# EVOLUTION OF FATIGUE HISTORY

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***Abstract.*** *The fatigue of the materials has been referred a long time ago. However, with the advent of the industrial revolution, the interest in studying this subject became more frequent and important. In this context many books and papers about fatigue were published, but limited to the description of results. In this paper, the authors presented a description of the historical evaluation and the contribution of the importance of scientists and engineers and their work for the further development of fatigue technology and knowledge.*

***Keywords****: fatigue, history of fatigue , materials, researchers*

## 1. INTRODUCTION

The word “fatigue” was introduced about the 1840 and 1850 to describe failures occurring from repeated stresses (Stephens, R I., *et al* 1980). Many books and papers about this subject were published, but the most part of the publications are limited to the description of results. In this paper, the authors presented a description of the historical evaluation and the contribution of the importance of scientists and engineers and their work for the further development of fatigue technology and knowledge.

One of the first definitions of fatigue was presented by the International Organization for Standardization in 1964 in Geneva, American Society for Testing Materials in 1972 (ASTM, 1972), as follows:

*“Fatigue is a process of progressive localized permanent structural changes occurring in a material subjected to conditions that produce fluctuating stresses at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations”.*

This definition being generalized is valid for the fatigue of nonmetallic materials whose failure can occur in several ways, namely by mechanical fatigue, thermal fatigue, corrosion fatigue and others types.

## 2. HISTORICAL EVOLUTION

The fatigue of materials is referred a long time ago. The failures occurred in the masts and sails of boats that traveled long distances, are referred to as the phenomena of fatigue. However, with the advent of the industrial revolution the interest in the study of the phenomena of fatigue became more frequent and of crucial importance, because the problem of fatigue has never had great importance since the equipment used were essentially manual or animal drawn where the requests were essentially statics (Suresh, S, 1998).

So the principals historical descriptions were mentioned by the German, English and American engineers and scientists.

The history of fatigue begins with Albert, 1830, in the mines of the Oberharz, (Suresh, 1991 and A. Morin, 1853). In 1837, he published the first fatigue test results known, using a test machine for the conveyor chains which had failed in service in the Clausthal mines. Due the great cost of these structural elements, Albert invented the wire rope-surely more important than first fatigue tests.

With the development of metallic materials and their application in bridges and railways, the fatigue ruptures begin to appear more important and the accidents become more frequents. So in 1842, were performed research on fatigue of materials due to the accident occurred near Versailles, in France, claiming the lives of 60 peoples, according to the article published by the Times of London, 1842. In this context scientists and researchers were proposed to study the phenomenon of fatigue namely the British and German governments. Hodgkinson was proposed by British government to study the phenomena of fatigue in bridges and railway equipment.

In 1842, Rankine, English engineer, becomes famous for his contributions in the field of mechanical engineering and recognized that stress concentration areas in mechanical components were preferred for the appearance of failures (Rankine, 1842).

But it was Wöhler, in 1850 and 1860, German engineer, which conducted the investigations on the axes of axles of carriages for the railway. The tests were performed in laboratory fatigue under repeated stresses subjected to bending, torsion and axial loads (Wöhler, A., 1860).

These studies showed that the fatigue life increased with decreasing applied stress field so that below a certain amount of tension component seemed to have infinite life. On the other hand, he found that the fatigue life was drastically reduced by the presence of notches. The studies having suggesting a safety factor of two for static strength and an additional one of two for fatigue materials that are valid for infinite design life.

Wöhler represented his test results in the form of tables. Spangenberg, his successor, as director of the "Mechanisch-Technische-Versuchsanstalt" in Berlin, plotted the results of Wölher as curves forms, although in the unusual form of linear abscissa and ordinate, obtaining SN curves (Spangenberg L., 1874 *and* 1879). The SN curves were called "Wöhler curves" since 1936, W. Kloth *and al* (1936). The influence of mean stresses and notches on fatigue life in this period does not appear so important to the researchers

In 1910, Basquin, (Basquin O. H.,1910), represented the finite life region of the "Wöhler curves" in the form (*log* $\sigma_a$) on the ordinate (*log N*) on the abscissa and describe it by the simple formula:

$$\sigma_a = CR^n \tag{1}$$

which is still used even today or in a similar actual form:

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f^{'}}{E}\left(2N_f\right)^c \tag{2}$$

that relating elastic strain amplitude, $\Delta\varepsilon_e/2$, with the number of reversals to crack initiation $2N_f$, where $\sigma_f^{'}$ and $c$ are, respectively properties of the material and $E$ is the Young's modulus.

