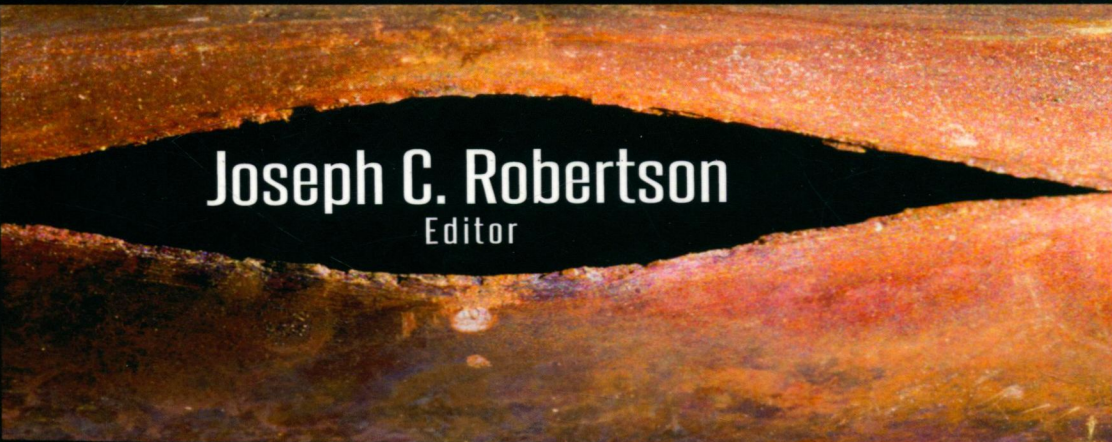


Materials Science and Technologies

Fracture Mechanics



Joseph C. Robertson
Editor

Theory, Applications and Research

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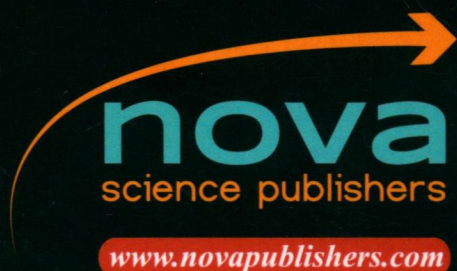
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MATERIALS SCIENCE AND TECHNOLOGIES

FRACTURE MECHANICS
THEORY, APPLICATIONS
AND RESEARCH

JOSEPH C. ROBERTSON
EDITOR



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PREFACE

Classical fracture mechanics that emerged during the 1920s has gained popularity via LEFM from the 1940s to the 1960s. The principles of classical fracture mechanics evolved from experimental observation of the behavior of glass that contains pre-existing cracks and is largely supported by physical reasoning. Chapter One presents a robust analysis of problems encountered in the field of pipeline networks and boiler components as a result of structural imperfection. Chapter Two deals with an analytical model of cracking, which is induced by thermal stresses in a porous multi-particle-matrix system. This system consists of spherical pores and isotropic spherical particles, which are both periodically distributed in an isotropic infinite matrix. Chapter Three reports on an analytical model of cracking in a multi-particle matrix system with isotropic whiskers, which are periodically distributed in an isotropic infinite matrix.

As explained in Chapter 1, the growth of energy demand generates an increase in the size of industrial structures. From 1910 to 2000, the diameter of the largest “transport” pipelines were multiplied by 4 and the transport pressure by a value of 60. As a result, the various components relating to power plant, oil and gas facilities as well as petrochemical networks which are under mechanical pressure have an attractive deal for research scientists for several decades. However, the design for a pressure vessel component is considered to be a difficult challenge once the defects in the base material develops. This problem is frequently encountered in the field of pipeline networks and boiler components due to various structural imperfections.

The modern approach intends to replace experimental evaluation with virtual simulation. While numerical calculations may enable researchers to gain a better understanding, there may be several limitations. There is a small convergence when dealing with industrial products due to the dissimilarity between design concepts, manufacturing performances and cost of the software products. A robust review that focused on the multi-scale approach of fracture mechanics was applied in order to overcome these issues and prove the potential of innovative solutions by corroborating the industrial standards with fundamental research.

