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Damage Tolerance of Metallic Aircraft Structures

Materials and Numerical Modelling

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Preface

This publication traces its origin to the involvement of the authors in several European Union R&D aeronautical projects, as SMAAC, ADMIRE and DATON, among others. It aims at giving an up-to-date view of the technical aspects of the field in the context of the applicable regulatory environment. The references will guide the reader to details not included here, due to the conciseness expected from this series of books (aptly called the Springer brief collection).

The book is organized in two parts. Part I sets the scene, with a retrospective of the evolution of fatigue design approaches for aerostructures, up to current regulations, including introductory reference to materials and technical aspects to be solved.

From safe-life to fail-safe and damage tolerance approaches, the last one emerged as the main design philosophy for aerostructures, allowing weight savings and at the same time increasing reliability and structural integrity in the presence of damages which may have occurred during the manufacturing process or during service. The application of damage tolerance philosophy requires extensive know-how of the fatigue and fracture properties, corrosion strength, potential failure modes and nondestructive inspection (NDI) techniques, particularly minimum detectable defect and inspection intervals.

To face scatter in material properties, conservative approaches considering the worst scenario or statistical methods dealing with the variability of material have been employed in the fatigue assessment of structures. The fatigue life estimation can display substantial variability, illustrating the need for a probabilistic assessment in practical applications. The main focus of this work is on metallic structures; nevertheless, a concise reference is made to composite structures, namely, to highlight the specific different approaches involved.

The 2010 FAA rule establishing an LOV (limit of validity) puts a bound in the indefinite operational life allowed for by earlier regulations. This requirement, together with the diminishing role of aluminium in airframes, will certainly shape the directions of fatigue, fracture and damage mechanics research in years to come, expanding the knowledge based upon which substantiation of LOV values is made and ensuring safety under sustainable conditions.

Part II of the present book addresses the characterization of mechanical behaviour of materials and the numerical analyses for damage tolerance with a focus on integral structures, giving comprehensive worked examples that take into account residual stresses. Given the importance of welding in some applications, this topic is reviewed in some detail, when relevant including information from other industrial applications.

Aluminium alloys were for many decades the material of choice for aircraft structures. Although this prominence no longer exists, these alloys still represent a substantial part of the aircraft. This book briefly reviews the fatigue crack propagation behaviour of typical Al alloys, including Al–Li alloys of interest because of their low weight and high strength. The dominant joining technology for aircraft Al fuselage is riveting, but welding is occasionally also found.

Welding involves the creation of residual stresses and distortions. Thermal gradients introduce geometrical variations creating residual stress and distortion; their reliable prediction is required for economical and sound welding.

The prediction of welding behaviour is complex because of the many physical–chemical phenomena involved. With the finite element method, the integration of all the physical–chemical phenomena is feasible, and elaborated computational models exist for most welding cases. As with general-purpose FEM software as ABAQUS or ANSYS, commercial FEM packages as Sysweld address fusion welding; mesh sensitivity analysis is required in order to evaluate the minimum element size required for accurate results.

Examples discussed include aluminium plates welded by laser beam. Reinforced and stiffened shells involve the use of T-joints; other example concerns T-joint arc and laser beam welded. The capability of Sysweld is illustrated modelling arc-welded double-side T-joint with different procedures, particular attention being dedicated to the interaction of welding passes on residual stress distribution.

Residual stresses of welded metallic structures are discussed with an emphasis on numerical modelling using the finite element method and experimental measurement using the contour technique. Residual stresses affect the behaviour of the structure, in particular, crack propagation behaviour. Fatigue crack propagation behaviour on welded metallic structures, with emphasis on aeronautical applications, is reviewed in this book, and an aeronautical example is presented.

Different crack growth simulation models which were introduced for fatigue crack growth assessment in the context of the EU DATON project are compared. First, different simulation approaches were applied to determine a stress intensity factor (K) calibration as a function of the crack length for a two-stiffener panel with a central crack. Different manufacturing processes introduced residual stress fields, and their influence was included in the numerical models to determine K. K calibrations were applied in different crack growth models/laws (Paris, Walker, Forman and NASGRO) in order to determine the fatigue life under cyclic loading. R ratio variation and residual stresses were taken into account in all of them allowing to determine the influence of the residual stress field in the fatigue crack growth. The results were tested and compared with experimental results with the purpose of validation of the models.

These numerical models illustrate how to predict the fatigue life in stiffened welded panels and made clear that the residual stress field originated by welding processes can be detrimental or beneficial depending on the location where the crack starts.

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Contents

Acronyms and Symbols

Acronyms

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
3PB	Three-point bending
AA	Aluminium association
AAWG	Airworthiness Assurance Working Group
AC	Advisory circular (FAA)
ADL	Allowable damage limit
AIAA	American Institute of Aeronautics and Astronautics
AM	Additive manufacturing
AMC	Acceptable means of compliance (EASA)
Amdt	Amendment
APDL	ANSYS parametric design language
ARAC	Aviation Rulemaking Advisory Committee (USA)
ARALL	Aramid reinforced aluminium laminate
ASIP	Aircraft structural integrity program (USAF)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AVT	Applied vehicle technology
BVID	Barely visible impact damage
CAI	Compression after impact test
CAR	Civil Air Regulations (FAR after 1965)
CBM	Condition-based maintenance
CDT	Critical damage threshold
CFR	Code of Federal Regulations (USA)
CMM	Coordinate measuring machine
COS	Continued operational safety
CS	Certification specification (EASA)
CT, CTS	Compact tension specimen

CVM	Comparative vacuum monitoring
CX	Cold expansion
DATON	Innovative fatigue and damage tolerance methods for the application of new structural concepts (EU R&D project)
DBEM	Dual boundary element method
DOD	Department of Defence (USA)
DoE	Design of experiments
EASA	European Aviation Safety Agency
EBSD	Electron backscatter diffraction analysis
EDM	Electrical discharge machining
EPFM	Elasto-plastic fracture mechanics
EPRI	Electric Power Research Institute (USA)
ESA	European Space Agency
EU	European Union
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations (prescribed by FAA, and part of Title 14 of the CFR)
FC	Flight cycle
FCG	Fatigue crack growth
FE	Finite elements
FEM	Finite elements method
FEUP	Faculdade de Engenharia da Universidade do Porto
FIB-SEM	Focused ion beam scanning electron microscopy
FML	Fibre metal laminate
FSW	Friction stir welding
GAG	Ground-air-ground
GARTEUR	Group for Aeronautical Research and Technology in Europe
GB	Grain boundary
GLARE	Glass-reinforced aluminium laminate
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat-affected zone
HCLL-TBM	Helium-cooled Lithium lead test blanket module
HE	Hydrogen embrittlement
HEWABI	High-energy, wide-area, blunt impacts
HMSO	Her Majesty's Stationery Office (UK)
HPDL	High-power diode laser
HSM	High speed machining
IDMEC	Instituto de Engenharia Mecânica
IIW	International Institute of Welding
ILA	Internationale Luft- und Raumfahrtausstellung (Berlin Air Show)
IMechE	Institution of Mechanical Engineers
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering (Portugal)