"十二五"国家重点图书

Advances in Materials and Mechanics

Fracture Mechanics in Layered and Graded Solids

Analysis Using Boundary Element Methods

层状和梯度材料断裂力学的边界元法和应用（英文版）

Hongtian Xiao, Zhongqi Yue

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Preface

In general, all solid materials can be considered as non-homogeneous because their properties can vary with locations in a three-dimensional space. One special type of solid material is characterized by the variations of its physical and mechanical components, structures and properties along only one given coordinate; the material properties have very small or no variations in any other direction perpendicular to the given coordinate. These types of solid materials are called functionally graded materials (FGMs). For example, plant and tree stems, animal bones and other biological hard tissues have gradient variations in their microstructures and functions. Bamboo is a self-optimizing graded structure constructed with a cell-based system for sensing external mechanical stimuli. Learning from nature, material scientists have increasingly aimed to design and fabricate graded materials that are more damage-resistant than their conventional homogeneous counterparts. As a design concept, FGMs were originally proposed as an alternative to conventional ceramic thermal barrier coatings to overcome their well-documented shortcomings and to meet the demands of new technologies.

The mechanical responses of FGMs have an important significance in many engineering fields and are of great interest to material scientists, and design and manufacturing engineers. The problems of fracture and crack propagation in FGMs are particularly important and have been studied in depth. The boundary element method (BEM), also known as the boundary integral equation method, is now firmly established in many engineering disciplines and is increasingly used as an effective and accurate numerical tool. Fracture mechanics has been the most active, specialized area of research in BEM and is probably the one most exploited by industry. The traditional BEM is based on the Kelvin's fundamental solution and meets the difficulties encountered when analyzing the fracture mechanics of FGMs.

Since 1983, the second author of this book has devoted much of his research to understanding the elasticity of a multilayered medium and has achieved important results. One of these results is the analytical and closed-form formulation of fundamental solutions for a multilayered elastic medium and a transversely isotropic bi-material. These solutions can be applied to investigate and analyze many problems in multilayered media encountered in the science and engineering disciplines using the BEM. Since 2000, the authors have dedicated their efforts to the development of the new BEMs based on these fundamental solutions under the funding of The University Grants Committee of Hong Kong, The University of Hong Kong and the National Natural Science Foundation of China.

This book brings together the descriptions of the new boundary element formulation based on the two fundamental solutions and new analyses and results for the fracture mechanics of layered and functionally graded materials. This method overcomes the mathematical degeneration that is associated with the solitary use of the displacement boundary integral equation for cracked bodies by developing the multi-region and single-region methods of BEMs. Effective implementation of the methods is detailed, devoting special attention to the description of accurate algorithms for the evaluation of various singular integrals in the boundary element formulations. The layered discretization technique is used to simulate the variations of the material property of FGMs with depth. The proposed numerical methods, together with fracture mechanics theories, are used to calculate the stress intensity factors of three-dimensional cracks in FGMs and to analyze the crack growth. The influence of the material parameters and crack dimensions on the fracture properties has been analyzed and quantified. The new material presented in this book is supported by recent articles published in relevant peer-reviewed journals in English or Chinese.

