the materials does not undergo fatigue failure even after a seemingly large number of loading cycles called the fatigue limit. The tests for finding fatigue limit have to be conducted over a large number of cycles and thus time consuming and expensive. The fatigue limit of materials is found using statistical methods like the Probit method and Staircase method (Lin et al, 2001; Pinto et al., 2005). A study by Soltani et al. (2012) have found that the accepted values of fatigue limit are applicable to high strength steel bars and are likely conservative.

3.2.2 Load Patterns

The load patterns to which the engineering component is subjected on a regular basis is a very important factor that will determine the fatigue life of the component. The proper specification of the loading details is required in order to carryout accurate fatigue predictions. The load specifications may include the intensity, frequency, stresses induced on the member and loading range.

The fatigue life of a material or engineering component decreases as the stress range applied increases. Besides the applied stress range, it was found that the mean stress applied also plays an important role in determining the fatigue life of engineering components. The following observations can be used to sum up the effects of mean stress on the fatigue properties of components: (i) As the stress ratio becomes more positive, the $S-N$ curve shows greater allowable values of maximum stress for a specified number of cycles. (ii) As the algebraic values of mean stress increases, the allowable values of alternating stress reduce for a specified number of cycles. (Bhadhuri, 2018)

The effects of mean stress have been accounted using the following theories: (i) The Goodman theory, (ii) The Soderberg theory and (iii) the Gerber theory. The Soderberg theory is the most conservative of the three. The Soderberg and Goodman theories are the best representation of the various types of steel and the difference between then actual and obtained values will vary more as the carbon content increases (Bader and Kadum, 2014). There have been other methods developed to corelate the effects of mean stress on the strain life of materials (Dowling, 2009)

3.2.3 Component Geometry

Geometry of the member influence the fatigue life of engineering component. Geometrical features like vertices, notches, pits, holes, welds, bolts etc. becomes localized zones of high stress concentrations. These localized zones of stress concentration increase the rate of fatigue damage. The effects of geometry of an engineering component on fatigue life is quantified using stress concentration factor (K_t) which is defined as the ratio of the maximum stress at the tip of the discontinuity to the applied nominal stress. The fatigue strength and fatigue limit observed from the $S-N$ curves are expected to reduce by a factor of K_t. However, the reduction in fatigue strength and fatigue limit is lesser than those predicted by stress concentration factor because localized yielding occurs at the root of the discontinuity and the notch root stress reduces. The actual effectiveness of the stress concentration in reducing fatigue strength and fatigue limit is expressed in terms of fatigue strength reduction factor (K_f), also called as fatigue notch factor. This factor is defined as the ratio of the fatigue strength at a number of cycles (N) of a member with no stress concentrations to that of the same member with the specified stress concentrations. The fatigue life is dependent not just on the stress at the notch tip field but also on the stress distribution ahead of the notch (Teh et al., 2006; Benedetti et al., 2008). Neuber's rule and Peterson rule helps to quantify the effects of notches in components. Neuber's rule overestimates the actual stresses and strains at notch tip (Ye et al., 2008) while the Peterson equation underestimates the fatigue reduction factors (Majzoobi and Daemi, 2010).

3.3 Finite Element Analysis of Fatigue

Physical testing of members for gathering fatigue life data is a lengthy and tedious procedure which requires a lot of time and resources. Study of fatigue has amassed a large amount of fatigue data and how the various factors influence the fatigue life of materials and engineering components. These data can be used as the basis of modelling a large number of fatigue analysis scenarios. The availability of such amounts of fatigue data and the technological advancements in the field of computation mechanics have made software analysis of fatigue very reliable. Finite element simulations can be effectively used for predictions of different engineering components once the material properties are known (Agrawal et al., 2014).

A number of studies have been conducted across the globe to study and understand fatigue properties of various engineering components. Finite element packages can be used to find the fatigue life of members having complex geometry. Finite element studies have showed substantiable results for the variation of notch sensitivity and notch angles (Köksal et al.,2013). Pandiyarajan et al. (2020) was able to effectively predict the fatigue life of components. Kala et al. (2005) was able to conduct a sensitivity analysis of a plate girder using ANSYS. Anoop et al. (2010) was able to study the shear fatigue life of steel plate girders used by Indian Railways. Shewale and Madhekar (2015) found that the numerical analysis of a girder using ANSYS with Soderberg theory yielded near accurate results and on the safer side by a factor of 4.31%. The finite element models can be calibrated to field specifications and be used to produce very accurate results (Bougacha and Cai, 2018; Silva et al., 2019).

4 Fatigue Life Provisions and Standards

In India, IS 800: 2007, General Construction in Steel- Code of Practice lays down the standards and the procedure to be followed for the fatigue life prediction of steel members. The procedure laid down by the IS 800: 2007 is based on stress life methodology and makes use of S-N curves to effectively predict the fatigue life of steel members. Provisions given in the IS 800:2007 are applicable to high cycle fatigue. Besides IS 800: 2007, EN 1993-1-9:2005, AS4100: 1998 and AISC360: 2010 are the various standards used across the globe. While there exists a prevalent difference between the various standards, it can be attributed explicitly to the use of partial safety factors. The Indian standard is conservative for flexural as well as shear stress under fatigue assessment (Shah and Patel, 2016). However, there is a requirement to reexamine the fatigue analysis provisions as laid down by the Indian Standards to take into account more factors related to the conditions of the engineering component (Shewale and Madhekar, 2015)

5 Conclusions

From this study and the review of the various literature available on fatigue, the methods and approaches to fatigue analysis and the latest research that is being carried out in the area, the following conclusions can be drawn:

- Fatigue life analysis proves to be a very effective method to predict the life span up to which an engineering component can work before undergoing failure. The vast amounts of fatigue analysis data and the advancements in computer-based simulation techniques have made it possible to assess and predict the fatigue life of even complex engineering components. There is still a need to investigate and find more fatigue data and the variation in fatigue effects due to various factors.

- A number of factors have been found to influence the fatigue life of various engineering components. Understanding the influence of these factors will help to improve the fatigue life of engineering structures.
- Many studies are being carried out in order to assess the various methods to improve the fatigue life of structure. A deeper knowledge about the mechanism of fatigue initiation needs to be developed in order to truly understand and design structures with minimal fatigue effects.
- Models and methodologies that helps to relate one form of fatigue data to another has to be developed in order to reduce the number of physical experiments that is needed to be conducted.
- While the provisions of fatigue in steel laid down by IS 800: 2007 is found to be conservative among the various standards, it is still found to predict fatigue life values which are higher than those observed from actual experiments. This underlines the need to reexamine the provisions laid down by the various standards about fatigue.

Fatigue has been found to be one of the biggest reasons that defines the useful life of a structure. The high property taxes and rent are forcing people to live in old, dilapidated properties in many major cities. Proper study of fatigue and the methods to improve fatigue life can prolong the useful life of the structures.

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