Notch Strength and Notch Sensitivity of Materials

FRACTURE CRITERION OF NOTCHED ELEMENTS

材料的切口强度与切口敏感性
——切口件的失效准则

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内容简介

本书通过对切口件应力应变分析和材料切口敏感性理论的介绍，给出了适用于包括切口件、裂纹件和光滑试件的断裂准则，主要涉及切口件在拉、弯、扭、压条件下的低应力脆断准则和强度问题，也对产生低应力脆断的内、外部条件，如环境温度、加载速率等进行了探讨，涵盖钢铁、非铁金属、陶瓷、玻璃、高分子材料和复合材料等多种材料。

本书为工程技术人员在结构设计中选用材料和进行强度校核提供了有用工具，也为材料研究工作者改善材料的性能提供了依据，同时，本书也可作为材料、机械类研究生教学的参考用书。

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Preface

The study on the failure of structure members is accompanied by the application of materials in engineering and has long been attracted the attention of scientists and engineers. The purpose of failure study is to prevent failure of structure members, especially the critical members, such that the engineering structures could work safely under service conditions.

The fracture of a structure is a most dangerous form of the failure, which would induce a large amount of the economic loss, even the life loss. For the ductile metals, the main form of failure is plastic yielding, which occurs before the final fracture. The plastic yielding criterion in the books on "Mechanics of Materials" and "Mechanical Behavior of Materials" can be applied to the ductile metals with low and medium strength. In World War II, a large number of ships failed along the welding lines. Based on the results obtained by testing the Charpy-V notch specimens taken from the area around welding lines of the failed ships under impact loading, the criterion of the minimum impact work of 15 ft-pound (20.35 J) was thus proposed, which is empirical but useful in ship building industry. It is well known that, early in 1950s, an accident of missile happened in launching process led to the study and development of the fracture mechanics of cracked elements, i.e., the so-called linear elasticity fracture mechanics (LEFM). Thus, the fracture criterion of the cracked elements, i.e., $K_{\mathrm{I}} = K_{\mathrm{IC}}$ (or K_{C}) was developed and could be called as K criterion, where K_{I} is the stress intensity factor and K_{IC} (or K_{C}) is the fracture toughness, a new material constant. The formation of elastoplastic fracture mechanics was accompanied by the research concerning the steels with low and medium strength. Base on the above brief description, it can be seen that the failure study contains two aspects: developing the failure criterion and defining the failure resistance of materials, both of which are closely interrelated.

However, most structure members always contain the geometric discontinuities, such as fasten holes, shoulder, fillets and grooves, which are usually taken as the notch in broad sense. The existence of notch causes the stress concentration at notch root and the stress distribution change around the notch and thus affects the fracture and strength of notched elements. In order to understand fracture phenomenon in practical components, the notched specimen is usually employed to simulate the structure member in the fatigue and fracture research of materials. The notch strength determined by testing notched specimens was used to evaluate the fracture resistance of materials and the notch strength ratio (NSR) used to evaluate the notch sensitivity of materials.

Later in 1950s and earlier in 1960s, the notch strength of metals was widely studied. This is because that various kinds of metals, such as high strength steels, aluminum alloys, titanium alloys, stainless steels and heat resistant steels, as well as welding structure are widely applied in aeronautic, aerospace and nuclear industries and cryogenic engineering. Almost all the test results of notch strength and NSR of metals were summarized in *Aerospace Structural Materials Handbook.* However, the test results show that the notch strength and NSR are not material constants but also depend upon the geometry of test specimens. Therefore, the quantitative expression of notch strength is needed, which can be applied to evaluate the fracture resistance of notched elements of materials and to take as the fracture criterion in the design of structure members.

Although the analysis of stress and strain around the notch has been studied theoretically and experimentally very early, there is no effective model for characterizing fracture of notched elements. The notch strength was correlated with the tensile property of materials and the geometry of notched elements and expressed in the form of figures and tables, engineers can conveniently use those figures and tables in the aforementioned handbooks in design of structures. The above-mentioned approach is usually applied to solve the problems in engineering practice and plays an important role in various engineering fields when the quantitative expression of the fracture strength of notched elements, i.e., the notch strength of materials has not been developed.