Chapter 2 deals with an analytical model of cracking, which is induced by thermal stresses in a porous multi-particle-matrix system. This system consists of spherical pores and isotropic spherical particles, which are both periodically distributed in an isotropic infinite matrix. The infinite matrix is imaginarily divided into identical cubic cells. Each cell contains either a central particle or a central pore. The thermal stresses, which originate during a cooling process, are a consequence of different thermal expansion coefficients of components of this system. With regard to the analytical modelling, this porous multi-particle-matrix system represents a model system, which is applicable to porous two-component materials of the precipitate-matrix type. The cubic cell dimension, as well as radii and volume fractions of both the particles and the pores, are microstructural parameters of this precipitate-matrix type. The thermal stresses are functions of these microstructural parameters. The analytical modelling results from fundamental equations of mechanics of a solid elastic continuum (Cauchy's and equilibrium equations, Hooke's law). The analytical model of the thermal-stress induced cracking includes analytical determination of both the limit state and crack propagation. The limit state defines such a condition, which is critical with respect to the crack initiation. The crack initiation is followed by the crack propagation at the supercritical condition.

Chapter 3 deals with an analytical model of cracking in a multi-particle-matrix system with isotropic whiskers, which are periodically distributed in an isotropic infinite matrix. This model system is applicable to real two-component materials of a precipitate-matrix type with precipitates of a cylindrical shape. The cracking is induced by thermal stresses, which originate during a cooling process as a consequence different expansion coefficients of the material components. The determination of a new analytical model of the thermal stresses is based on an application of suitable mathematical procedures on fundamental equations of mechanics of a solid elastic continuum, and

solutions for the whiskers and the infinite matrix are obtained. The crack modelling represents analytical determination of a critical condition for the crack initiation as well as a mathematical description of a shape of the crack, which is formed at a supercritical condition.

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Chapter 1

THE INDUSTRY REQUIREMENTS SOLVED BY FRACTURE MECHANICS

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Abstract

The growth of energy demand generates an increase in the size of industrial structures. From 1910 to 2000, the diameter of the largest “transport” pipelines were multiplied by 4 and the transport pressure by a value of 60[1]. As a result, the various components relating to power plant, oil and gas facilities as well as petrochemical networks which are under mechanical pressure have an attractive deal for research scientists for several decades. However, the design for a pressure vessel component is considered to be a difficult challenge once the defects in the base material develops. This problem is frequently encountered in the field of pipeline networks and boiler components due to various structural imperfections.

The modern approach intends to replace experimental evaluation with virtual simulation. While numerical calculations may enable researchers to gain a

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better understanding, there may be several limitations. There is a small convergence when dealing with industrial products due to the dissimilarity between design concepts, manufacturing performances and cost of the software products. A robust review that focused on the multi-scale approach of fracture mechanics was applied in order to overcome these issues and prove the potential of innovative solutions by corroborating the industrial standards with fundamental research.

Introduction

Researchers have yet to address how open innovation structures can be effectively applied within industries while diminishing its potential cost and challenges. Therefore, the first and most important challenge is the intellectual property (IP) issue. Although the industry aims to collaborate in mainly non-competitive and/or pre-competitive areas, securing and protecting internal technical knowledge is still recognised as being a priority for any active firm [2].

The oil and gas industry consists of complex systems generating robust Design Specification (DS). It is of paramount important to adopt a scientific approach to describe them. The industrial process may be required to combine these two methods so as to ensure a high degree of understanding as well as making it as specific as possible. The incidents are extremely rare; however, it could potentially result in major accidents which in turn increases the fear of an occurrence within the organisation while it may reduce the visible benefits of safety investments. By describing the precursor incidents with related probabilities and consequences, proactive management can be integrated. A more comprehensive understanding of the precursor incidents will offer the potential to control variability rather than constraining it. In order to have the ability to control every variability, it is necessary to consider that precursor incidents are taken seriously.

The past accident analysis (PAA) enables researchers to develop an understanding of the ways in which the accidents may occur while also providing useful input about the development of loss prevention strategies. In spite of the inherent shortcomings associated with PAA which mainly arise from nonreporting, under-reporting, or improper reporting of accidents in several parts of the world, PAA remains a highly important component of loss prevention R&D [3].

