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Failure analysis – Techniques and few case studies

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ABSTRACT

Engineering components are designed to perform a specific function for a certain minimum period of time. Failures therefore, means its inability to perform its intended function. In spite of best effort, because of inherent uncertainty in design parameters and material behavior it is certainly impossible to avoid failure. A proper analysis of such case provides valuable insight into the mechanics of the process, identify the factors responsible for failure and suggest necessary steps to be undertaken to overcome such incidents in future. Such studies have led to many innovations in design, development of new materials and process. The paper presents a broad overview of the tools and techniques used for such analysis.

INTRODUCTION

Although an engineering component is designed to survive for specified period, sometime it fails much before its design life is reached because of a variety of reasons. When a components ceases to perform its intended function it is said to have failed. Failure need not always be associated with fracture. It is just one of the several modes of failure. However, since it could have the most disastrous consequence it has always received major attention. As an illustration, the criteria of failure for a variety of components have been listed in Table 1. A proper analysis of failure helps us not only in identifying defects in design or solution of material but also point out our lack of knowledge of the material behaviour or design application. Failure analysis of Comet air craft used by BOAC during early fifties is a classic example. This was designed to fly at an altitude of 35000 ft. by turbojet engines. In comparison to the turbo-prop civil aircraft having an altitude ceiling of about 17000 ft., it was a very advanced concept for its time.

The first failure took place near Calcutta on 2 May, 1953 in an exceptionally severe tropical storm. The accident involved structural failure of the air frame although there was no evidence of any flaw in design or construction of the aircraft.

Table 1 : failure criteria of a few typical components

Components	Failure criteria
Boiler tube (super heater)	Rupture strength
Spring	Yield strength
Bearing	Fatigue, Wear
Column	Buckling

The subsequent failures in 1954 near Rome took place in good weather conditions The wreckage of one of these was salvaged from the sea. The fuselage was recon structed and the failure was traced to a crack which had started at the corner of a window in the cabin roof from a revet hole. The main crack was longitudinal. Cir cumferential cracks developed later. Passengers cannot be carried at high altitud unless the cabin is pressurized. The comet cabin was pressurized at 0.57 bar gauge which was 50% more than the pressure in other civil aircrafts at the time. Durin flight therefore fuselage functioned as a pressure vessel and was subjected to bot axial and circumferential stress. Each flight comprised of a single cycle of pressur loading. The failure took place after the aircrafts have flown 1290/900 flights re spectively. This leads one to conclude that a relatively small number of cycles ha generated along enough crack to cause fast fracture.

In order to verify that the failure had indeed been caused by fatigue a full scal simulation test was done on a comet air craft which had already flown 1230 times The result showed that the cabin failed after another 1830 cycles.

The nature and location of the crack was identical to that encountered in service The fuselage was repaired and re-stressed after placing a number of strain gauges The maximum stress appeared at the corner of the window and its magnitude wa found to be 50% more than that estimated using the then available techniques. I presence of rivet holes which act as stress raiser, fatigue failure within a few fligh cycle is indeed expected.

In retrospect, this may seem obvious. However, one must remember when actually happened, Coffin Manson law for low cycle fatigue (it was published i 1966) and Paris's classic equation on fatigue crack growth rate were not known (appeared in an obscure journal in 1961 after three leading journals had refused t publish it).

Investigators could not even estimate the length to which fatigue crack mu have grown to make the skin fail by fast fracture. This is not surprising as the mod ern concept of fracture mechanics such as stress intensity factor (SIF) and fractu toughness was still under development (Irwin 1957). Subsequent analysis howev showed that a_c for the DTD 546 aluminium alloy having 3.5–4.8 Cu, ≤1.0 Fe, ≤1.5 Si, ≤0.6 Mg, ≤1.2 Mn, ≤0.3 Ti was of the size of the bolt head. Therefore, there was every likelihood that critical cracks could go undetected during inspection.

A detailed analysis of such a failure provide impetus and suggests new methods/ approach to overcome such problems. Modern air crafts now increasingly use epoxy resin glue in place of rivets for joining the skin to the frame to avoid stress raisers. Computer based stress analysis packages not only provide more accurate stress estimates in complex geometries but can also pin point hot spots having higher stresses. The skin in such areas can be left a little thick in comparison to others by controlled electro chemical machining. This is to cut down weight, keeping the skin less highly stressed. In additions current materials of construction have a much higher fracture toughness and hence a much longer critical crack size, a_c so that growing crack could be easily spotted during routine inspection and removed much before it becomes dangerous. All these developments were instrumental in making air travel one of the safest modes of public transport.

WHY COMPONENTS FAIL IN SERVICE ?

