ICAF 2009, Bridging the Gap between Theory and Operational Practice

M.J. Bos

Editor

ICAF 2009, Bridging the Gap between Theory and Operational Practice

Proceedings of the 25th Symposium of the International
Committee on Aeronautical Fatigue, Rotterdam, The Netherlands,
27–29 May 2009

Editor

M.J. Bos

National Aerospace Laboratory NLR

Amsterdam

The Netherlands

The papers on pp. 15–54, 123–142, 279–299, 643–660 were created within the capacity of an Australian governmental employment and therefore are in the public domain.

The papers on pp. 301–327, 811–837 were created within the capacity of a Canadian governmental employment and therefore are in the public domain.

The papers on pp. 187–207, 309–353, 407–425, 909–920, 1035–1068, 1215, 1345–1364 were created within the capacity of an US governmental employment and therefore are in the public domain.

ISBN 978-90-481-2745-0

e-ISBN 978-90-481-2746-7

DOI 10.1007/978-90-481-2746-7

Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2009927714

© 2009 Springer Science+Business Media, B.V.

No part of this work may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, microfilming, recording or otherwise, without written permission from the Publisher, with the exception of any material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work.

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

TABLE OF CONTENTS

Preface xiii

ICAF General Secretary & National Delegates xvii

**FULL-SCALE FATIGUE TESTING OF AIRCRAFT AND
AIRCRAFT STRUCTURAL COMPONENTS**

A test concept for future aircraft fuselage panels
R. Best, Th. Fleischer, M. Götze, M. Sachse and M. Semsch 3

Marker loads for quantitative fractography of fatigue cracks in aerospace alloys
S.A. Barter, L. Molent and R.J.H. Wanhill 15

Substantiations of an airborne composite radome mounted on an aircraft dome
*I. Kressel, U. Ben-Simon, M. Elyahu, D. Peled, A. David, T. Nachshon,
Y. Gary, M. Interator, G. Ghilai and A. Simon* 55

AIRWORTHINESS CONSIDERATIONS

Development of a “low stress criterion” that eliminate a large portion of the
aircraft from damage tolerance based maintenance program for structural
repairs required by the new part 26 federal regulation
Girindra K. Das and Matthew Miller 61

Damage tolerance philosophy for bonded aircraft structures
C.D. Rans and R.C. Alderliesten 73

First diamond: ‘Damage tolerance’ for the structural honeymoon
Steve Swift 91

Survey of structural repairs and alterations in transport category airplanes
Michel D. Bode, Walter Sippel and John G. Bakuckas 109

Enhanced teardown of ex-service F/A-18A/B/C/D centre fuselages
*L. Molent, B. Dixon, S. Barter, P. White, T. Mills, K. Maxfield,
G. Swanton and B. Main* 123

NDI, INSPECTIONS AND MAINTENANCE

Glare teardowns from the MegaLiner Barrel (MLB) fatigue test
*R.J.H. Wanhill, D.J. Platenkamp, T. Hattenberg, A.F. Bosch and
P.H. de Haan* 143

30 Years of damage tolerance – Have we got it right? <i>Robert G. Eastin and Jon B. Mowery</i>	169
Compilation of damage findings from multiple recent teardown analysis programs <i>Gregory A. Shoales, Scott A. Fawaz and Molly R. Walters</i>	187
Detection of arrested crack for foam core sandwich structures using optical fiber sensors embedded in a crack arrester <i>Shu Minakuchi, Ippei Yamauchi, Nobuo Takeda and Yasuo Hirose</i>	209
LIFE EXTENSION AND MANAGEMENT OF AGEING FLEETS	
Concept of the new A320 fatigue test <i>N. Rößler, C. Peters, O. Tusch, G. Hilfer and C. Herrmann</i>	225
The use of composite material strips to extend the damage-tolerance life of integrally stiffened aluminium panels <i>A. Brot, Y. Peleg-Wolf, I. Kressel and Z. Yosef</i>	237
Structural integrity of a wing upper skin with exfoliation corrosion <i>Andreas Uebersax, Cyril Huber, Guillaume Renaud and Min Liao</i>	245
Helicopter structural integrity program of Polish Mi-24 Hind helicopters <i>Slawomir Klimaszewski, Andrzej Leski, Krzysztof Dragan, Marcin Kurdelski and Mirosław Wrona</i>	263
Airframe life extension by optimised shape reworking – Overview of DSTO developments <i>M. Heller, M. Burchill, R. Westcott, W. Waldman, R. Kaye, R. Evans and M. McDonald</i>	279
Evaluation, modification and damage tolerance of an in-service aircraft critical area <i>R.S. Rutledge, D.S. Backman and R.J. Hiscocks</i>	301
Procedures for aircraft structural teardown analysis: Development of a best practices handbook <i>Gregory A. Shoales</i>	329
Fatigue lifetime improvement of arrestment hook shanks by application of laser peening <i>Mike Leap, Jon Rankin, Jim Harrison, Serena Marley, Lloyd Hackel and Joe Nemeth</i>	355