Fracture process of the notched elements is a phenomenon depending on the microstructure of materials and the geometry of structure components and the external environment. External environment or the service conditions of notched elements includes the stress state, the loading speed, the temperature and the surrounding medium. Therefore, all above-mentioned factors should be taken into consideration in the research on the fracture criterion of notched elements. It should be realize that the macroscopic model for the fracture and the strength of notched elements could not be proposed based on the research of the fracture micromechanisms only. However, a philosophic model and approach for characterizing the fracture of notched elements could make significant contributions to develop the quantitative expression of the notch strength of materials.

The experiments show that the fracture process of a notched element could be divided into three stages: the crack initiation at notch root, the stable crack propagation until the crack length growing to a critical size and the unstable crack propagation, i.e., the final fracture of the notched element. After crack initiation at notch root, the notched element becomes a cracked one. So, the final fracture of a notched element is actually the fracture problem of a pre-cracked element, which can be successfully solved by the LEFM or the elastic-plastic fracture mechanics. However, neither the LEFM nor the elastic-plasticity fracture mechanics can be applied to deal with the problem of the crack initiation at notch root. This is because that the prerequisite of either the LEFM or the elastic-plasticity fracture mechanics is the crack having existed in materials. However, the crack is not allowed or restricted in structure components, especially in the critical ones. Therefore, the mechanical model for the crack initiation at notch root should be first developed in the study on the fracture and the strength of notched elements.

Earlier in 1980s, the mechanical model for the crack initiation at notch root was developed. Based on the assumption that the fracture of notched elements occurs right after crack initiation at notch root, the formula of the notch strength for the metallic materials, including ductile and brittle ones could be derived and checked by the test results of notch strength in available literature. Consequently, the notch sensitivity factor was thus defined and applied to quantitatively evaluate the notch sensitivity of materials. The above-mentioned formulas could be applied for predicting the notch strength and the notch sensitivity of metals from the tensile properties. Since 1990s, the notch strength and the notch sensitivity of ceramics, Al-Li alloy, cast irons and glasses were experimentally studied in our group. Test results show that the aforementioned formulas of the notch strength and the notch sensitivity factor for the ductile- and the brittle materials are available, which can provide the material scientists to improve the fracture resistance of materials, i.e., the notch strength and notch sensitivity of materials. This is the reason that the present book can be entitled as *Notch Strength and Notch Sensitivity of Materials*.

Geometrically, the smooth specimen could be taken as the notched element with the radius at notch root tending to be infinite, i.e., $\rho \to \infty$ and the cracked specimen taken as the notched element with the radius at notch root tending to zero, i.e., $\rho \to 0$. Therefore, the smooth specimen and the cracked specimen could be thought as the upper- and the lower boundaries of the notched element. Based on the above consideration and the aforementioned formulas of notch strength and notch sensitivity of materials, attempts will be made to develop the so-called "Notch Strength Diagram" of materials, which could express the notch strength as a function of the stress concentration factor ranging from $K_t = 1.0$ to $K_t \to \infty$. It would mean that the values of the fracture strength of notched elements, cracked ones and the smooth one could be found from the notch strength diagram. Consequently, the notch strength diagram could be taken as the fracture criterion to provide the engineers in the design of structures. This may be the reason that the present book could have a subtitle of *Failure Criterion of Notched Elements*.

The present book will cover the research on the notch strength and notch sensitivity of metals, ceramics, glasses and composite materials from available literature and our group. The authors wish that the publication of this book would fill up the vacancy of the research on the strength and the failure criterion of materials and also bridge the gap between the material science and engineering applications.

At this moment, the authors would like to express sincere thanks to Mr. Wang Gongrong, Mr. Liu Caimu, Ms Peng Yanping, Mr. Hu Yuankai, Profs. Zhao Jiaxiang and Zhou Ruifa from China former Aeronautic Ministry and Aeronautical Scientific Foundation for their kind supports to our research. Many thanks are also given to Mr. Xue Zhenghua for the logn-term cooperation in teaching and research with us, and the related colleagues in Department of Materials Science and Engineering and Section for Scientific Research of Northwestern Polytechnical University for their support to our research. Drs. Wang Fenghui, Meng Liang, Yan Junhui, Zhao Kang and Wang Hong were as Ph D candidates to do research work in this field. The authors acknowledge their arduous and creative works.

