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Failure analysis of metallic structures and components: part I- methodology and tools

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This is the first of two papers dealing with failure analysis of metallic structures and components. In this paper, an overview for a generalized approach for the determination of main cause(s) of failure is illustrated. Failure analysis is vital to both profitability and liability. The general characterization of the failure surfaces as related to load and environment has been shown for metallic materials. It is shown that the combination of both load and environment may alter the behavior of some materials, such as steel, from ductile to brittle resulting in catastrophic failure. Failure analysis requires the knowledge in many diverse fields.

هذا البحث هو الجزء الأول من بحثين في موضوع تحليل أسباب الانهيار في المنشآت والأجزاء المعدنية. أن بحث أسباب الانهيار له فوائد جمة وخاصة فيما يتعلق بتحديد المسؤليات أو الفوائد الاقتصادية من ناحية تحسين الأداء عن طريق تلافى العيوب. وهذا البحث و التحليل يتطلب معلومات في مجالات متنوعة. وقد تم تقديم طريقه عامه لعمل هذا التحليل متضمنة بعض الأدوات التي تساعد على التعرف على سطح الانهيار و ذلك بالنسبة للأحمال و كذلك البيئة القاسية المحيطة بالمنشأ أو الجزء المعدني. أن وجود بيئة قاسيه حول منشأ أو أي جزء مجهد قد يؤدى إلى تغير في سلوك المادة من مادة مطيله إلى مادة قصفه مؤديا إلى انهيار مفاجئ. لذلك فان دراسة البيئة المحيطة وفهم تأثيرها قد يمثل حجر الزاوية في حل بعض الحالات.

Keywords: Failure, Analysis, Stress corrosion cracking, Embrittlement, Stress concentration

1. Introduction

Failure analysis is an engineering field that deals with the determination of the main cause(s) of failure in a structure or a component. Failure analysis is vital to both profitability and liability in the sense that if the cause(s) of failure can be determined, the prospective structure or component can be better engineered or the liability of the failure can be evaluated.

The issue of profitability is emphasized in the case of the Liberty Ships [1] during the Second World War. Failure analysis of these ships has substantiated the field of fracture mechanics and has a great impact on the concept of brittle fracture of steel structures. Thus, failure analysis in this case revealed a great change in the concept of ductility of steel structures and components in the several fields. Furthermore, post the Northridge earthquake in 1994, Federal Emergency Management Agency (FEMA) [2] has considered several preventive measures to lower the potential of failure of steel structures via the initiation and propagation of cracks as the failure analysis of many structures has shown an extensive cracks in the steel structures after this earthquake [3].

An example for the liability determination through failure analysis is the Hyatt Regency skywalk, Kansas City, Montana [4]. In this case, a two-level catwalk failed under live load causing many fatalities. Failure analysis has revealed that the original design called for nuts where they could not actually be installed. Blame and liability for the failure were shared by many parties.

Failure analysis requires a variety of information in different fields including structural analysis, stress analysis, metallurgy, fracture mechanics, material characterization, chemical background concerning environmental effects (e.g. corrosion), and many other disciplines. This is one of the reasons why this type of analysis is rather complicated.

The main focus of this paper is to illustrate the logical steps of failure analysis in addition to show the typical failure surface for the different loading and environmental conditions to be used as tools for failure identification. These tools will help in recognizing the failure causes especially where crack initiation and propagation in metallic structures and components are involved. More emphasis will be devoted to the identification of crack causes leading to the failure of metallic materials.

2. What is failure?

An engineering system, a structure, or a machine component fails if it does not function according to its intended design. This is the most common definition of failure and will be considered throughout this paper. However, this definition is considered vague by some researchers in different fields. For instance, in the reliability analysis for code development, the "limit states" are considered as the failure criteria [4]. Three limit states are always considered in this regard: the ultimate, serviceability, and fatigue limit states. Even in this respect, exceeding the deflection limits for example, as proposed by any code, does not mean that the structure fails.

3. A generalized failure analysis approach

A successful approach for failure analysis should consider the following steps: (a) failure data preservation, (b) formation of the analysis team, (c) analyzing the data and proposing a hypothesis, (d) communicating findings and recommendations, and (e) tracking results. Many researchers have implemented similar approaches (e.g. Latino [5]).

Preserving the failure data is essential for determining the main cause(s). Typical failure data include parts from the failure scene, timing of failure, all corresponding data such as position, loading, and any other records.

The diversity of the professions of the failure analysis team is crucial in determining the failure causes. One major mistake is to concentrate the effort of searching on certain team with unique background (e.g. metallurgy or structural only). For some simple cases, failure analysis could be conducted by one person with diverse background, however, it is usually better to have more than one opinion in this regard.

