Prediction of Crack Growth and Fatigue Life Estimation of Shaft-A Review

R. S. Pokale*,V. S. Khangar**

**M.Tech. Student, Mechanical Engineering Department, G. H. RaisoniCollege of Engineering Nagpur-440016, Maharashtra State, India.*

*** Assistant Professor, Mechanical Engineering Department, G. H. Raisoni College of Engineering,Nagpur-440016,Maharashtra State, India.*

Abstract

Fatigue life estimation techniques and pump shaft failure are reviewed in this paper. Failure (fracture) of a pump shaft is selected as investigation topic. It essentially focuses on fatigue analyses, followed by fatigue life estimation of the component using fracture mechanics concepts. Fracture mechanics can be used to analyse the growth of small cracks to critical size by fatigue loading and to evaluate the fitness-for-service, or life extension of existing equipment. Linear elastic fracture mechanics (LEFM) is selected as a theoretical method for predicting the fatigue life of the notched component (pump shaft). LEFM estimates the fatigue life based on the fact that a crack pre-exists in the component and that the fatigue life is directly dependent on the stress intensity factor, which in-turn depends on initial crack length.

Keywords:*FEM, LEFM, pump shaft, crack growth, fatigue life*

Introduction:

Along the years, many unexpected failures of equipment's and various machines have occurred throughout the industrial world. A number of these failures have been due to poor design. However, it has been discovered that many failures have been caused by pre-existing notches or flaws in materials that initiate cracks that grow and lead to fracture. This discovery has, in a sense, lead to the field of study known as fracture mechanics. The life of component subject to a fatigue type of load is made up of two parts. The number of cycles until a crack initiates and the number of cycles required for the crack to grow, to a size where it become unstable. The first socalled life to initiation can normally be predicted based on the stress historywhich can be obtained from a suitable stress analysis. However the prediction of the life once the crack has initiated requires a model which can simulates the crack path and the fracture properties, so crack growth is very slow until the final stage in the fatigue life, where a relative short number of cycle will result in fast crack growth leading to failure.

Fatigue Life Estimation Techniques

The idea behind the selection of project, in today's structural design, the analysis of the crack within the structure is an important application if the damage tolerance and durability of structure and components are to be predicted. As parts of engineering design process engineers have to assess not only how well the design satisfies the performance requirements but also how durable product will be over its life cycle. Often cracks cannot be avoided in structures; however the fatigue life of the structure depends on the location and size of these cracks. In order to predict the fatigue for any component a fatigue life and crack growth study needs to be performed. Fatigue is a stochastic process. For this reason fatigue life estimation has become the important aspect for the replacement of worn out components.

Zhang Dayi et al. [2013] discussed on bending fatigue failure of a micro straight bevel gear used in a lubricating pump .A series of examinations were performed to identified the possible of the causes failure including macroscopicalinspection,

Diego F.B. Sarzosa et al. [2013] discussed a numerical and experimental investigation of fatigue crack growth behaviour in steel weldmentsincluding crack closure effects and their coupled interaction with weld strength mismatch. A central objective of this study is to extend previously developed frameworks for evaluation of crack closure effects on FCGR to steel weldments while, at the same time, gaining additional understanding ofcommonly adopted criteria for crack closure loads and their influence on fatigue life of structural welds. Fatigue crack growth tests conductedon plane-sided, shallow-cracked C (T) specimens provide the necessary data against which crackclosure effects on fatigue crack growth behaviour can be assessed. Overall, the present investigation provides additional support for estimation procedures of plasticity-induced crack closure loads in fatigue analyses of structural steels and their weldment. [2]

H.R. Amiri et al. [2013] explained a new method of simulating ductile fracture in steel structures under large amplitude cyclic straining experienced in earthquakes. The method is developed based on an existing micromechanical model originally proposed for predicting crack initiation in ultra-low cycle fatigue, ULCF. It involves a step-by-step simulation of material degradation within the framework of conventional nonlinear FEM. The method is validated through simulating fracture in a structural detail (column-to-base plate connection)for which several cyclic tests has been previously conducted. It is found that the method can successfully predict the cracking site, its propagation path, the number of cycles corresponding to crack initiation, and also final fracture. [3]

Bruno Serrano et al. [2013] discussed on to predict the fatigue lifetime (TVF) of the Portuguese Air Force (PoAF) Epsilon aircraft based on the computational fatigue crack growth modelling. In order to predict the TVF by a generic spectrum was computationally implemented a methodology for

