Fatigue Mechanical Life Design-A Review

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Abstract

Fatigue is due to cyclic loading and unloading of one kind or the other. It is due to the presence of discontinuities in the material. Mostly fatigue failure is progressive and plastic in nature. It is due to the nucleation, growth and propagation of a micro crack at the point of a discontinuity. There are materials having unlimited fatigue life (plain low carbon steels) as well as limited fatigue life (nonferrous as well as ferrous materials). Fatigue is mostly due to tensile stresses and is random as well as sudden without any warning. 90 % of the service failures are due to fatigue. Lot of work on fatigue failures has already been done and is still continued because of very complex nature of fatigue failures which result in loss of life and property. Fatigue failures thus must be avoided by a proper selection of material, surface finish, stress raisers, residual stresses, reliability, surrounding environment and temperature as per type the cyclic loading and unloading. Fatigue can be reduced by proper selection of fatigue resistant material like composites, by drilling a hole at the point of a probable crack, use of laser peeing and high frequency mechanical impact (HFMI) treatment of welds. Stress fatigue and strain fatigue life approaches have been used for plastic and elastic deformations respectively. This short review paper cannot treat the vast subject thoroughly and the reader is advised to consult more references for additional knowledge.

Keywords: Fatigue, endurance limit, discontinuity, fatigue life, cyclic loading and unloading, residual stresses, surface finish, reversal of stresses.

INTRODUCTION-

Under cyclic loading and unloading, failure is due to fatigue. Fatigue/endurance limit (σ_e) represents a stress level below which the material does not fail even after infinite number of cycles. Fatigue is reduction in strength due to a progressive and localized structural damage. Fatigue takes place in a moving component only such as automobiles on roads, ships at sea, aircraft wings and fuselages, nuclear reactors, jet engines, and turbines. Fatigue was initially recognized in early 1800 in Europe from the observed fact that bridge and railroad components were cracking subjected to repeated loading[1-10]. Three basic factors to cause fatigue are: (1) a sufficiently high tensile stress, (2) a large variation in the applied stress, and (3) a sufficiently large number of repetitions in loading and un-loading. The nominal maximum stress which causes fatigue is much less than the ultimate tensile strength of a brittle material and the yield stress of a ductile material. If the stress present is above a certain threshold value, microscopic cracks will start at the points of stress concentrations like a scratch, keyway, square holes or sharp corners. The crack then travels along weaker points and ultimately results in a fracture. Fatigue is thus a progressive plastic failure. This phenomenon occurs in three phases namely crack initiation, crack propagation catastrophic overload failure.There are two types of materials experiencing fatigue. One type which has a fixed endurance limit as plain low carbon steels. These steels do not undergo fatigue even for infinite life if the actual stress present in the component is slightly less than the fatigue limit. While other materials brittle or ductile which do not have a fixed fatigue limit (Cast iron, Copper, Aluminum and their alloys), these are designed for a fixed number of cycles 5 x 10^8(500 million cycles). If the component has 750 RPM with one reversal per cycle, it will have a life of about four years. If the RPM increases, life will reduce [1-16]. Thus importance of fatigue is that it directly governs the useful life of a component under cyclic loading. Lots of research has been carried on fatigue because number of well-known catastrophic fatigue failures which took place all over the world. Fatigue failures must be avoided by a proper selection of material, surface finish, stress raisers, residual stresses, reliability, surrounding environment and temperature as per type of cyclic loading and unloading. Salient features of fatigue include randomness and sudden failure without any warning, mostly due to tensile stress and the presence of a stress raiser, strongly affected by the surrounding environment, temperature, surface finish and residual stresses. Fatigue can be reduced by proper selection of fatigue resistant material like composites, drilling a hole at the point of a probable crack, use of laser peeing and use of high frequency mechanical impact (HFMI) treatment of welds. Out of different fatigue design approaches, stress life and strain life has been used for plastic and elastic deformations respectively [17-24].

LITERATURE STUDY

[i]. 1837: Wilhelm Albert published the first article on fatigue related to conveyor chains used in the Clausthal mines.
[ii]. 1839: Jean –Victor Poncelet described fatigue failure as metals being tired.