In spite of all possible steps being taken to overcome service failure, such incidents do take place. However, due to our ever increasing knowledge base and growing availability of better technology frequency of such an occurrence has significantly gone down. Most of the current day failure can be traced to mistakes on the part of operator, fabricator/manufacture, designer or inspector. This will be evident when we go through some of the case studies. The reasons for failure could broadly be classified as follows:

* Design deficiencies (lack of knowledge)
* Material selection deficiencies
* Processing deficiencies
* Assembly and installation error
* Operational and maintenance error
* Environmental impact

In addition, one must realize that every design has a probability of failure. This is because both the material property and the loading are random variables having a definite mean and standard deviation. Therefore, in spite of the best effort there would always be a few incidents where the loading may exceed the critical value. In most cases however depending on the factor of safety used, the probability of failure could be very low ($10^{-6}/10^{-7}$). With prolonged service, probability of failure of a component should obviously increase, if so far no failure has occurred. In other words, old components may be more prone to failure. Besides this, there are

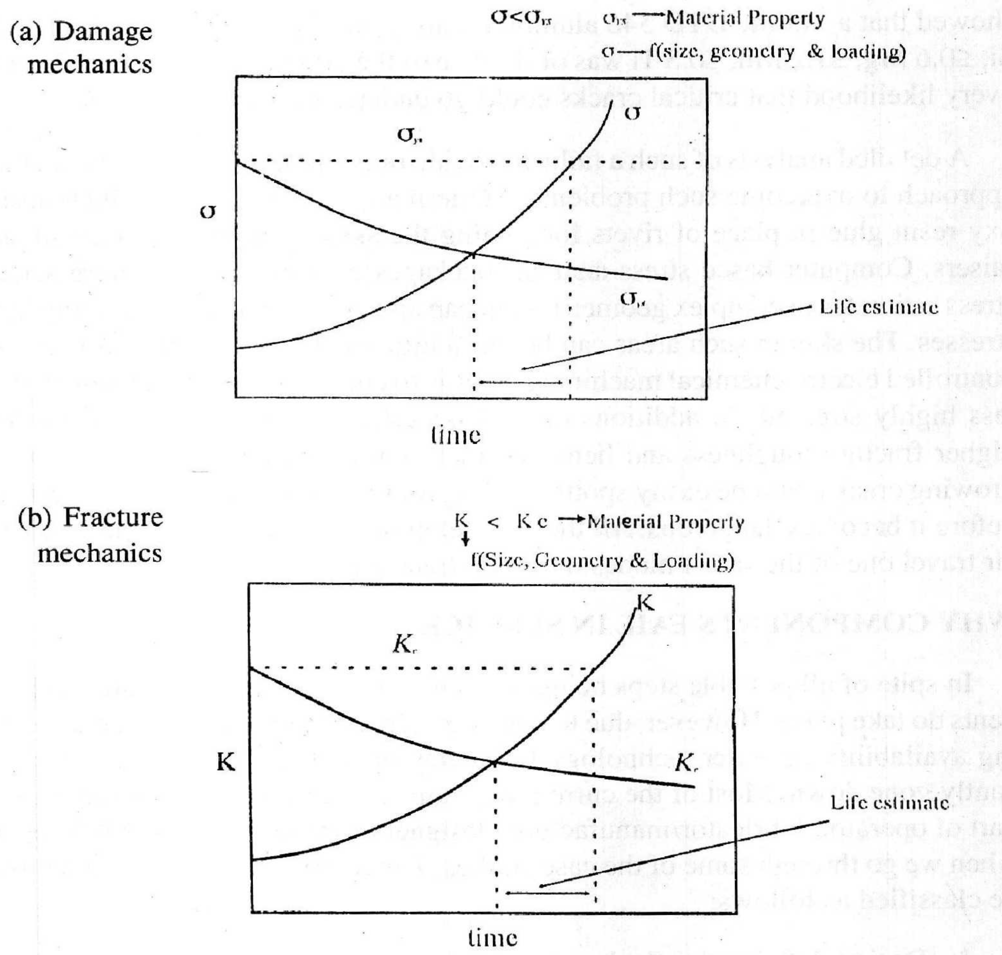

Fig. 1 : Schematic diagram showing life preidction procedure and failure criteria