Geometrical examination,fractography investigation and other necessary metallurgical examination. Finite element methodcarried out to give more comprehensive analysis. [1]

automatic crack propagation. Through the development of aninterfacebetween ANSYS and MATLAB was possible to determine the stress intensity factors andhence the geometric factor for the specimen geometry which was designed by PoAF in previousworks. The stress intensity factors were validated with the methods available in theliterature: Pickard, Pommier and Newman. in order to predict the fatigue lifetime of the aircraft, the manufacturers of the Epsilon carried out a real scale fatigue test at the Centre d' EssaisAeronautique de Toulouse (CEAT). During these tests the manufacturers realised that the aircraft lifetimeis determined by the fracture of the second bulkhead beam CEAT [1]. In this test the manufacturers used a spectrum that was considered characteristic of the typical aircraft operation. [4]

A book by Dr. P.J.G. Schreurs [2011] explained an introduction to Fracture mechanics. The importance of stiffness, strength and Fracture mechanisms such as shear fracture, cleavage fracture,fatigue fracture,crazing,de-adhesion is given. A study on ductile - brittle behaviour& techniques to reveal surface cracks by dye penetration in the stiffening cone of a turbine is made. Also direct visualization of a crack is done using electromagnetic waves, ultrasound, acoustic emission, adhesion tests. All data is based on assumption that the material behaviour is linear elastic and isotropic. The stress state was calculated using Airy stress functions. An analysis on plane stress and Mode I, Mode II, Mode III fracture is described. A discussion on multi-mode crack loading, maximum tangential stress criterion, strain energy density criterion is made. Further an explanation of the dynamic fracture mechanics crack growth rate, elastic wave speeds, crack tip stress, crack branching & fast fracture are given. [7]

Toshio Hattori et al. [2011] discussed an estimation of low cycle fretting fatigue life based on new critical distance theory, which is modified for high stress region using ultimate tensile strength σB, and fracture toughness KIC has been made. Firstly the critical distance for estimating low cycle fatigue strength was calculated by interpolation of critical distance on fatigue limit (estimated from σw0 and ΔKth) with critical distance on static strength (estimated from σB and KIC). The validity of this method is confirmed by the V notch specimens. And then the method is applied for estimation of low cycle fretting fatigue strength and life.[5]

Yibing Xiang et al. [2009] discussed a general methodology in for fatigue life prediction using crack growth analysis. Part I of the paper focuses on the fatigue life prediction for smooth and notched specimens under uniaxial loading. Part II of the paper focuses on the fatigue life prediction under proportional and non-proportional multiaxial loading. The proposed methodology is based on a previously developed equivalent initial flaw size (EIFS) concept. Various experimental data of different metallic materials are used to validate the proposed methodology and reasonable agreement is observed between model predictions and experimental data. [6]

David Taylor et al. [2005] discussed a modification to the traditional Griffith energy balance as used in linear elastic fracture mechanics (LEFM). The modification involves using a finite amount of crack extension (Δa) instead of an infinitesimal extension (da) when calculating the energy release rate. This modification is extremely useful because it allows LEFM to be used to make predictions in two situations in which it is normally invalid: short cracks and notches. Introducing a new term Δa /2: we denote this length as L and assume that it is a material constant. The value of L can be expressed as a function of two other material constants: the fracture toughness Kc (or threshold ΔKth in the case of fatigue) and an inherent strength parameter σ_0.[17]

[B] Shaft Failure

Shafts are one of the most common components in machinery. They show up everywhere from small motors, pumps and compressors to large rolls in paper mills, steel mills and power generating facilities. Properly designed and maintained they are expected to operate for years without problem. However, shafts still represent one of the most common types of machinery failures. Failure of shafts in these applications usually is unexpected and result in considerable and expensive collateral damage.

BabakEftekharnejad et al. [2012] explained Shaft breakage is one of the most catastrophic failures in any transmission system that can ultimately lead to significant financial loss. Although advances in shaft design have lead to improvements in endurance life, shaft failures are still common today. This paper presents an experimental investigation inwhich several technologies such as Acoustic Emission, vibration and motor current signature analysis, were applied to identify the presence of a naturally fatigued pinion shaft in an operating gearbox. It was concluded that the combination of these methods could offer good diagnostic information thoughSuccessful diagnosis is very dependent on the diagnostic path taken by the investigator. [9]