[iii]. 1842: William John Macquorn Rankine recognized the importance of stress concentrations of railroad axle failures. The Varsaillies train crash was caused by axle fatigue.

[iv]. 1843: Joseph Glynn reported fatigue failure due to a keyway.

[v]. 1848: The Railway Inspectorate reported fatigue failure due to a rivet hole in tire failure of railway carriage wheel.

[vi]. 1849: Eaton Hodgkinson is granted a "small sum of money" to report to the UK Parliament on his work in "ascertaining by direct experiment, the effects of continued changes of load upon iron structures and to what extent they could be loaded without danger to their ultimate security".

[vii]. 1854: Braithwaite reported on common service fatigue failures.

[viii]. 1860: Systematic fatigue testing undertaken by Sir William Fairbrain and August Wöhler.

[ix]. 1870: Wöhler summarised that cyclic stress range is more important than peak stress in railroad axle's failures and gave the concept of endurance limit.

[x]. 1903: Sir James Alfred Ewing demonstrated the origin of fatigue failure is microscopic cracks.

[xi]. 1910: O.H.Basquin proposed a log-log relationship for S-N curves, using Wöhler's experimental data.

[xii]. 1954: The world first disaster de Havilland Comet of three planes breaks up in mid-air caused replacement of square apertures like windows with oval ones.

[xiii]. 1954: L.F.Coffin and S.S.Manson explained fatigue crack-growth as plastic deformation.

[xiv]. 1961: P.C.Paris proposed the methods for predicting the rate of growth of individual fatigue cracks under cyclic loading and unloading.

[xv]. 1968: Tatsuo Endo and M.Matsuishi devised the rainflow-counting algorithm and applied Miner's rule to random loadings.

NOTABLE FATIGUE FAILURES

1. Versailles train disaster

A train returning to Paris crashed in May 1842 by breaking of a leading locomotive axle which was found to be due to stress concentration. At least 55 passengers were killed.

2. The 1862 Hartley Colliery Disaster was caused by the fatigue fracture of a steam engine beam and killed 220 people.

3. De Havilland Comet crash

Two de Havilland Comet passenger jets crashed in mid-air killing all persons and the failure was caused by fatigue due to the repeated pressurization and de-pressurization of the aircraft cabin.

4. Alexander L. Kielland oil platform capsizing

The Alexander L.Kielland, a Norwegian semi-submersible drilling rig capsized (1980) killing 123 people. The investigations concluded that the rig collapsed owing to a fatigue crack in one of its six bracings.

5. The 1919 Great Molasses Flood, the 1948 Northwest Airlines Flight 421 crash, the 1957 of Philippine President aircraft crash, the 1965 capsize of UK's first offshore oil plateform, the 1968 Los Angles Airways Flight 417 crash, the 1968 MacRobertson Miller Airlines Flight 1750 crash, the 1977 Dan-Air Boeing 707 crash, the 1980 Lot Flight 7 crash, the 1985 Japan Airlines Flight 123 crash, the 1988 Aloha Airlines Flight 243 crash, the 1989 United Airlines Flight 232 crash, the 1992 EI AI Flight 1862 crash, the 1998 Eschede train disaster, the 2000 Hatfield rail crash, the 2002 China Airlines Flight 611, the 2005 Chalk's Ocean Airways Flight 101 and the 2009 Viareggio train derailment were all due to fatigue failure in one part or the other. There are many more to quote.

FATIGUE MECHANICAL LIFE

There are various types of mechanical failures. Some of these are buckling, corrosion, creep, fatigue, fracture, impact, wear, yielding and mechanical overload. However 90 % of the service failures are due to fatigue alone of one or the other type. Fatigue failure is thus the most important. It is due to any one of the following cyclic loadings:

DIFFERENT TYPES OF CYCLIC LOADINGS CAUSING FATIGUE

(i) Tensile load increases from zero to maximum and then back to zero

(ii) Compressive load increases from zero to maximum and then back to zero

(iii) Shear load increases from zero to maximum and then back to zero

(iv) Tensile load increases from zero to maximum and then back to zero, then to maximum compressive and back to zero (like a vibratory load), maximum tensile being equal to maximum compressive

(v) Tensile load increases from zero to maximum and then back to zero, then to maximum compressive and back to zero (like a vibratory load, completely or partially reversible load), maximum tensile is not equal to maximum compressive

(vi) Completely or partially reversible torsion load

Thus the cyclic loads can be static, repeated and reversed, fluctuating and shock or impact.

