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FATIGUE: A DISASTROUS FAILURE OF WELDED STRUCTURES

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ABSTRACT

Fatigue is the phenomenon of decrease of resistance of the material to repeated loading and failure take place at the value of the stresses well below the ultimate tensile strength of the material. It has been recognised as a distinct mode of failure for at least 150 years and 80 to 90% of the structural failures can be attributed to it. The review deals with the history of developments and failures, causes and remedial measures, the engineering practice and with an investigation.

1. INTRODUCTION

Fatigue is the formation of crack(s) as a result of repeated application of loads each of which insufficient by itself to cause normal static failure. It is not confined only to the metals but also occurs in nonmetals like wood, plastics, concrete and even in human bone. Thermal fatigue, contact fatigue, surface or pitting fatigue, subsurface cracking or subcase fatigue and corrosion fatigue etc. are the various forms of it. The fatigue fracture is caused by the simultaneous action of cyclic stress, tensile stress and plastic strain. If any of these three is not present, fatigue crack will not initiate and propagate. Cyclic stress and plastic strain initiate the cracks while tensile stress is responsible for its initiation and propagation.

The process of fatigue thus consists of three stages as:

- crack initiation
- crack propagation and
- final fracture.

The various theories proposed by several authors are based on elasticity and secondary stresses and are mutually complemtntary and no one is sufficient to explain the mechanism of fatigue. It must be accepted that when local stress exceed the cohesive strength of the metal, the crack takes a course along lines of least resistance within the metals and follows discontinuity brought about by notches, grooves, scratches, inclusions etc. Many metallographic observations have confirmed thast fatigue deformations occur by slip on the same crystallographic planes. In the mechanism of fatigue the metal undergoes progressive modification without impairment of its strength and crack appears and develops until fracture occurs. A fatigue crack may precipitate brittle cracking but a brittle fracture may start in otherways as well in both the advance signals of distress are either absent or difficult to detect and in either, such plastic deformation as occurs is highly localised.

2. THE WELDING AND FATIGUE

The use of welding by industry is so extensive that around 62 million welding rod is used in the country (Honavar, 1981).

The welding is applied to ships, missiles, tanks, boilers, heavy pressure piping, presses, rail road equipments, freight and passenger cars, bridges, gas transmission lines, smoke stake, penstock, earth moving machinery, farm machinery, canal lock gates, conveyors, fans, frames, chasis, girders, weigh bridges etc., where the strength of the finished article is an important consideration. In Britain alone, losses are reported to the tune of several million pounds due to the fatigue failures of welded structures each year (Saxe, 1960). Normally welding introduces the stress raisers, defects, metallurgical changes and the residual stresses which reduce the fatigue strength of the welded joints. The welded structures generally attribute to cracking due to fatigue. The majority of these fatigue cracks normally initiate adjacent to a weld toe. In civil engineering structures, fatigue failures have been most prevailent in the floors beam hangers of rail road truss bridges. Shank has reported hundreds of fatigue failures in fabricated structures. Sandberg (1950) has reported the failures of 170 floor beam hangers in 83 spans of 50 bridges. In a study by Fisher, (1976) all but 5 out of the 130 cases of cracking in bridges were attributed to fatigue. Following are the examples of fatigue failures of the early steel bridges on Indian Railways (Ananthanarayana, 1988) :

- Ganga bridge near Balawali, Moradabad - Laskar section of Northern Railway.
- Mahanadi bridge near Cuttuck, South - Eastern Railway.
- Berupa bridge near Cuttuck, South - Eastern Railway.
- Baitarni bridge near Bhadrak, South - Eastern Railway.
- Poney truss girder, Howrah - Nagpur main line.
- Sheonath bridge and
- Godavari girder bridge.

3. CHRONOLOGY

Since the very beginning of the use of metals in machines and structures, engineers have been concerned to know how components which are required to sustain variable loads will behave in respect of load carrying capacity and length of service. The fact that the subjection of a metal bar to many cycles of stresses can produce fracture by much smaller forces than would be required for static failure, has been recognized by practical engineers for a very long time. Poncelet (1839) was the first to discuss the property by which materials resist repeated cycles of stress and that he introduced the term 'fatigue'. Brief chronology of the history, development and failures is summarised below.

1800 - 10s

- Shank and Parker reviewed and reported many structural failures.

1820 - 30s

- The first test to this end appear to have been made in 1829 by Albert Wohler (1819-1904) in Germany on mine hoist chains 1829.