F. Jiménez Espadafor et al. [2011] discussed the failure mode of the six impellers of a centrifugal pump in an irrigation system used for street washing has been analyzed. In order to ascertain whether the anomaly was metallurgically related, the original pump impellers were replaced with others of the same geometry but made of stainless steel; these new pumps also presented the same failure mode. The system was analyzed using a non-excited torsional lumped model, in which the stiffness of several degrees of freedom was evaluated with a finite element code, and an experimental analysis of the pumping system. The results show a very high level of torsional vibrations induced by severe pulsations of engine torque. These vibrations were mainly responsible for damage to the impellers.[11]

Jordan Tolev n, Andreas Mandelis et al. [2010] explained a statistical non-contacting and non-intrusive method for revealing the presence of cracks in unsintered (green) parts manufactured by powder metallurgy (PM) technology based on photo thermal radiometry (PTR) .The technique relies on the interaction of a modulated laser- generated thermal wave with the crack resulting in change of amplitude and phase of the detected signal. The crack exist points in high stress regions of a group of green sprockets was evaluated through the proposed method. The results were validated by an independent destructive technique microscope observation of the tested green sprockets following sintering, sectioning, and polishing at the locations where signal changes were observed in the green state. Statistical analysis confirmed the excellent sensitivity (91%) of the method in detecting the presence of hairline (5–10 mm) cracks. Ultimately, the method has been developed for non-destructive quality and feedback control of the metal forming process of green automotive parts. It has been shown that photo-thermal radiometry can be a valuable NDT technique for monitoring the presence of subsurface hairline cracks created during the forming process of green auto- motive parts. [10]

WouterOst et al. [2009] discussed about the shafts of the pump and the pneumatic piston are fixed toeach other with a C-shaped split bush, which fits over a groove in both the pump andthe piston shaft. A number of piston- and pump shafts failed prematurely at the location of the coupling.Following the first fractures, all shafts in use were subjected to a magnetic particle inspectionand cracks were found in a large number of them.From the fracture investigation it was shown that the shafts failed due to the propagation of a fatigue crack, starting from a bottom radius of the groove for the coupling bush, caused by cyclic loading during operation.It uses microscopic examination, metallographic investigation for further analysis. [12]

XuXiaolei et al. [2009] discussed about a failure investigation has been conducted on a locomotive turbocharger main-shaft. The fracture position is located at a sharp edged groove between two journals with different cross-sectional area. It was reported that a locomotive turbocharger main-shaft fractured, which had serviced for 140,000 km before failure.The failed main-shaft was made of 42CrMo steel. The hardness of core material is specified as HB260-300. Some journalsof main-shaft are specified to be induction-quenched to obtain the surface hardness of HRC56-62.The paper describes the careful fractographic and metallurgical investigation on the failed main-shaft, and the damage of the bearing-sleeve assembled with main-shaft was examined. The possible reasons for failure were assessed. The chemical composition of the failed main-shaft material was determined by spectroscopy chemical analysis method. [13]

M. Elforjani et al. [2009] explained results of an experimental investigation to assess the potential of the Acoustic Emission (AE) technology for detecting natural cracks in operational slow speed shafts. A special purpose built test rig was employed for generating natural degradation on a shaft. It was concluded that AE technology successfully detected natural cracks induced on slow speed shafts. [14]

Gautam Das et al.[2003] discussed on “Fatigue failure of a boiler feed pump rotor shaft” deals with a detailed failure investigation of a rotor shaft in a boiler feed pump of a thermal power plant. The investigation mainly included chemical analysis, microscopy, fractography, hardness measurement and residual stress measurement. [15]

S.K. Bhaumik et al. [2002] discussed a case study on the fatigue failure of a hollow power transmission shaft is described. A micro/hairline crack was noticed on a low speed, hollow shaft of a single stage helical gearbox during service. Though this had not resulted in a catastrophic failure, the shaft was withdrawn from service because of leakage of oil. The fatigue crack initiation was due to stress concentration arising from a depression mark at the keyway end surface. The problem was further aggravated due to inadequate radius at the keyway edges and rough machining marks. An analysis of the failure, together with recommendations for failure prevention, is presented in this paper. [16]

Conclusion:

From the above study, manytechniques for fatigue life estimation have been researched and developed along the years. But in least cases it has been directly applied to practical problems. Many methods are available on fatigue life estimation of shaft directly. Also it has been found that LEFM is an excellent method for crack growth and fatigue life prediction and it is generally used.Hence there is need to developed computer program for predicting the fatigue life of shaft before actualfailure of component based on Linear Elastic Fracture Mechanics method [LEFM].

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