Bauschinger, Professor of Mechanics at the Munich Polytechnical School, which is now the Technical University of Munich, that suggested the Bauschinger effect, in his words, "the change of the elastic limit by often repeated stress cycles" (Bauschinger, 1880 *and* 1886), and this concept was the basis for the hypotheses of Manson and Coffin (Manson, 1953 and Coffin, 1954), which presented independently the concept of plastic strain which are responsible for cyclic damage, resulting later the well-known empirical relationship Coffin-Manson establishing the relationship between the number cycles to rupture and to the plastic strain which are still being used today in the LCF, (Low Cycle Fatigue), as follows:

$$\frac{\Delta\varepsilon_P}{2} = \varepsilon_f^{'}\left(2N_f\right)^c \tag{3}$$

that relating plastic strain amplitude, $\Delta\varepsilon_p/2$,with the number of reversals to crack initiation $2N_f$, where $\varepsilon_f^{'}$ and $c$ are, respectively properties of the material.

In the early 1960, low-cycle-fatigue strain-controlled fatigue behavior became prominent with the Coffin-Manson relation between plastic strain amplitude and fatigue life. These ideas promoted by Topper and Morrow, providing an equation for total strain-life that is the sum of the elastic and plastic strains. An alternative version of Morrow's, including the effect of mean stress, $\sigma_m$, at long lives is given as follows:

$$\frac{\Delta\varepsilon_T}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f^{'} - \sigma_m}{E}\left(2N_f\right)^c + \varepsilon_f^{'}\left(2N_f\right)^c \tag{4}$$

Other contributions were introduced especially by Fairbairn in 1864 and Gerber in 1874, that developed the design methods for different fatigue stress cycles. Similar studies were performed by Goodman in 1899, by Bauschinger and they concluded that the elastic limit of metals under cyclic elastic limit was different from the monotonic regime, which came to confirm the results published by Wöhler. Soderberg, Goodman and Gerber included, in design of fatigue, the effect of the mean stress. Other researchers may be cited in the field of fatigue of materials, (Stephens, R I., *et al* 1980), (Suresh, 1991and Walter S., 1996), such as:

1915- Smith, Moore e Seeley;
1919- Ludwik;
1920- A.A Griffith;
1923- Hanson.

### 2.1. Griffith´s and Irwin theories

In 1920, A.A. Griffith, an English aeronautical engineer, published the results of his theoretical calculations and experiments, to explain the failure of brittle materials, developed during World War. Griffith suggested that the low fracture strength observed in experiments, as well as the size-dependence of strength, was due to the presence of microscopic flaws in the bulk material, (Griffith, A. A., 1921).

To verify the flaw hypothesis, Griffith introduced an artificial flaw in his experimental specimens. The artificial flaw was in the form of a surface crack which was much larger than other flaws in a specimen. The experiments showed that the product of the square root of the flaw length $a$, and the stress at fracture $\sigma_f$ was nearly constant, which is expressed by the equation:

$$\sigma_f \sqrt{a} = C \tag{5}$$

With this classical pioneering work on the importance of cracks, Griffith developed the preliminaries bases of fracture mechanics.

George Rankine Irwin, born on February 26, 1907, suggested a modification in the theory proposed by Griffith, that was largely ignored by the engineering community until the early 1950, because Griffith's theory provides excellent agreement with experimental data for brittle materials, such as glass but for ductile materials, such as steel, though the Griffith's theory still holds, the surface energy is usually unrealistically high.

In 1938, Irwin headed the Ballistics Group during World War II, a group working under G. R. Irwin at the U.S. Naval Research Laboratory (NRL), realized that plasticity must play a significant role in the fracture of ductile materials, (Irwin G, 1958). At that time, his scientific interests were focused on the impact penetration of bodies and, in particular, bullet damages to the skin of the aircraft. He developed a method for measuring variations in penetration forces and new bulletproof nonmetallic materials, which were then extensively used in military engineering. His scientific achievements in this field were classified as secret and became partially known.