FACTORS AFFECTING ENDURANCE LIMIT

Endurance limit 'σ_e' depends on the following factors:

(i) Surface factor, k_a

(ii) Size factor, k_b (considered only for bending and torsion loads)

(iii) Load factor k_c

(iv) Temperature factor k_d

(v) Reliability factor, k_e

(vi) Factor of safety, k_f

CAUSES OF FATIGUE FAILURES

1) A high tensile stress
2) A large variation in the applied stress
3) A large number of cyclic repeated cycles
4) Stress concentration
5) Overloading
6) Residual stresses
7) Complex or Combined stresses
8) Corrosion
9) Working as well as surrounding environment
10) Type of cyclic loading/stress
11) Notch sensitivity
12) Grain size
13) Type of material
14) Surface finish
15) Types and distribution of internal defects
16) Environmental conditions

Each parameter reduces the life under fatigue.

DIFFERENT PHASES IN FATIGUE

Fatigue phenomenon is a progressive plastic failure and takes place in four steps.

1) Crack nucleation at the points of high local stress due to a geometric stress raiser, flaws and pre-existing crack
2) Stage I Crack-growth due to repeated plastic deformation
3) Stage II Crack Growth
4) Ultimate sudden ductile failure when the section becomes sufficiently weaker

FATIGUE SALIENT FEATURES

(i) All fatigue failures originate at the surface of a part.

(ii) Compressive residual stresses increases resistance to fatigue failure.

(iii) Cold working also increases resistance to fatigue failure

(iv) Plain low carbon steels exhibit a theoretical endurance limit below which no fatigue failure can ever occur.
(v) Fatigue is a cumulative effect due to the slow movement of a micro crack inside the material.
(vi) In majority of the cases, starting of the crack is due to tensile stress but in few cases only, it can due to other stresses also.
(vii) Fatigue depends on the type, size and orientation of discontinuities like scratch, hole, dent, sudden change of cross section and a keyway. All these cause stress concentration which give rise to the birth of a micro-crack.
(viii) Because of so many affecting factors, fatigue is random in nature.
(ix) Fatigue failure strongly depends on parameters like temperature, surface finish, microstructure and surrounding corrosive atmosphere.
(x) Fatigue life is less at higher stress and vice versa.
(xi) Fatigue life is infinite for low plain carbon steels.
(xii) Fatigue life is less for brittle materials.
(xiii) Fatigue failure is catastrophic, very suddenly and without any warning
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(xv) Fatigue life is less at higher stress and vice versa.
(xvi) Fatigue life is infinite for low plain carbon steels.
(xvii) Fatigue life is less for brittle materials.
(xviii) Fatigue failure is catastrophic, very suddenly and without any warning
(xix) Fatigue failure is like a brittle fracture.

PRACTICAL APPLICATIONS OF FATIGUE FAILURES

[i]. Shafts, buckets, disks and blades of jet engines
[ii]. Crank shafts of ground vehicles
[iii]. Gears used in ground vehicles, mining equipment and marine equipment
[iv]. Compression springs n ground automobiles
[v]. Anything or everything in motion under cyclic loading of one kind or the other.
[vi]. Low amplitude and high cycle loading is the common cause for fatigue as in jet engines Vanes, Spacers, Disks, Blades and Sheet metal work.
[vii]. Compressors, pumps, turbines and bridges

STEPS TO REDUCE FATIGUE

[i]. Drill a hole at the point of a probable crack.
[ii]. Use a fatigue resistant material like composites.
[iii]. Use of a laser peening
[iv]. Use high frequency mechanical impact (HFMI) treatment of welds

PRINCIPAL CONSIDERATIONS IN DESIGN AGAINST FATIGUE

Durable and Dependable design against fatigue-failure requires thorough deep knowledge as well as practical experience. Thus while designing for fatigue, it is important to know which loads are frequent, which are occasional, and which are exceptional. Past experience is very helpful in this determination. Fatigue is found in every sphere of life. There are a few important principal considerations in fatigue design

1. Design to keep design stress below threshold of endurance limit.
2. Design to select materials free from discontinuities.
3. Design to shape free of stress raisers.
4. Design for a limited safe life say for 5/10 years.
5. Predict the fatigue life based on fatigue crack growth rates for a crack of a certain size.
6. Check design on the basis of strength, stiffness, stability, wear and also with the various theories of elastic failures before manufacturing the part.