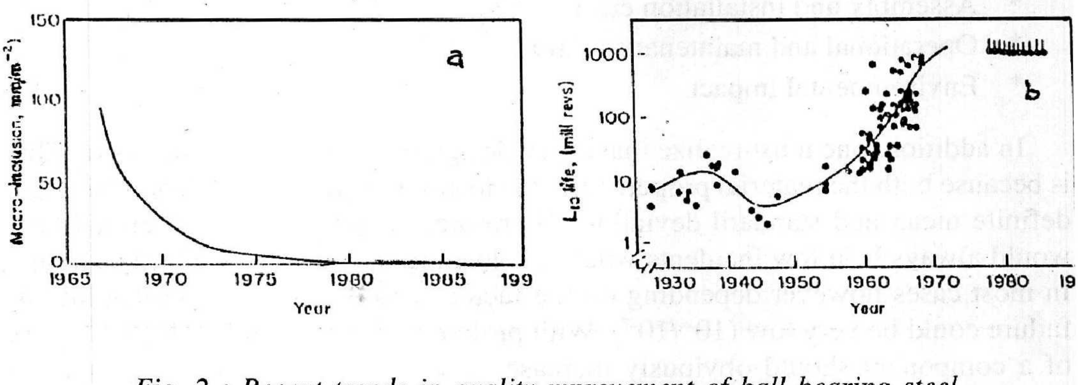

Fig. 2 : Recent trends in quality mprovement of ball bearing steel
(a) Reduction of oxygen in steel (b) Corresponding inprovement in performance

several natural processes of aging of materials. This may take place due to fatigue, corrosion, wear, shock loading and creep. Structural damages keep on accumulating in the component due any one or a combination of the above factors. Concepts of damage and fracture mechanics are now quite developed to give us a reliable estimate of the safe life of such components using these information. Figure 1 gives an idea of how appropriate failure criteria should be used for such an exercise.

REMEDIAL MEASURES

As a failure analyst it is not enough to find out the cause of failure. He or she is expected to suggest remedial measures as well. Suggestions can often be classified as follows:

- Improved design/manufacture/installation/operation for greater reliability
- Improved knowledge concerning material properties and behaviour
- Improved methods of forecasting, material response and greater accuracy in life assessment under environmental uncertainties
- improved materials technology

Whilst importance of some of these is quite ob... it could be worthwhile to illustrate how improvement in suational technology significantly reduced the failure rates in bearings. The predominant damage mechanisms in bearings is contact fatigue and wear. Wear is taken care of by improved lubrication, however longer life under contact fatigue loading would demand clean steel, virtually free from inclusions. Dissolved oxygen in steel is the primary source of inclusions which act as stress raisers in the bearing. During service the areas close to these inclusions are subjected to full cycle fatigue loading. As the area is alternately subjected to both tension and compression a lot of heat is generated in localized areas. Such overheating may result in the formation of localized hard spot susceptible to crack nucleation. Over the years with the adoption of ladle metallurgy, vacuum degassing techniques, inclusion contents of the steel has significantly come down. This has substantially improved the performance (fatigue life) of steel bearings (Fig. 2).

TECHNIQUES OF FAILURE ANALYSIS

A failure analyst must consider a broad spectrum of possibilities that might have led to its occurrence. Often a large number of factors, frequently interrelated, must be understood to unveil the cause of failure. In this respect the role of a failure analyst is similar to that of Sherlock Holmes, attempting to solve a mystery. Like the great detective, he is must carefully examine and evaluate all evidence available, then prepare a hypothesis – or a possible chain of events – that could have caused the failure (or crime). If the failure can be duplicated in laboratory under controlled service conditions, a lot can be learnt about how the failure has taken place.

ASM Metals handbook (Vol. 10, 8th edition) provides a basic guideline for investigation of a failure. However, it is needless to mention that collection of background information and visual examination of the failed part are the two most important steps. This would help the analyst to think evolve a hypothesis and raise critical questions whose answer would automatically lead to the solution. Important steps in an investigation are summarized below:

- Collection of background information
- Visual examination
- Nondestructive testing
- Mechanical testing
- Macroscopic examination
- Microscopic examination (optical, SEM, TEM)
- Chemical analysis (bulk and local)
- Stress analysis
- X-ray diffraction
- Fracture mechanics based analysis
- Electrochemical tests
- Simulated tests
- Heat-treatment and material processing
- Analysis of all evidence, formulation of conclusions and report writing (including recommendations)

However, in many cases it is not necessary to go through all of them. An experienced failure analyst on the basis of visual examination and background information can pick up (or suggest) the most appropriate steps to be followed. The above list though not complete does indicate how elaborate the scope can be. Indeed failure analysis could sometime be quite complex. A good failure analyst must have some idea on a wide range of fields viz. mechanics, physics, metallurgy, chemistry, manufacturing processes, stress analysis, fracture mechanics etc. It is certainly impossible for a person to be expert in all areas. Depending on the needs a failure analyst should not hesitate to seek advice from experts in different areas.