The modifications proposed by Irwin appear to be in according whit the actual structural materials theory. The level of energy needed to cause fracture is orders of magnitude higher, than the corresponding surface energy proposed by Griffith, because there are always inelastic deformations around the crack tip that would make the use of linear elastic theory at the crack tip, highly unrealistic. In ductile materials and even in materials that appear to be brittle, a plastic zone develops at the tip of the crack (E. Erdogan, 2000). As the applied load increases, the plastic zone increases in size, until the crack grows and elastic strain energy is released as a crack grows. The plastic loading and unloading cycle near the crack tip leads to the dissipation of energy as heat. Hence, a dissipative term has to be added to the energy balance relation devised by Griffith for brittle materials. In physical terms, additional energy is needed for crack growth in ductile materials when compared to brittle materials.

Irwin's theory was to partition the energy into two parts:

- The stored elastic strain energy which is released as a crack grows. This is the thermodynamic driving force for fracture.
- The dissipated energy which includes plastic dissipation and the surface energy. The dissipated energy provides the thermodynamic resistance to fracture. Then the total energy dissipated is represented by $G$, as follows:

$$G = 2\gamma + G_p \tag{6}$$

where $\gamma$ is the surface energy and $G_p$ is the plastic dissipation energy of crack growth.

The modified version of Griffith's energy criterion can then be written as:

$$\sigma_f \sqrt{a} = \sqrt{\frac{EG}{\pi}} \tag{7}$$

For brittle materials such as glass, the surface energy term dominates and the total energy is $G \approx 2\gamma = 2J/m^2$ and for ductile materials such as steel, the plastic dissipation term dominates and the energy is $G \approx G_p = 1000\ J/m^2$.

In 1958, Irwin proposing the concept of the stress-intensity factor, given by the formula:

$$K = \sigma\sqrt{\pi a} \tag{8}$$

where, *K* is the stress intensity factor (SIF), $\sigma$ is an applied stress and *a* is the crack length. If *K* reaches a certain critical value depending on the "fracture toughness" of the material, the collapse occurs. The critical fracture toughness value can be defined in terms of the stress intensity factor, *K*, as follows:

$$K_{Ic} = Y\sigma\sqrt{\pi a} \tag{9}$$

where *Y* is a geometrical factor that depends on both specimen and crack geometry.

With this concept, linear elastic fracture mechanics was born, where the stress intensity factor, *K*, is used to predict the stress state "stress intensity", near the tip of a crack caused by a remote load or residual stresses. When this stress state becomes critical, the crack grows and the material fails.

## 2.2. Fracture Mechanics

Fracture mechanics was the name coined for the study which combines the mechanics of cracked bodies and mechanical properties. As indicate its name, fracture mechanics deals with fracture phenomena. The establishment of Fracture Mechanics is closely related to some well disasters in recent history namely with fractures observed in ships and aircrafts during World War II. The failures occurred primarily because of the change from riveted to welded construction and the major factor was the combination of poor welds properties with concentrations and poor choice of brittle materials in the construction. Of the roughly 2700 ships built during World War II, approximately 400 presented serious fracture and some broke complexly in two. The Comets accidents in 1954 sparked an extensive investigation of the causes, leading to significant progress in the understanding of fracture and fatigue.

So the Fracture Mechanics was divided into Linear Elastic Fracture Mechanics (LEFM) and Elasto-Plastic Fracture Mechanics (EPFM). LEFM gives excellent results for ductile materials like high-strength and low–carbon steel, stainless, aluminium alloys, where the plasticity will always preceded fracture. Nonetheless, when the load applied is low the linear fracture mechanics provides a good approximation to the physical reality. For a geometry, where the stress intensity factor increases with the crack length, the curves that describe the crack length as a function of the stress application cycles has the shape represented in the Fig.1. In this illustration of fatigue propagation curves are represented for three different stress values, $\sigma_1$, $\sigma_2$, and $\sigma_3$. For all curves the cracks start from the same initial defect, $a_{ci}$, growing until reaching a critical dimension, $a_c$, responsible for the rupture. The applied stress is an important parameter in the propagation process. For the stress $\sigma_1 > \sigma_2 > \sigma_3$ the propagation curves are similar, but $a_{c1} < a_{c2} < a_{c3}$ and consequently $N_{f1} < N_{f2} < N_{f3}$.