Hongtian Xiao, Zhongqi Yue
September 1st, 2013

Contents

Chapter 1

Introduction

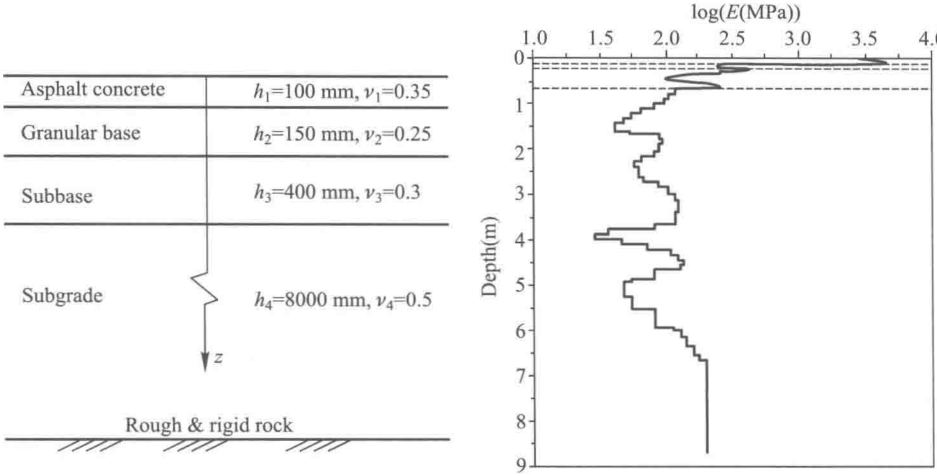
1.1 Functionally graded materials

The homogeneity of solid materials represents the distribution rule of physical and mechanical properties at each point within their occupied space. The physical and mechanical properties of a homogeneous material are spatially constant, namely, they are identical at each point within its occupied space. The physical and mechanical properties of a heterogeneous material on the other hand are spatially variable, having different values at different points. A homogeneous material is an ideal case of a heterogeneous material.

At micro and nano scales, any natural material shows non-uniformity and heterogeneity. However, at meso and macro scales, many engineering materials can be assumed to be homogeneous. This assumption is a first-order average approximation to represent engineering materials in mathematical and physical models and plays an important role in solving the corresponding physical and mechanical problems. In recent years, many new materials have been designed, developed and used, and their physical and mechanical properties have been extensively tested. The heterogeneity of materials at the meso and macro scales has become much more important in analyzing and predicting the mechanical responses and failures of these new materials. It is well known that the heterogeneity of materials plays a key role in practical problems; it is therefore necessary to make a second-order average approximation based on the first-order approximation of the traditional properties of materials in mathematical and physical models. This further approximation is necessary in order to meet the actual design requirements.

Amongst natural and synthetic materials, one type of natural or synthetic materials has their physical and mechanical properties variable along a given coordinate and keeping constant along the other two coordinates perpendicular to the given coordinate. Such materials are called functionally graded materials (FGMs) and can be regarded as a special type of general heterogeneous material that meets the requirements of the second-order average approximation.

Plant and tree stems, animal bones and other biological hard tissues have gradient variations of microstructures and functions in depth. After examining the ingenious biological construction of bamboo, Nogata and Takahashi (1995) concluded that bamboo is a self-optimizing graded structure constructed with a cell-based sensing system for external mechanical stimuli. Such graded structures can also be seen in the gradual changes observed in the elastic properties of sands, soils, and rocks beneath the Earth's surface that control the settlement and stability of structural foundations, plate tectonics, and the ease of drilling into the ground (Suresh, 2001). In-situ surveys show that the elastic modulus of a specific type of soil can be approximated by the function $E = E_0 z^k$, where E_0 is the elastic modulus of a homogeneous soil, and z is the depth beneath the ground surface and $0 \leqslant k \leqslant 1$. When $k = 1$, the soil is referred to as a Gibson soil (Gibson, 1967). Figure 1.1 illustrates the structure of a typical layered pavement system (Yue and Yin, 1998). According to the composition and structure of the materials, this pavement system can be divided into four layers (Fig. 1.1a) and the elastic modulus of each layer varies with depth (Fig. 1.1b).



(a) A typical layered pavement system

(b) Piecewise variation of elastic moduli of the structural layers with depth

Fig. 1.1 Structural layers of asphalt concrete pavement with variable elastic moduli in depth

Learning from nature, material scientists have increasingly designed and engineered graded materials that are more oriented to be damage-resistant than their conventional homogeneous counterparts. Historically, people understood that the variations of structures and composites of materials along one direction can enhance the material properties and lower the cost. Early examples of the use of synthetic materials with graded properties can be traced back to the manufacture of blades for steel swords that used a graded transition from a softer and tougher core to a hardened edge. However, the theoretical understanding of such phenomena has not received much attention due to the difficulties encountered in analytical and mathematical analyses.

As a new design concept in recent years, FGMs were originally proposed as an alternative to conventional thermal barrier ceramic coatings to overcome their well-documented shortcomings and to meet the demands of new technologies, particularly in microelectronics, aerospace and high temperature applications. We can use the engine of the space shuttle as an example to illustrate this concept: The exterior surface of an engine has to withstand high temperatures, so ceramic is used to efficiently shield against thermal conductivity while on the interior surface a cooling gas is required to keep the engine at an optimal working temperature, which requires the use of a metal with good thermal conductivity, high strength and toughness. The composition profile of materials in the interfacial zone varies from 0% metal near the outer surface to help withstand the high temperature to 100% metal near the inner surface in contact with the cooling gas. The resulting non-homogeneous material exhibits the desired thermomechanical properties. Other applications of FGMs include interfacial zones to improve bonding strength and reduce the residual and thermal stresses in bonded dissimilar materials and wear resistant layers in such components as gears, ball and roller bearings, cams and machine tools (Erdogan, 1995).