CONCLUSION

1) Fatigue behavior is based on many factors which are random in nature.
2) Fatigue design is closely related to the geometrical shape and the dimensions, quality of the fabrication as well as the type and size of acceptable defects.

3) The designer should be skillful to do fatigue load analysis in detail to know the stress strain behavior in actual use.
4) Designer should also be knowledgeable and experienced to interpret main factors affecting fatigue resistance.
5) Selection of the material of construction should be after considering all possible considerations affecting fatigue.
6) The designer must then select the proper fatigue strength curve as per details of use of the component.
7) Fatigue life selection should be done with utmost care.
8) Design should be based analytical research, experimental findings and experience.
9) Before designing, various codes and standards available such as AASHTO for steel bridges, ASTM fatigue and fracture standards, FEM analysis of welded joints must be consulted
10) Design should be checked for failure on the basis of strength, stiffness, stability, wear and also with the various theories of elastic failures as applicable to the selected material of construction.

REFERENCES:

[1]. R.C. Juvinall, "Engineering Considerations of Stress, Strain, and Strength", 1967
[2]. J.A. Graham, "Fatigue Design Handbook", SAE, 1968
[3]. A.F. Madayag, "Metal Fatigue: Theory and Design" 1969
[4]. Little, R.E. &Jebe, E. H., "Statistical design of fatigue experiments",1975
[5]. *Kim, W.H.; Laird, C. Crack, "Nucleation and State I Propagation in High Strain Fatigue- II Mechanism". ActaMetallurgica. pp. 789–799, 1978*
[6]. H.O Fuchs and R. I. Stephens, "Metal Fatigue in Engineering", 1980
[7]. The Alexander L. Kielland accident, "Report of a Norwegian public commission appointed by royal decree of March 28, 1980, presented to the Ministry of Justice and Police March", 1981
[8]. C.C. Osgood, "Fatigue Design", 2nd Ed. 1982
[9]. J.A. Ballantine, J.J. Conner, and J.L. Handrock,"Fundamentals of Metal Fatigue Analysis", 1990
[10]. *Bäumel, Jr and T. Seeger, "Materials data for cyclic loading, supplement 1. Elsevier"(1990).*
[11]. N.E. Dowling, "Mechanical Behavior of Materials", 1993
[12]. *Schutz, W. "A history of fatigue". Engineering Fracture Mechanics, **54**: 263–300.1996*
[13]. Subra Suresh, "Fatigue of Materials", Second Edition, Cambridge University Press, 1998
[14]. *Stephens, Ralph I.; Fuchs, Henry O., "Metal Fatigue in Engineering (Second Ed.)". John Wiley & Sons, Inc. p. 69.2001*
[15]. Mott, "Machine Elements in Mechanical Design", 2003
[16]. Ali Fatemi - University of Toledo, "Fatigue Design Methods", Chapter 2,2004
[17]. N. Pugno et al. / J. Mech. Phys. "Solids", 54, 1333–1349, 2006
[18]. N. Pugnoa,, M. Ciavarellab , P. Cornettia , A. Carpinteria, "A generalized Paris' law for fatigue crack growth", Journal of the Mechanics and Physics of Solids 54, 1333–1349, 2006
[19]. Tapany Udomphol. "Fatigue of Metals", p. 54. sut.ac.th, 2007.
[20]. *Pook, Les. "Metal Fatigue, What it is, why it matters", Springer.*
[21]. *Draper, John, "Modern Metal Fatigue Analysis", EMAS,2008*
[22]. Leary, M., Burvill, C. "Applicability of published data for fatigue- limited design", Quality and Reliability Engineering International, Volume 25, Issue 8, 2009.
[23]. *Schijve, J., "Fatigue of Structures and Materials", 2nd Edition with Cd-Rom. Springer, 2009*
[24]. *Lalanne, C., "Fatigue Damage", ISTE – Wiley, 2009*