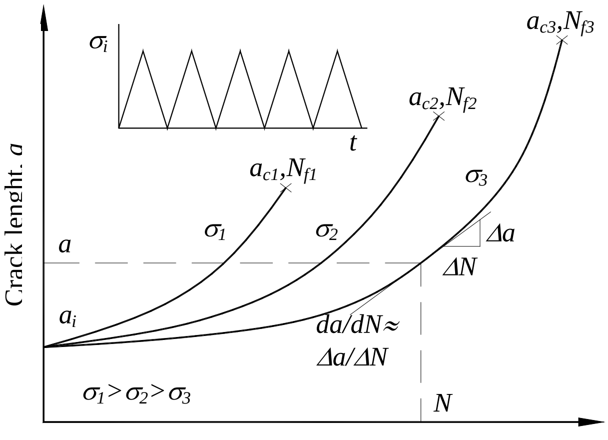

Figure 1. Schematic representation of fatigue crack growth curves for three different stress levels.

This behavior observed in the propagation of fatigue cracks led many authors to propose empiric laws with the following general forms, Walton *et al* (1967):

$$\frac{da}{dN} = \alpha \ f\left(\sigma, a\right) \tag{10}$$

or:

$$\frac{da}{dN} = \alpha \sigma^m a^n \tag{11}$$

that express the importance of stress and crack length in the crack propagation rates.

If the analysis is restrict to states of stress amplitude constant, the fatigue crack growth rate, can be expressed in the following formula as function of several factors such as:

$$\frac{da}{dN} = f\left(\Delta K, F, R, T, n\right) \tag{12}$$

where: $\Delta K, F, R, T, n$ is the stress intensity amplitude, load frequency, stress ratio, temperature and a constant depending of the environment respectively.

The first law that characterizes the fatigue crack propagation rates, between the rate of crack growth, *da/dN*, and the amplitude of the stress intensity $\Delta K$ parameters, is an empirical formula and it was proposed by Paris (Paris and Erdogan, 1963).

Prior to the 1960, fatigue crack growth rates were not utilized for purposes of safety in some structural situations, such as aircraft. However, it was recognized that could be gained advantages if methods of analysis could be developed to predict the rates of crack growth. An early model analysis was attempted by Head Paris, C. P., *et al* (1999), but it did not supply a useful method of prediction for applications. McEvilly, in 1960, provided a wide range of crack growth data on two aluminum alloys and correlated his data using a parameter based on Neuber's notch analysis, which was somewhat awkward for adaptation to crack analysis (McEvilly AJ Jr,. 1958). However, despite the fact that it was the first successful correlation, he has not been given sufficient credit in the literature for that work.

Paris of Lehigh University, in his Ph.D. Thesis of 1962, (P. C. Paris, 1962) and in a previous paper, P. C. Paris, *et al* (1963), established that fatigue-crack propagation could be described using the Irwin's theory to the crack stress analysis method to fatigue crack growth as follows:

$$\frac{da}{dN} = C\left(\Delta K\right)^m \tag{13}$$

where *da/dN* is the fatigue crack propagation rate, $\Delta K = K_{max} - K_{min}$ represents the range of the stress intensity factor and *C* and *m* are constants obtained experimentally.

This equation soon set out on a veritable triumphant advance around the world and it's called Paris's law and suggested that fatigue crack growth rates could be correlated using the stress intensity parameter, $\Delta K$ (Paris PC. 1957 and P.C., *et al*, 1961). He used this parameter to predict the crack growth rates in structural materials from laboratory. However, lacking test equipment to try the method, that data became available to verify that this method did work for a wide range of crack growth rates between $10^{-7}$ to $10^{-2}$ millimeters per cycle, from three independent sources on two materials.

The paper written on that work at that time was not published until 1960 Paris, C. P., *et al* (1999), since it was delayed by rejection by three journals (ASME, AIAA, and Phil. Mag.). Though that method is widely accepted today, in the late 1960 at Boeing it was rejected by an outside review panel for federal supersonic transport exploratory studies as “it simply won't work”. Moreover, the federal agency funding the most extensive fatigue studies on multiple occasions stated ‘no interest’ in such work, although since 1970 they have funded more work than any other source.