1830 - 40s

- Rankine W.J. Macquorn, a British railway engineer later to become famous in the study of the mechanism and recognised the distinctive characteristics of fatigue fracture and underlined the danger of machine parts containing sharp edges and presented the first English paper in this field 1843.
- Hodgkinson was commissioned by the British Govt. to study the use of wrought iron and cast iron on railway particularly in the construction of bridges 1848.
- During the year 1849 - 50 the same problem was discussed at the several meetings of the instt. of Mech. Engrs. (London) Oct. 24, 1849.

1850s

- Systematic investigation of the fatigue, laboratory tests in Germany by August Wohler.
- French Government appointed a commission to study the deterioration in the axles of railway vehicles 1852.

1860s

- Fairbrain made repeated bending test on iron beams 1864.

1870s

- Expanded Wohler's work, Gerber and others investigated the influence of meanstress. Goodman proposed a simplified theory concerning the mean stresses.

1880s

- Bauschinger confirmed the accuracy of several of the points which Wohler had established 1884.
- Failure of 250-ft-high water standpipe at Gravesend Long Island, Newyork Oct. 1886.

1890s

- Failure of Gas-holder, Brokiyn New York Dec.23 1898.

1900s

- Ewing, Rosenha and Humfrey studied the fatigue mechanism and shown the formation of slip band 1900.

- Gilchrist proposed the theory of 'Localised stresses' 1900.
- Failure of water stand pipe Sanfard Main Nov. 17, 1904.

  Guillet analysed the leffect of lthe internal damping in the study of fatigue 1909.

1910s

- Bairstow demonstrated the existence of hystresis of elastic deformations and shown its connection with fatigue 1910.
- The scientific review "La Technique Modern" inaugurated an inquiry in to the fatigue of metals. 1910.
- At the congress of lthe international Association for the Testing of material held at Copennagen in 1910 Le Shateller estimated the research data on fatigue was insufficient.
- Nussbaumer published a comparison of results of the single, repeated impact and rotating bending fatigue tests using the method of Wohler in 'La Revue de Metallurgie' 1914.
- Fremant presented a paper to the 'Academie des sciens' entitled 'The Premature failure of steel machine parts under repeated stress' 1919.
- Catastrophic failure of molasses (2.3 m gal and loss of 12 lives 40 injuries). tank, Boston Jan 1919.

1920s

- Griffith's theoretical calculation and experiments on brittle fracture using glass to relate the size of microscopic cracks 1920-21.
- Failures of general small vessels in US 1920-21.
- Failure of crude oil storage tank, Poncacity Oklahoma Dec. 19, 1926.
- Gough published a book entitled 'The fatigue of metals' 1926 (19)
- Heih used the concept of notch strain analysis and residual stress 1929 - 30 .
- Almen correctly explained the improvements in fatigue strength of the components like spring axles etc., 1929 - 30.
- The French contribution under the guidance of M. Albert Caquot permitted fatigue tests to be included among acceptance tests of metals intended for aircraft constructions 1929 - 30.
- Buck Motor Division of General Motor Corporation contributed the improvement in fatigue strength by shot peening 1929 - 30.

1930s

- Failure of eight crude oil tands, south and midwest U.S.
- Neuber introduced the stress gradient effect at notches 1937.

- The Martime commission was established in 1937 with the authority to inaugurate a long range merchant ship building programme 1937 (18).
- Failure of Vierendeel Truss Bridge Albert canal Hasselt Belgium March-14 1938.

1940s

- A mannual on the prevention of failure of metals under repeated stresses was prepared for the use by the Bureau of Aeronautics 1941.
- During 1942 and World War II many brittle fracture in welded tankers and liberty ships. Out of 5000 merchant ships built, over 1,000 had developed cracks of considerable size by 1946, between 1942 - 46 more than 200 ships had sustained fracture, and at least 9 T-2 tankers and seven liberty ships had broken completely in two.
- Failure of spherical hydrogen tank schemctody NY Feb. 1943.
- Failure of spherical ammonia tank Pennsylvania March 1943.
- Failure of oil storage tank Middle West U.S. Dec. 14, 1943.
- Failure of spherical pressure vessel Morgan Town West Virginia Jan. 1944.
- Failure of cylindrical gas pressure vessel Cleveland Ohlo Oct. 1944.
- Miner formulated cumulative fatigue damage criterion 1945.
- ASTM held a symposium on fatigue of metals and formed a research committees on fatigue 1946.
- A Symposium on the failure of metals by fatigue was also held at University of Melbourne in Dec. 1946.
- In France "La Societe de Metallurgie in the course of its autumn session in 1946, arranged a series of conferences.
- The American Bureau of Shipping introduced restrictions on the chemical composition of steel 1947.
- Failure of Fire Oil storage tanks in Russia Dec. 1947.
- Lloyds Register formed some committee 1949.
- Failure of Transcontinental Natural Gas Transmission pipe lines United State 1948 - 51.