It should be pointed out that the pioneer work of the research on the notch strength and notch sensitivity of metals was done by X.L. Zheng in ICOM, EPFL (Institute of Metallic Structures, Swiss Federal Institute of Technology, Lausanne) and got support from Prof. J.-C. Badoux and Prof. M.A. Hirt. The authors also wish to express the thanks to Prof. Badoux and Prof. Hirt for the support to the above research.

The authors wish this work would make the contributions to education, science and technology in the new century. Since modern science and technology develop rapidly and the new materials and structures appear day by day, we believe all of us have to face the new subjects in research.

Zheng Xiulin, Wang Hong, Zheng Maosheng and Wang Fenghui
On China Teacher's Day 2007
In Northwestern Polytechnical University

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Chapter 1
General Introduction

1.1 Purpose and Importance of Failure Research

The machines and engineering structures should perform the functions required by design first, and safety under service conditions in their lifetime, and low costs including the design, manufacture and maintenance. To ensure the safe operation of the machines and structures under service conditions, the failure of the structure members, especially the critical members must be prevented.

In 1800s, Industrial Revolution resulted in an enormous increase of the use of metals, mainly irons and steels in engineering structures. Unfortunately, many accidents occurred simultaneously with the loss of properties, even the human life, owing to the failure of the structures such as the steam boiler explosions and the railway equipment failure. Therefore, the failure study is one of the substantial fields of material research in viewpoint of preventing material and structure from failure. Therefore, the purpose of failure research is to prevent the failure, especially the fracture of materials and structure elements.

Up to date, accidents concerning the failure of materials and structures still occur in various fields[1]. A study completed by the U.S. Department of Commerce and National Institute of Standards and Technology show that the total costs induced by the fracture of materials per year were about 4% of the gross national product (GNP) in U.S. in 1980's[1]. In the above study, the definition of fracture was in broad sense, including cracking, fracture, deformation and related problems such as delamination, but wear and corrosion were excluded. The fracture costs in Europe also yielded an overall cost of 4% GNP [2], which means a similar value is likely to apply to all industrial nations[1].

It was also shown in Ref.[1] that roughly one third of the annual fracture cost in U.S. could be eliminated through the better use of current technology. Another third could be eliminated through research and development, i.e., by obtaining new knowledge and developing ways to put this knowledge to work. The final roughly one-third would be difficult to eliminate without major research breakthrough [1]. Recently, the research on the failure criterion is still going on [3,4].

As may be seen, the failure mechanisms and the failure criterion should be further investigated under conditions close to real service circumstance of structure members to provide corresponding knowledge and patterns, which can be adopted in engineering practice to enhance the performance and safety of structures. Meantime, the utilization efficiency of existing materials could be increased, and the new materials could be easily and earlier adopted in engineering structures. Therefore, it is still of technical and economical importance to do the fracture research, which would bring the benefits to the society.

1.2 Main Considerations in Failure Research

In the present book, the failure could be defined as the fracture for materials, especially for the notched elements occurred at the stress lower than the ultimate strength of materials, which can be referred to as the low-stress brittle fracture. The yielding condition of notched elements of ductile materials will also be briefly discussed.

One aspect of the fracture research is developing the new failure criterion, which could provide designers for checking the strength of structures so as to ensure the safety of engineering structures under service conditions such that the loss of properties, even the loss of life can thus be avoided. How to evaluate the fracture resistance of materials is another aspect of the fracture research. Both the two aspects mentioned above are closely interrelated.

In fracture research, the material characteristic should be considered first, and the structure geometry and the real service conditions, such as load and environment, should also be taken into consideration.

1.2.1 Material Characteristics

Various materials are currently employed in engineering, all materials can be classified into two kinds: ductile material and brittle material, according to the characteristics of deformation and fracture of materials [1,5]. Ductile material undergoes elastic and plastic deformation before fracture in tensile loading condition, while brittle material undergoes only elastic deformation before fracture in tensile loading condition. Different failure criterion could be held for such two kinds of materials due to their different mechanism and features of deformation and fracture [1,5~8].

Ductile materials could be divided into the low- and high- ductility materials