The representation proposed in Eq. (2) to model fatigue crack propagation rates leads to a different curve, for each different stress values considered, not being a practical form. In alternative, several laws have been proposed by several researchers (Hoeppner *et al* 1974 and Beden, S. M. *et al* 2009).

A typical experimental curve that relates *da/dN* with $\Delta K$, for cyclic loads with constant stress amplitude and $R=0$, it is represented on Fig. 2 in a schematic way.

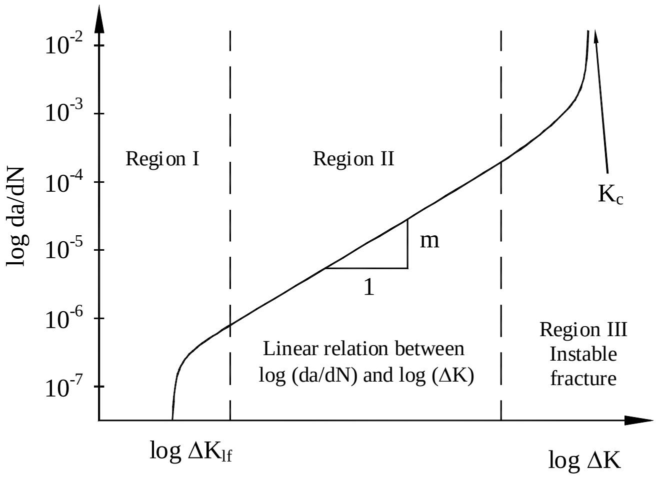

Figure 2. Schematic representation of the relation between *da/dN* and *ΔK*.

The *da/dN versus ΔK* curves are usually derived, for the majority of high strength materials, for crack propagation rates ranging between $10^{-7}$ and $10^{-2}$ mm/cycle. The diagram illustrates three different propagation regions, usually designated by regions I, II and III. In the region I, the propagation rate depends essentially on the stress intensity factor. In this region there exists a $\Delta K$ value below which no propagation is verified, or if propagation exists the propagation rate is below $10^{-7}$ mm/cycle. In the region II a linear relation between *log(da/dN)* and *log (ΔK)* is observed.

Region III appears when the maximum value of the stress intensity factor approaches the critical value, $K_{Ic}$. This region is characterized by an acceleration of the crack propagation rate that leads to an unstable propagation of the crack that consequently to the final rupture.

### 2.3. Miner's rule

In 1945, M. A. Miner popularized a rule that had first been proposed by A. Palmgren in 1924. The rule, variously called *Miner's rule* or the *Palmgren-Miner linear damage hypothesis*, states that where there are $k$ different stress magnitudes in a spectrum, $\sigma_i$ ($1 \leq i \leq k$), each contributing $n_i$ ($\sigma_i$) cycles, then, if $N_i$ ($\sigma_i$) is the number of cycles to failure of a constant stress reversal $\sigma_i$, failure occurs when:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C \qquad (14)$$

where $C$ is an experimental value found varying between 0.7 and 2.2. Usually for design purposes, $C$ is assumed to be 1.

## 3. EXAMPLES OF FATIGUE FAILURES

About 1920-1945, at war time period, the fatigue starts with frequency due to the industrial development observed and several accidents were reported. In all industrial countries fatigue was investigated. The number of papers, fatigue meetings and books on fatigue increased so considerably. These efforts were furthered by failures on all types of fatigue-loaded structures, automobile components, military and civil aircrafts.

### 3.1. In structures

In January 15th, 1919, something alarming happened on Commercial Street in Boston: a tank 27 meters in diameter and about 15 feet tall and fractured catastrophically about 7.5 million liters of molasses poured into the streets (Suresh, S, 1998).

*"Without an instant's warning the top was blown into the air and the sides were burst apart. A city building nearby, were the employees were at lunch, collapsed burying a number of victims and a firehouse was crushed in by a section of the tank, killing and injuring a number of the firemen ".*
*"On collapsing, a side of the tank was carried against one of the columns supporting the elevated structure [ of the Boston Elevated Railway Co.]. This column was completely sheared off ... and forced back under the structure ... the*

*track was pushed out of alignment and the superstructure dropped several feet ... .Twelve persons lost their lives either by drowning in molasses, smothering, or by wreckage. Forty more were injured. Many horses belonging to the paving department were drowned, and others had to be shot".*

The audit committee that investigated the accident after years of study, made public its conclusions (Hertzberg, R. W., 1989).