The main step in the failure analysis process is analyzing the data by logically deduce the failure data through a cause-effect relation. At this point, a hypothesis for the failure and a rational plan of attack should be proposed. Several approaches are available and they mainly identify the causes through experimental results, examining the failure surface, exploring the failure consequences, and conducting a comprehensive stress analysis if needed. An approach will be utilized in the second part of this paper illustrating a plan of attack for the failure analysis of a case study.

Communicating the findings and recommendations of the previous analyses to the appropriate party (usually the client) is critical; otherwise, the analysis will be worthless. The main benefits of failure analysis are to improve design or determine liability, thus conveying this information is of utmost importance. For the failure analysis to be successful, it is important to be implemented and to track the effect of corrective measures taken in the recommendation part.

4. Tools for failure analysis

A structure or a component may fail due to several factors that can be classified into load-related and environmental-related. Some tools exist which help in determining the cause(s) of failure and these tools are the typical shapes or characteristics of failure surface and are categorized into load-related and environmentally related. Only metallic materials will be considered in this paper especially steel, as it is one of the most commonly used construction material.

5. Load related tools

Generally, steel structures or components are designed and operated in the elastic zone of the material behavior. However, if overloading occurs, it may lead to failure. One should differentiate between ductile overloading and brittle overloading since this may reveal the cause(s) of failure. In the former, there is a substantial distortion in the material due to yielding dislocation leading to a well recognized plastic deformation [6]. On the contrast, brittle failure is always associated with very little deformation and is caused mainly by the initiation and propagation of cracks. Example of the overloading due to an earthquake is shown in fig. 1 as crack formation at a joint of a steel frame.

Another vital observation is the identification of the plane of failure with respect to the axis of the member. This will reveal the direction and type of loading at failure moment, keeping in mind that cracks always propagate perpendicular to the direction of maximum tensile stresses. For instance, a plane of failure perpendicular to the element axis means high tensile loading or torsion. Inclined plane of failure, in pipes for example, leads to the conclusion of applied torsion or torsion and tension pending on the inclination. It is worth mentioning that the material may be ductile, however, it may fail prematurely in a brittle fashion. For instance, Liberty Ships [1] were made of ductile steel; nevertheless, they failed due to fracture as other factors entered into the picture.

Other causes of failure in metals through crack initiation and propagation related to load are fatigue and stress concentration.

5.1. Fatigue failure.

According to linear elastic fracture mechanics (LEFM) (e.g. Broek [7]), fracture is imminent when the crack length (a) reaches a critical value where the stress intensity factor " K_I" (where I stands for the tensile mode of fracture) due to loading and member configuration reaches a critical material property called "fracture toughness K_{Ic}". The main difference between overloading and fatigue is the magnitude of the stress intensity factor. The value of the stress intensity factor in the general form is,

Fig. 1. Example of overloading induced cracking in steel frame joint.

$$K_I = Q\sigma^{\infty}\sqrt{\pi a} \quad . \qquad (1)$$

Where Q is a geometric function of crack length and member configuration, σ^{∞} is the remote stress, and a is the crack length. In the case of overloading, the remote stress σ^{∞} increases to the value that $K_I = K_{Ic}$ and failure is catastrophic. On the other hand, in case of fatigue loading, the remote stress magnitude itself is not enough to cause fracture. With load repetitions, the crack propagates a certain length after each load cycle till reaching the critical value then fracture occurs. This simple introduction to fatigue failure is necessary for fatigue failure surface identification. Fatigue failure is always recognized by a series of concentric half-moon or straight and parallel shaped lines. As the crack advances in each cycle, it marks a new line and the final fracture surface may appear as in fig. 2. Sometimes this type of fractured surface is called "beach marks".

Another aspect related to the beach-marks associated with fatigue loading is the load type. If the beach-marks are parallel, it indicates that the loading direction is constant (one way loading, either bending or tension) as shown in fig. 3-a. However, if the beach-marks are inclined as shown in fig 3-b, it reflects the introduction of torsion (rotation). Furthermore, the size of the Instantaneous Zone (*IZ*), which carries the load just before fracture, reflects the intensity of loading. Heavy loads result in larger *IZ* zone while light loading is indicated by small *IZ* zone as shown in fig. 3-c.

5.2. Stress concentration

Stress concentration in a general sense is a physical or metallurgical condition that increases the local stress in the structural components by a certain factor. This aspect is always overlooked in design of steel components as designers always think of steel as a ductile material and deal only with the net section around the geometrical discontinuity.