The mechanical responses of FGMs are especially important in many engineering fields and are of great interest to material scientists, and design and manufacturing engineers. Birman and Byrd (2007) reviewed the principal developments in various aspects of theories and applications of FGMs. They include the following:

(1) Approaches to homogenization of a particulate-type FGM.

(2) Heat transfer problems where only the temperature distribution is determined.

(3) Mechanical response to static and dynamic loads including thermal stress.

(4) Optimization of heterogeneous FGM.

(5) Manufacturing, design, and modeling aspects of FGM.

(6) Testing methods and results.

(7) FGM applications.

(8) Fracture and crack propagation in FGM.

The problem of fracture in FGMs is extremely important and has been studied in depth. Birman and Byrd (2007) listed several recent papers that illustrate the variety and complexity of fracture problems.

1.2 Methods for fracture mechanics

1.2.1 General

Graded materials have complex fracture mechanisms because of the variations in the composition, structure, and mechanical properties of FGMs. At the meso and macro scales, crack-like flaws exert an important influence on the mechanical properties of FGM structures. Erdogan (2000) proposed that some of the following research into the fracture mechanics is needed:

(1) Three-dimensional corner singularities in bonded dissimilar materials.

(2) Determination of local residual stresses in bonded anisotropic solids and their effect on crack initiation.

(3) Three-dimensional periodic surface cracking and crack propagation in coatings.

(4) The effect of temperature dependence of the thermo mechanical parameters in layered materials undergoing thermal cycling and thermal shock.

(5) The effect of material and geometric nonlinearities on spallation.

(6) Crack tip singularities in inelastic graded materials.

(7) Crack tip behavior in graded materials – additional nonsingular terms.

(8) Developing methods for fracture characterization of FGMs at room and elevated temperatures.

The research methods used to investigate the fracture mechanics of FGMs include both analytical and numerical methods. The analytical methods use the singular integral equation method, etc. while numerical methods include the finite element method, the boundary element method, meshless methods, etc.

1.2.2 Analytical methods

Many analytical investigations of crack problems in FGMs have been conducted. Delale and Erdogan (1983) analyzed the crack problem for a non-homogeneous plane where the Poisson's ratio is in the product form of linear and exponential functions and the elastic modulus varies exponentially with the coordinate; it was found that the effect of the Poisson's ratio is somewhat negligible. Delale and Erdogan (1988) considered an interface crack between two bonded half planes where one of the half planes is homogeneous and the second is non-homogeneous in such a way that the elastic properties are continuous throughout the plane and have discontinuous derivatives along the interface. The results lead to the conclusion that the singular behavior of stresses in the non-homogeneous medium is identical to that in a homogeneous material provided that the spatial distribution of material properties is continuous near and at the crack tip. Ozturk and Erdogan (1996) considered a penny-shaped crack in homogeneous dissimilar materials bonded through an interfacial region with graded mechanical properties and subject to axisymmetric but otherwise arbitrary loads. Pei and Asaro (1997) analyzed a semi-infinite crack in a strip of an isotropic FGM under edge loading and in-plane deformation conditions. Jin and Paulino (2002) studied a crack in a viscoelastic strip of a FGM under tensile loading conditions. Meguid et al. (2002) investigated the singular behavior of a propagating crack in a FGM with spatially varying elastic properties under plane elastic deformation and examined the effect of the gradient of material properties and the speed of crack propagation upon the stress intensity factors, the strain energy release rate and the crack opening displacement.

In the above analyses it is assumed that the elastic properties are given as simple functions. In most cases, the elastic properties of the FGMs are described by exponential functions while in other cases they are described by power functions. Only in these simplified cases can the analytical solutions of some crack problems in FGMs be obtained. For three-dimensional crack problems in FGMs, only penny-shaped cracks under axisymmetric but otherwise arbitrary or torsional loads are analyzed in closed forms (Ozturk and Erdogan, 1995, 1996). In their analyses, the shear modulus of the FGM is also described by an exponential function.