*"Weeks and months were devoted to evidence of stress and strain, of the strength of materials, of the force of high explosives, of the bursting power of the gas and of similar technical problems.... I have listened to a demonstration that piece "A" could have been carried into the playground only by the force of a high explosive. I have thereafter heard an equally forcible demonstration that the same result could be and in this case was produced by the pressure caused by the weight of molasses alone. I have heard that the presence of Neumann bands in the steel herein considered along the line of fracture proved an explosion. I have heard that the presence of Neumann bands proved nothing. I have listened to men upon the faith of whose judgment any capitalist might well rely in the expenditure of millions in structural steel, swear that the secondary stresses in a structure of this kind were negligible and I have heard from equally authoritative sources that these same secondary stresses were undoubtedly the cause of the accident. Amid this swirl of polemical scientific waters it is not strange that the auditor has at times felt that the only rock to which he could safely cling was the obvious fact that at least one- half the scientists must be wrong. By degrees, however, what seem to be the material points in the case have emerged"* (Hertzberg, R. W., 1989).

### 3.2. In aicrafts

The Havilland "Comet", was designed in 1948, as the first commercial aircraft jet of the Western world, to reach commercial production. Developed and manufactured by Havilland at the Hatfield, Hertfordshire, United Kingdom headquarters, it first flew in 1949 and was a landmark in aeronautical design. It featured an extremely aerodynamically clean design with its four de Havilland Ghost turbojet engines buried into the wings, a low-noise pressurized cabin, and large windows; for the era, it was an exceptionally comfortable design for passengers and showed signs of being a major success in the first year upon launching.

However, a few years after introduction into commercial service, the Comet suffered from catastrophic metal fatigue, which in combination with the pressurization caused two well-publicized accidents where the aircraft tore apart in mid-flight. The Comet had to be withdrawn and extensively tested to discover the cause; the first incident had been incorrectly identified as having been caused by an onboard fire. Several contributory factors, such as window installation methodology, were also identified as exacerbating the problem. The Comet was extensively redesigned to eliminate this design flaw. Rival manufacturers meanwhile developed their own aircraft and heeded the lessons learnt from the Comet.

In 1954 two "Comets" crashed, one near Elba, one near Naples, by failure of the fuselage at a window cutout (HMSO 1954). In a large research and test program (RAE, 1954), the cause was clarified according to the level of knowledge of the day: the full-scale fatigue test had been carried out with a fuselage which had before been pressurized to twice the maximum pressure differential in service. This was done to save a static test aircraft. In the window corners beneficial residual compressive stresses were thereby induced, which obviously were not present in the accident aircraft. Besides, an ultra-high-strength aluminum alloy of the 7000 series had been used, the unfavorable fatigue behavior of which Gassner had already described in 1941. As late as 1987 Swift of the FAA (T. Swift, 1987) showed, however, that in reality a design fault had been the cause of the accidents: the fuselage frames of the "Comet" were in one piece, whereas in more modern aircraft types they are built up of two independent frames. Therefore, a fast fracture could not been contained in the "Comet" design.

### 3.3. In hip femoral components

One of complications resulting from the hip replacement procedure is the possibility of fatigue failure in the metallic femoral components. A case history of such fracture phenomena in hip replacement is based on the work of Rimnac, (Rimnac, et al 1986). A metallic total hip component, known as Trapeziodal 28$^{TM}$ was made of surgical grade 316L stainless steel and known with the name. T-28. This name was given for this component because of the trapezoidal cross section of its stem and neck, and 28 is the diameter in millimeters of the femoral head.

Between 1973 and 1979, 805 patients received this implant at The Hospital for Special Surgery in New York City.

Out of this population, at least twenty-one patients are known to have received medical treatments for the removal of a fractured femoral component. This failure rate was four times higher than that reported for the others femoral component designs.