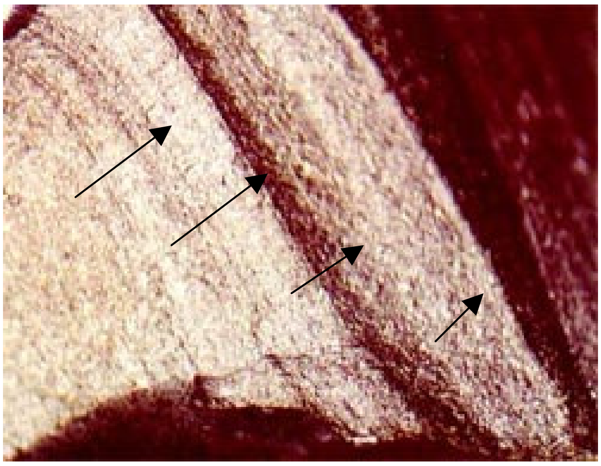

Fig. 2. Beach marks as observed in fatigue failure.

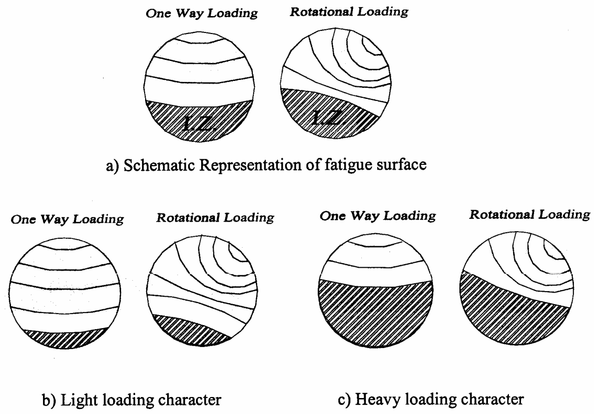

Fig. 3. Characterization of failure surface.

However, this is very critical issue as these zones works as stress raisers. A simple example is the multiplication of the remote stress by a factor of three to obtain the maximum stress in case of a circular hole in a large plate. Fillets in steel components do not eliminate stress concentration, however, they reduce it. Also, any abrupt change in the section configuration will result in the same problem. In most cases, these highly stressed zones represent a high potential for crack formation starting the fracture zone. Furthermore, any impurity in the material composition, no matter how small it is, will lead to crack initiation as well. It is worth mentioning that any defects resulting from environmental factors, as will be described in the following section, lead to stress concentration as well, which accelerates the failure.

6. Environmentally related aspects

Metals corrode when used in environments where they are chemically unstable. Copper and precious metals such as gold, silver, platinum, and alike are found in nature in their metallic state. However, iron is processed from minerals and ores into metals that are inherently unstable in their environments. As metals corrode, they result in several defects in their internal structure leading to the formation of cracks. This type of defects if combined with stresses usually results in what is known as "stress corrosion cracking SCC" [8]. It is beyond the scope of this paper to describe the chemical reactions under several environmental conditions since it is usually studied on a case by case basis. However, the consequences of these reactions for a specified case will be discussed in detail in the second part of this paper.

In general, Stress-Corrosion Cracking (SCC) is caused by the simultaneous effects of tensile stresses and a specified environment. The origin of stresses in this process may be related to applied loads, residual stresses from manufacturing (e.g. welding or cold forming), or the combination of both [9]. Cracks are the visible manifestation of the combination of both stresses and environment and usually create the impression of inherent brittleness. Although metals usually conform to ductility standards in most cases, the combination of hostile environment, tensile stresses and material composition and microstructure arrangement (*body-centered-cubic "bcc"* or *face-centered-cubic "fcc"*) play the dominant rule in transferring their behavior into a brittle one.

7. Environmentally related fractured surface identification

Several forms of fractured surface in metals exist which have a strong tie to the SCC. One of the most common examples is the river branching pattern as shown in fig. 4-a which is unique to SCC. Further, SCC may result in a single crack as shown in fig 4-b which represents a SCC in stainless steel material subjected to chloride attack in condensate lines. Another form of a single crack due to SCC is shown in fig. 5 which occurred in one of the framed carbon steel structure in one of the chemical factories. These types of cracking can be identified through naked eye or simple magnifying lenses. Other types of SCC can be identified only through Scanning Electron Microscope (SEM) such as the intergranular SCC as shown in fig. 6 for an aluminum alloy which has been subjected to residual stresses and salt water [10].

a- River branching cracks.

b- Single crack in stainless steel

Fig. 4. Typical SCC patterns.

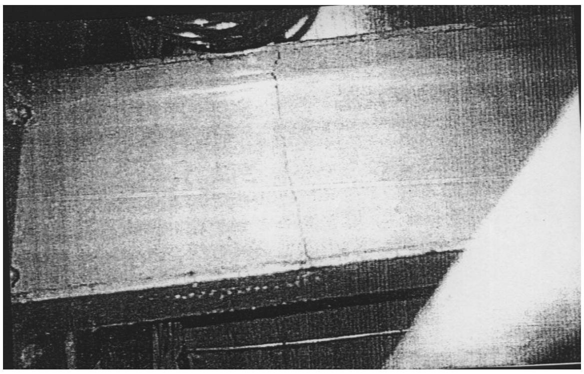

Fig. 5. SCC in carbon steel frame.