1950s

- KI became the basis of Linear Elastic Fracture Mechanics (LEFM)
- Several failures of the steam turbines and generator rotors.
- Failure of penstock at the Anderson Panch dam Boise, Idaho Jan.1950.
- Failure of Duplessis Bridge Trassrivers Quebec Canada Jan. 31, 1951.

- Use of electron microscopy to analyse the fatigue mechanism introduction of stress intensity factors KI by Irvin 1952.
- Failure of two oil storage tanks, England Feb. - March, 1952.
- Fractures still occurred in ships in the early 1950s. Between 1951 - 53, two comparatively new all welded cargo ships and a transversely framed welded tanker broke in two.
- Fatigue failure of the first plane Jan., 1954.,
- Catastrophic fatigue failure of the two comet aircrafts at the higher altitude 1954.
- The failure of F-III aircraft 1954.
- A longtudinally framed welded tanker constructed of improved steel quality using up-to-date concepts of good design and welding quality broke in two 1954.

1960s.

- Low cycle strain controlled fatigue behaviour became predominant.
- Paris showed that fatigue crack growth rate (da/dn) could be best describes by KI (18).
- Brittle failure of welded steel penstock leading to the Lake Echo Power Station in Tasmanis 27 Feb. 27, 1960. (24)
- Brittle failure in 100 ft. span girder of kings bridge Melbourne July, 1962 (24)
- Fractures still have occurred in ships, between 1960-65. Boyd's described 10 such failures and a number of unpublished reports.
- Catastrophic failure of the point Pleasent Bridge at Point Pleasent, West Virginia (loss of 46 lives), Dec. 15, 1967.

1970s

- Use of fracture mechanics in US was made fro B-1 Bomber.
- Failure of 584 ft. long Tank Barage 1972.
- AASHTO adopted the material toughness requirements 1973.
- Provision for damage tolerance against fatigue by AASHTO 1974.

1980s

- T. Mura and his associates proposed several theories on fatigue crack initiations 1983.

1990s.

- Karamchandani, Tornyet et al. proposed a system reliability process to fatigue and fracture of structures 1992.

4. CAUSES

A reasonable question is why fatigue failures still occur with such regularity and in so many parts?. One reason is that there are always uncertainities about the loads and environment a part will experience in service. Another is the scatter, is probably greater than that of the other metal properties. The predominant reason, however is that complex metal structures may contain hidden of unrecognized areas of stress concentration or stress raisers. The causes of the service failure can be classified as :

- Inappropriate design,
- Structural defects and
- The environmental effects.

The design of welded structures involve complex problems that vary in nature from one structure to another, the attention to design details alone is not sufficient to ensure against failure because most of the service failures are caused by structural defects rather than the inappropriate design. The structural defects may include:

- Stress raisers:

  The majority of fatigue failures originate at some form of stress raisers, further they can be classified by their origin as :

- Those resulting from the design requirements such as shape discontinuities, change in cross section, notches, holes, corners, keyways and threads etc.
- Those caused in advertently during fabrication, such as laps, seams, tears and cracks etc.
- Those carried over from the metals refining process, such as pipe, inclusion and segregation etc.
- Those incurred as a result of the operating or maintenance, environment such *as corrosion, stress corrosion, stress rupture, foreign object damage etc.*
- Material properties:

  Such as strength, composition etc.

- *Weld defects:*

  Like slag inclusions, lack of penetration, liquation cracking, hydrogen cracking etc., and

- Residual stresses:

  caused by processing like forming operations, welding, differential cooling rates, cold working, permanent or plastic deformations of some alloyed metals.

The environmental factors include such as corrosion and temperature as they give rise to corrosion fatigue and thermal fatigue. The chances of failure becomes much more when corrosion and fluctuating stress combined together at high temperature gradient.

5. REMEDIES

The following salient points when carefully taken into account during design and manufacturing stage can minimise fatigue failures as :

- Proper distribution of the load throughout the part of the structure so that there is no concentration of the load resistance in any localised area.
- Removal of the rough machine marks like burrs, tears in punching etc.
- Elimination of the high tensile stress from inappropriate grinding, weld repairs etc.
- Removal of the Hydrogen from plating, surface decarburisation etc.

The occurance of fatigue failure can also be minimised by maintaining routine inspection that may include :

- Visual inspection
- Non-destructide testing
- Identification marking and
- The record of failures etc.