Eighteen of the twenty-one components of hip femoral components failed by fracture of the stem. The picture shows that fracture occurred proximal third of the stem portion (Suresh, S., 1998). In the remaining three cases, fracture occurred in the neck region and multiple cracks where observed in the majority of the components, where crack nucleation was sighted on the medial side of the stem. Figure 3, we can observed the failure of the T-28 femoral component.

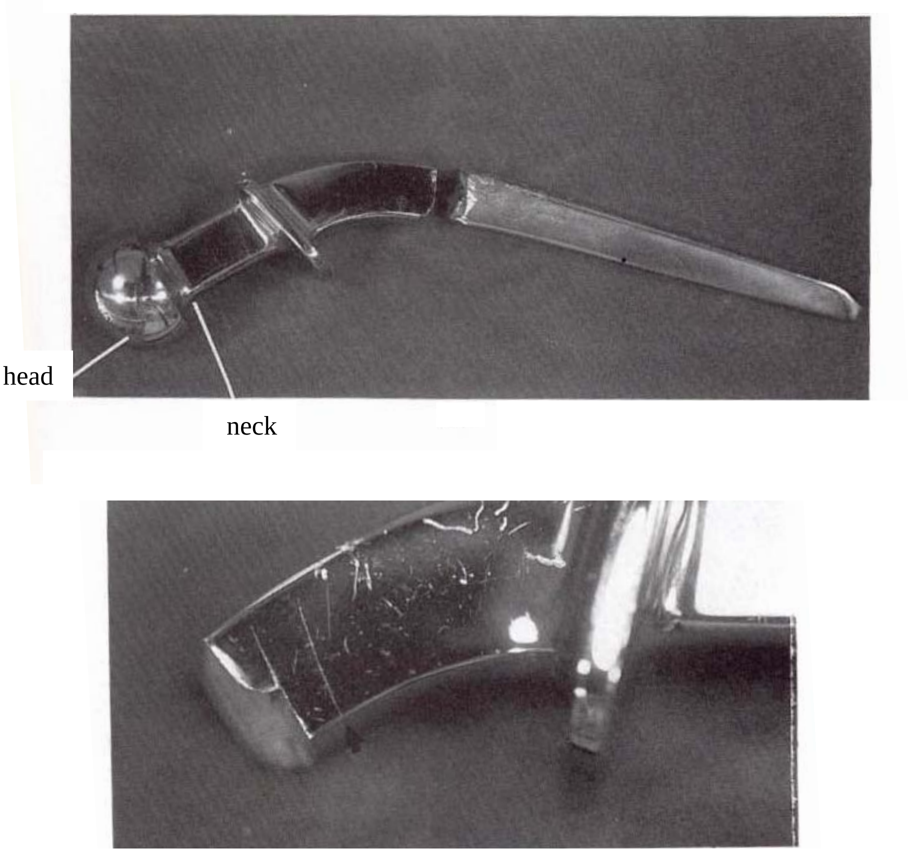

Figure 3. Photograph of failure of the T-28 femoral component (Suresh, S., 1998).

The origin of the femoral component failure was traced to fatigue loading where the components were subjected to a tensile stress of 115 to 244 MPa where was observed the combinations of axial and bending loads on the femoral components resulted in cyclic compressive stress on the side where the cracks initiated.

### 3.4. In Portuguese bridges

In Portugal there is a number of steel riveted railway and highway bridges more than one hundred years old, still in operation, requiring rehabilitation.

In order to assure high safety levels in old riveted steel bridges, highway and railway authorities have to invest heavily in their maintenance and retrofitting. Fatigue failures are a concern for steel bridges due to the likelihood of the steel to deteriorate under variable stresses.

A consistent residual fatigue life prediction should be based on actual fatigue data from bridge members which is often limited, mostly for ancient steel riveted bridges.

The Viana Bridge illustrated in the figure 4 a), was designed by Eiffel and inaugurated on 30th of June 1878. This bridge serves both highway and railway traffic, crossing the Lima river between Darque and Viana. This bridge has 573 meters in length and 6 meters width made of a continuous deck composed by nine spans. Recently, it can be observed several fatigue cracks near the riveted hole, as we can see in the figure 4 b).

Figure 4. Portuguese's bridge case: a) Overview of Eifel Bridge in Viana do Castelo; b) Crack propagation around the rivet hole.

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