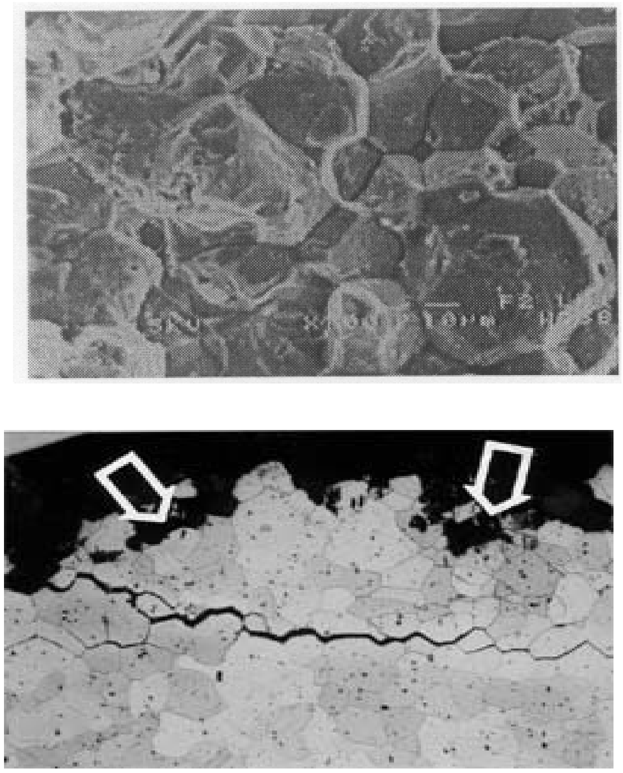

Fig. 6. Intergranular SCC in aluminum alloy [10].

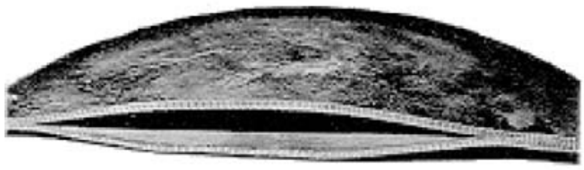

Fig. 7. A typical sign of hydrogen blistering.

One of the most severe damage, especially to high strength carbon steel, is due to the exposure to hydrogen. Hydrogen embitterment and blistering are encountered in several fields. Examples include oil, aircraft, petrochemical, and many others. This type of damage and its corresponding failure mechanism will be discussed in detail in the second part of this paper. A typical sign of hydrogen blistering, which may split the metal, is shown in fig. 7.

Several other forms of SCC exist. For instance, fretting corrosion occurs at the interface between contacts and highly loaded metal surface subjected to slight vibratory motion. Also, a combination of an aggressive chemical environment and high fluid surface velocity may result in erosion corrosion.

8. Analysis of failure data

After collecting all the data of the failure analysis, one should start analyzing the data through the determination of the most probable cause(s). At this point, a clear hypothesis regarding the failure cause and failure mechanism should be proposed. In order to support this hypothesis, several types of analyses should be conducted starting from simple calculations using general engineering formulae to the detailed fracture mechanics analysis and computer simulation of crack propagation. In some cases, simple calculations may suffice, however in others; more sophisticated techniques may be required. This step depends in large on the experience of the analysis team with previous cases, and the understanding of the actual failure mechanism. Usually the main emphasis of this step is to provide a theoretical support to the original hypothesis. Furthermore, experimental testing (chemical, mechanical, or physical) is an essential step in most failure analyses for the determination of material properties or any other chemical reaction.

9. Communicating findings and recommendations

After arriving at the main cause(s) of failure, findings should be presented in the form of recommendations for redesign, changing the material to suit the environment, special coatings for the structure protection, or determining the liability of the failure. This is crucial to failure analysis as it helps the client for prospective actions.

10. Conclusions

In this paper, a simple and generalized approach for failure analysis is presented. The following conclusions can be drawn:

1. Failure analysis is a diverse engineering field requires interdisciplinary communications to arrive at the main cause(s) of failure.
2. Conducting failure analysis always reveals important information leading to both profitability and liability such that prospective structure or component can be better engineered or the liability of the failure can be evaluated.
3. Some load and environmental tools for the identification of failure surface are presented. These tools are vital to failure analysis as it helps in characterization of the failure surface, and hence, building a solid hypothesis of failure.
4. Although most metals conform to ductility standards upon the construction of a structure or a component, they might fail in a brittle fashion under certain conditions. The combination of both stresses and hostile environment may alter the material behavior from ductile to brittle.

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