Heat generated by the welding process often will produce tensile residual stress approaching the yield strength of the material. These harmfull self stresses in the heast affected zone may contributes the poor fatigue characteristics of the weldments. The improvement in fatigue strength can be accomplished by improving the weld geometry and / or by introducing the surface compressive residual stresses by using the suitable method. Fatigue crack may devolve in the base metal, the weld material or in the heat affected zone (HAZ), once defected then can be repaired by:

- Reducing the stress concentration by avoiding spray arc strikes, grinding the weld cracks and by dressing the fillet.
- Replacing the weld metal and
- Inducting the beneficial residual compressive stresses.

The propagation of the crack depends on stress concentrations near its tip, crack arrest by residual compressive stress is based on the facts that a crack will not propagate unless a tensile stress force it opens up on it and the crack tip will not open as long as a compressive force acts upon it.

6. ENGINEERING PRACTICE

Building standards and regulations prescribe a reduction of the design strengths for members and connections that are subjected to alternating or vibrating loads by introducing a factor less than unity and also draw special attention to the necessity of employing designs that will not produce considerable concentrations of stresses. Fatigue design rules for welded structures have developed extensively over the last twenty years following a major review and statistical analysis of published fatigue data. Fatigue design rules for welded tubular structures were published, in Norway the classification society det norske veritas published rules for offshore structures which contain fatigue design data. In USA there are two sets of the rules one published by the AWS for general structural use and one by the American Petroleum Institute for offshore structures. In UK, the rules are published by the UK Department of Energy, the latter has been used the results of research conducted over the last ten years to revise the rules with a view to improve their relevance to the size and nature of offshore platform in the Northern sea. Initial efforts was directed at the steel bridges and the rules in BS-5400 evolved from those published by the institutes, later as a result of rapid exploitation of oil and gas fields in the northern sea, a number of major european research projects provided design data for tubular structures which together with the welded plate design data contained in BS-5400 were the basis of new fatigue design rules for offshore structures, broadly the same design rules have since been adopted for application in pressure vessel design and for considering fatigue of aluminium alloy welded structures. At the same time, considerable international collaboration has taken place, leading to design rules which are in good agreement with many national codes. Apart from these offshore codes several national fatigue codes exist all these codes are based on a classification of the fatigue strength of structural details and Miner's cumulative damage rule. The fatigue category is identified by the fatigue strength at a certain number of cycles and defined slopes of the S-N lines. In the Dutch code (27) this has been done by fixing the stress range at ten million cycles for a large number of structural details.

There are various techniques available for improving the fatigue strength of welded joints can be grouped as :

- Weld Geometry improving Methods which include:
- Machining methods: Burr grinding, Disc grinding
- Remelting methods: TIG dressing, Plasma dressing
- Special welding techniques: Weld profile control (AWS), Special electrodes.
- Residual Stress Methods include:
- Mechanical methods: Peening - Shotpeening, Hammer or wire bundle peening, explosive peening, overloading methods - initial over loading, local compression, vibration stress relief.
- Thermal methods: Thermal stress relief, spot heating, Gunnerts method.

7. INVESTIGATION

The fatigue strength of welded jopints have been analysed numerously by the several investigators under different test conditions like,

- Specimen material, geometry and the type of joints,
- Welding conditions and process,

Applied stress and nature of loading,

- Type of treatments i.e. local machining, shotpeening etc., and
- The environmental conditions etc.

Consequently, it is difficult to compile and interpret accurately the available significant experimental results. However, the authors have compiled the work of various investigators, and carried out the investigations over the welded structural steel and obtained the optimised values of the shot peening parameters for the repair and maintainance of joints. Shot peening over welded joints has shown improvement over fatigue strength as shown :

Steel	Endurance ratio (FS/UTS)	Test condition	Fatigue strength (MPa)	Impro-vement %
16mm	0.43	virgin	235	0
dia.		welded	172	-27
Structural		peened	288	23
steel		welded peened	203	-14

8. DISCUSSION

A study of fatigue failures reveals that not all the failures are caused by inappropriate design. In majority of the cases the failure could be attributed to geometric factors and imperfections in the structure. Obviously, then attention to design details alone is not sufficient to ensure against failure. Careful workmanship is essential in welding. It has become increasingly evident that defects introduced through poor workmanship or by accident must be detected by deligent and well trained inspectors prior to the time that the structure is put into service. Weld quality may also be implemented but in general welding imperfections are only significant if they introduce stress concentrations which are more severe than those already present as a result of the basic weld geometry. The presence of high tensile residual stresses in welded joints is also significant in that applied compressive stresses are just as damaging as applied tensile stresses. In most tensile practical circumstances this problem cannot be solved by thermal stress relief alone the best practice is thermal stress relieve, followed by controlled shot-peening.

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