Several strategies that can help to predict accidents were previously established. In particular, the modelling of gas clouds and explosion forces has been conducted in order to verify software tools as well as gain a better

understanding of the sequence of the accident. However, this cannot be applied in precursor incidents. Regardless of the purpose of an accident investigation, any conclusion should be arrived at in order to obtain a robust understanding of the events that result in an accident, as well as its potential consequences [4].

Fracture Mechanics Approach

Classical fracture mechanics that emerged during the 1920s has gained popularity via LEFM from the 1940s to the 1960s. The existing classical fracture mechanics formulation is limited in applications due to the lack of scientific-based derivation of the model. The principles of classical fracture mechanics evolved from experimental observation of the behavior of glass that contains pre-existing cracks and is largely supported by physical reasoning. Without rigorous mathematical justification, classical fracture mechanics equations are considered fundamentally weak and scientifically incorrect. Nevertheless, classical fracture mechanics has been developed and is employed in various areas of materials science and engineering. Such applications range from metallurgical failure analysis to advanced research, including the fracture development of the structure of nanocatalyst, delamination in diamond-like carbon coating and piezoelectricity research. The continuum-media postulate of fracture mechanics, however, may prevent us from predicting the failure of nanoscale materials, such as ultrathin films and nanowires, due to the fact that the continuum concept becomes less plausible as the size of the region of interest approaches the atomic scale [5].

According to Griffiths, the emergence and spread of classical fracture mechanics throughout the world during the early 1940s is evidence of its survival even when newer concepts were being introduced around that period of time. The skeptics' nightmare for the future of classical fracture mechanics is easily understood, yet it is serving very well in several limited application areas. The formulation of fractal fracture mechanics equations has demonstrated superiority with respect to the mechanics of the material over classical fracture mechanics. Advances in computational methods and affordability of computational power has enabled scientists and engineers to analyse the behaviour of structures containing cracks without having to understand the concept of classical fracture mechanics in detail. Detailed and in-depth computational studies are made possible by applying newer concepts of the characteristic length parameter associated with the fractal nature of the fracture. The success and failure of fatigued structures have generated a substantial in-service database that could be utilised in the design of new structures based on a statistical approach. Furthermore, the probabilistic

approach has demonstrated the ability to deliver a more promising prediction. Therefore, it has been speculated that the combination of probabilistic and fractal fracture mechanics will replace the classical fracture mechanics in the near future, starting with adopting a computational approach [6].

Within the design cycle, a practical engineering design that is resistant to damage requires a large number of iterations between both the designers and the stress and fatigue analysts. The former group of engineers create an initial design, which is refined iteratively through successive stress analyses and fracture propagation simulations under fatigue. The usual approach is to generate a mesh for stress analysis, computing the most highly stressed regions in the component and introducing a crack of dimensions defined by design codes at the location of maximum principle tensile stress in the component (this requires generating a new mesh, where the elements are typically several orders of magnitude smaller in size in comparison to the original stress analysis mesh). The size of the crack and its growth from the original flaw will provide an estimate in regard to the number of fatigue cycles. If the component's fatigue life happens to be unsatisfactory, the design will be modified and the whole process is repeated. It is evident that this approach is inefficient in terms of human intervention due to the fact that it is slow, expensive and non-robust, especially since a typical design iteration can take as much as a few months for a relatively simple component.

Simulating (fatigue) crack growth leads to a cumbersome number of requirements for the associated numerical methods: 1. Computing the displacement and stress fields within the component during crack growth; 2. Representing the crack surface as it grows; 3. Estimating the energy release rate along the crack; 4. Computing the crack propagation angle and crack propagation increment along to the crack front [7].

In general, a pipe is subject to many kinds of load which substantially contributes towards the SIF in piping. A general expression for the SIF in regard to the existing relationship between SIF and axial force, bending moment and torsion may be proposed since it can help to calculate fracture parameters by employing the simulation sampling method. The normalised axial force, bending moment and torsion at the location of flaws, which are necessary for the general sampling expression of SIF, can be easily obtained from conducting a structural analysis. This expression provides a critical basis for the development of SAPP-2003 software based on BS 7910, R6 and SAPV-99. The failure probabilities of piping can be estimated by applying the Monte-Carlo method which will enable the researcher to evaluate the flaws associated with operating loading, defect sizes, material fracture toughness and flow stress, etc. A practical example was proposed in a different paper to demonstrate SAPP-2003's application and its risk