Solid Mechanics and Its Applications

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Mechanics of Failure Mechanisms in Structures

Springer

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SOLID MECHANICS AND ITS APPLICATIONS
Volume 187

Series Editor: G.M.L. GLADWELL
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Waterloo, Ontario, Canada N2L 3GI

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ISSN 0925-0042
ISBN 978-94-007-4251-2 e-ISBN 978-94-007-4252-9
DOI 10.1007/978-94-007-4252-9
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2012937855

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

As manufacturing and transportation technologies have evolved and become more complex, the ranges of the operating conditions in structures, machines and vehicles have expanded. The consequences of failure in these systems can range from being minor to catastrophic events. The importance of the development of a basic understanding of the interactions of complex failure mechanisms is clear. The goals of the experimental investigations of failure mechanisms are also clear. They are to provide foundations for the development of analytical procedures that provide for the development of sound design methods, and effective monitoring procedures. Mechanisms that can lead to failure include fracture, fatigue, creep, collapse due to buckling, and dynamic excitation.

The emphasis is on failure mechanisms in metallic, ceramic, polymeric, and composite solids. Chapters are devoted to failure mechanisms that are characteristic of each of the materials. Failures in Chap. 1 of metals include time independent and time dependent tensile and compressive loading for both static and dynamic cases. Both theoretical and experimental results are presented. Chapter 2 includes a consideration of the basic elements of fracture mechanics, the effects of toughness gradients, and the effects creep induced brittleness.

The statistical, bimodal character of multi-site fatigue cracking in the small crack regime is discussed in Chap. 3. The use of the range of the stress intensity factor in computing the rate of fatigue crack growth rate in the long crack regime, the effects of variable amplitude loading including tensile and compressive overloading, and environment effects are also discussed.

Failure mechanisms in ceramic composites, polymeric composites and metallic composites are discussed in Chaps. 4, 5 and 6. Failures in biomaterials are discussed in Chap. 7. Failure mechanisms in systems with multiple structural elements are discussed in Chap. 8.

Professor Carlson would like to acknowledge the support and encouragement of Dr. C.J. Beevers of the University of Birmingham in England with whom he conducted research on fatigue. He would also like to acknowledge the benefit of his collaborative research with Prof. N.J. Hoff of Stanford University on the topic of structural stability. The second author, Prof. George A. Kardomateas gratefully acknowledges the benefits of being introduced to research in mechanics by Prof. F.A. McClintock of the Massachusetts Institute of Technology, and he would also like to acknowledge the long-term support and encouragement of Dr. Yapa D.S. Rajapakse of the Office of Naval research. In addition, he would like to acknowledge the benefit of stimulating scientific interactions with Profs. George Simitses, Victor Birman, Leif Carlsson, Izhak Sheinman and Shuki Frostig.

We acknowledge the contributions of Dr. Marcus Cappelli who conducted the experiments and analyzed data for our investigation on the growth of multiple-site fatigue cracks. We also want to cite the contributions of Tina Babanari who participated in our experimental fatigue crack growth investigations.

Finally, we would like to extend our thanks to Ms Nathalie Jacobs of Springer (Dordrecht, the Netherlands) for her help in making this work possible.

We hope that this book will enable the specialists who encounter questions regarding the failure mechanisms of structural elements to have the basic material and overview on this topic at their fingertips and to utilize it in their research or engineering practice.

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Contents

Chapter 1
Stability in Metallic Elements

Abstract The metallic alloys that are widely used in structures, machines and vehicles are chosen because they are, under many loading conditions, not subject to brittle fracture, and can withstand localized overloading. Nominally ductile metals can, however, fracture in a brittle manner under certain conditions. Cyclic loading can result in fatigue cracks that can lead to brittle fracture. Two modes of ductile instability are discussed: time independent loading and time dependent loading, or creep.

1.1 Time Independent Tensile Loading

The basic experiment for determining time independent loading properties in metals is the tensile test in which a prismatic specimen is subjected to unidirectional tensile loading. Its objective is to provide mechanical property data that can be used in the design of structures and machines. It provides, for example, data on the stiffness in the form of the elastic modulus, the transition from elastic to inelastic behavior, and the ultimate failure by fracture. Results from such tests are usually presented in the form of a stress-strain diagram such as shown in Fig. 1.1. By convention, the strain is plotted on the horizontal axis while the stress is plotted on the vertical axis, although in most testing the load (stress) is the independent variable.

Brittle metals exhibit only an initial elastic behavior leading directly to fracture. The behavior of a linearly elastic brittle material is characterized by the slope of the stress-strain which defines the elastic modulus and the fracture stress. Ductile metals such as low carbon steel exhibit a yield point, usually defined by the yield stress, which is the transition point between initial elastic and subsequent inelastic (or plastic) behavior (see Fig. 1.1). Detecting this transition can be difficult, and it is dependent on the sensitivity of the measuring instruments that are used. Since inelastic behavior is defined by the development of residual strain, it can be necessary to repeatedly apply increasing load/unload cycles until a residual strain is observed. Some materials such as steels exhibit a well-defined linearly elastic

R.L. Carlson et al., *Mechanics of Failure Mechanisms in Structures*, Solid Mechanics and Its Applications 187, DOI 10.1007/978-94-007-4252-9_1,