CASE STUDIES

The best way to illustrate how failure analysis should be carried out is to go through a few case studies. The cases to be discussed are as follows:

1) Failure of boiler tubes
2) Development of cracks in Horton Sphere

3) Fatigue failure of pulverizer shaft of a bowl mill
4) Bulging of wire rods (processing failure)

Failure of boiler tubes

Boiler tubes are subjected to high pressure at elevated temperature. These are mostly made of either plain carbon or low alloy steel. At high temperature steel creeps. It elongates with time even if the stress is significantly lower than its yield strength. Failure occurs when the accumulated strain reaches the creep ductility. Therefore major consideration for the designer is to see that (i) creep strain that accumulates over the design life is acceptable (ii) accumulated strain is lower than creep ductility (iii) design life is significantly lower than the time to failure.

The way creeping materials fail can often give us information about the conditions under which failure took place. There are three basic mechanism of fracture. Intergranular fracture takes place at low stresses. It is associated with thick lip rupture and crack originates from the outer surface. Transgranular fracture takes place at higher stresses. Tensile ductility and reduction in area near rupture is quite high. At higher temperature and stresses dynamic recrystallization operates leading to tensile rupture. The case studies presented would highlight how to establish the conditions under which failure has taken place and also suggest how to plan a simulated test in the laboratory to reproduce such failure.

Horton Sphere

These are large spherical pressure vessels typically used for storage of LPG. These are made of welded steel plate. The case investigated had developed long shallow cracks along the weldment and a few short deep cracks close to the heat affected zone. Whilst the former could be removed by grinding, the latter was of great concern. Examinations showed that the microstructure near the deep crack was acicular (martensite) which could have formed as a result of arc strike during welding. A simulated test was devised to generate similar cracks near the weldment. This showed that innumerable sites were there where such cracks could nucleate in future. The reason for failure was certainly poor inspection of fabrication process. To overcome such problems in future post weld heat treatment was recommended even if it is not mandatory for vessels having less than 25 mm thickness.

Pulverizer Shaft

Pulverizer shaft of a bowl mill was failing much before its design life. This was made of En-24 grade of steel. Preliminary examination showed that failure was due to fatigue and the crack initiated from a key hole. Microstructural examination revealed presence of sulphide inclusions. Steels having such inclusions are likely to have poor resistance to crack growth. Therefore initially the reason was thought to be due to these inclusions. Mechanical testing also showed that toughness was indeed very poor. Some of the test pieces were given suitable heat treatment to find whether optimum combination of strength and toughness could be developed. It was found that toughness can be improved several folds by annealing. A rough stress analysis showed that the requirement of high strength is not so critical. It was concluded that the premature failure was mainly due to improper heat treatment and not due to inclusions. As expected properly annealed pulverizer shafts subsequently was found to last much longer.

Bulging of Wire Rods

High carbon steel wire rods of a particular size (5.5 mm dia) made from 110 x 110 mm CC billets developed bulging at several isolated locations. Wires made from wire rods of all sizes were frequently failing by rupture during wire drawing process. Initial microstructural examination and EDS analysis indicated that the steel was dirty and failure was due to low melting inclusions having Si, Al, Cl as the major elements. However, examination of freshly fractured surfaces revealed that the steel was fairly clean but contained lots of cavities and pores of various sizes. Density measurement also confirmed presence of pores and shrinkage cavity. All indirect evidences showed that the high pressure of trapped hydrogen gas in cavities did not allow them to collapse and get welded during hot rolling. A simple model calculation showed that high pressure of trapped hydrogen gas can result in bulging in wire rods of 5.5 mm dia and not in other diameter – higher or lower than 5.5 mm dia. On the basis of these findings it was suggested that hot rolling temperature should be increased from 1050°C to 1150°C so that the gases could diffuse out. Once this was implemented the problem disappeared.

CONCLUDING REMARKS

The consequence of failure can be tragic and expensive. There are innumerable cases of engineering disasters resulting in loss of life and property. They are certainly unwelcome. However for an engineer it is a source of learning. Engineers learn their most important lessons when things go wrong. Failure often provides with an experimental test of a realism which is rarely possible to achieve in the laboratory or on the computer. Therefore, utmost care should be taken while conducting a failure analysis to preserve and not destroy any evidence. It is in fact a learning process. A few of the cause presented would reveal that often the most obvious thing is not the real cases of failure. A failure analyst must have an open mind and be ready to examine and evaluate the views of other involved in the work. The report should be convincing and easily understood and acceptable by those involved in its design/fabrication/operation, only then the recommendation is likely to be implemented, otherwise it will remain in files as a mere confidential investigation report.

FURTHER READING

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