ADVANCED MATERIALS AND INNOVATIVE STRUCTURAL CONCEPTS

Design and testing of advanced composite load introduction structure for aircraft high lift devices <i>Tamas Havar and Eckart Stuible</i>	365
Hybrid structure solution for the A400M wing attachment frames <i>Matthijs Plokker, Derk Daverschot and Thomas Beumler</i>	375
Control of crack growth rates and crack trajectories for enhanced fail safety and damage tolerance in welded aircraft structures <i>Phil Irving, Yu E Ma, Xiang Zhang, Guido Servetti, Stewart Williams, Gary Moore, Jorge dos Santos and Marco Pacchione</i>	387
Durability and damage tolerance of bonded repairs to metallic fuselage structure <i>John G. Bakuckas, Jr., Keith McIver and Ching Hsu</i>	407
Investigation on the design of bonded structures for increased damage tolerance <i>Ivan Meneghin, Marco Pacchione and Pascal Vermeer</i>	427
An experimental investigation on the fatigue performance of riveted lap joints <i>M. Skorupa, A. Skorupa, T. Machniewicz and A. Korbel</i>	449
Improving the fatigue life of aeronautical single lap bolted joints thanks to the hybrid (bolted/bonded) joining technology <i>E. Paroissien, C.T. Hoang Ngoc, H. Bhugaloo and D. Ducher</i>	475
An experimental approach to investigate detailed failure mechanisms in fibre metal laminates <i>Riccardo Rodi, René Alderliesten and Rinze Benedictus</i>	493
Experimental determination of energy release rate of CFRP structures by means of transverse crack tension tests <i>Ll. Llopart Prieto, G. Spenninger and H. Wagner</i>	513
Central material concept: towards aircraft wing structure insensitive to fatigue <i>Mohamed A.A. Attia</i>	529
Practical applications of improvements in FML crack bridging theory <i>Greg Wilson, René Alderliesten, Riccardo Rodi and H.J.K. Lemmen</i>	539

Simulation of the stress distribution on fuselage structures for the pre- and post analysis of curved panel tests
Matthias Ziegenhorn, Frank Schulze, Holger Sparr, Karsten Wenke and Thomas Fleischer 559

Low cycle lifetime prediction of AL2024 alloy
A. Vyshnevskyy, S. Khan and J. Mosler 569

Fatigue and damage tolerance aspects of metal laminates
J. Sinke and S.A.H. Johansson 585

Arall and Glare FML's: Three decades of bridging the gap between theory and operational practice
Cees van Hengel and Peter Kortbeek 601

FATIGUE CRACK GROWTH AND LIFE PREDICTION METHODS

Detailed strain field analyses of fatigue cracks in friction stir welded joints
H.J.K. Lemmen, R.C. Alderliesten and R. Benedictus..... 619

A study of interaction and coalescence of micro surface fatigue cracks in aluminium 7050
W. Hu, Q. Liu and S. Barter 643

Fracture behaviour of skin materials of civil airplane structures
Boris Nesterenko, Grirory I. Nesterenko and Valentin N. Basov 661

Fatigue life prediction of small notched TI-6AL-4V based on the theory of critical distance
Yoichi Yamashita, Masaharu Shinozaki, Hiroshi Kuroki and Yusuke Ueda 685

A case study of multiple-site fatigue crack growth in the F-18 Hornet bulkhead
B. Andersson, A.F. Blom, U. Falk, G.S. Wang, K. Koski, A. Siljander, J. Linna, A. Miettinen, K. Vaaraniemi and R. Lahtinen 707

Experimental and theoretical comparison of some multiaxial fatigue design criteria in the context of life assessment of rotating parts in turboengines
V. Bonnard, J.L. Chaboche, H. Cherouali, P. Gomez, P. Kanouté, D. Pacou, P. Paulmier, E. Ostoja-Kuczynski and F. Vogel 743

A contribution of environmental investigations for Glare riveted joint sizing
Thomas Beumler, Bob Borgonje and Jos Sinke 765

Advances in crack growth modelling of 3D aircraft structures
S.C. Mellings, J.M.W. Baynham and R.A. Adey 789

Development of advanced risk assessment methodologies for aircraft structures containing MSD/MED
Min Liao, Yan Bombardier, Guillaume Renaud, Nick Bellinger and Terence Cheung 811

Crack growth in fiber metal laminates under variable amplitude loading
S.U. Khan, R.C. Alderliesten and R. Benedictus 839

Effect of residual stresses from shot peening on fatigue strength and threshold to crack propagation of AL 7475 alloy components
G. Ratti, U. Mariani, M. Giglio and M. Guagliano 859

Experimental validation of stress intensity factor solutions for the pin loaded lug
D.R. Child, N.J. Moyle and A.F. Grandt 871

Properties of fatigue crack propagation in friction stir welded 2024-T3 aluminum alloy
T. Okada, K. Kuwayama, S. Fujita, M. Asakawa, T. Nakamura. and S. Machida 899

Fatigue crack growth in thick plate 7050 aluminum
Joel Schubbe 909

Fatigue life evaluation on tension type fitting
Nicolas Baréa and Marie Massé 921

Accelerated fatigue testing on hydraulic shaker
M. Fressinet, M. Panis and C. Bordes 931

Methods for FEM analysis of riveted joints of thin-walled aircraft structures within the Imperja project
Jerzy Kaniowski, Wojciech Wronicz, Jerzy Jachimowicz and E. Szymczyk 939

On the crack growth behaviour under simple compressive loads of 2024-T3 aluminium alloy
M. Krkoška, R.C. Alderliesten and R. Benedictus 969

An analytical model for load transfer in a mechanically fastened, double-lap joint <i>Ligieja Paletti, Calvin Rans and Rinze Benedictus</i>	987
Simulation of fatigue crack growth in the high speed machined panel under the constant amplitude and spectrum loading <i>Petr Augustin</i>	1005
Bonded composite patch to repair metallic structures: Disbond propagation testing and modelling <i>P. Madelpech, S. Juaneda and M. Pradels</i>	1019
Three dimensional crack growth prediction <i>Sarah E. Galyon, Saravanan R. Arunachalam, James Greer, Matthew Hammond and Scott A. Fawaz</i>	1035
Hybrid structures for concentrated load transmission in fibre composites: Initial experiments <i>Pascal Vermeer, René Alderliesten and Rinze Benedictus</i>	1069
STRUCTURAL HEALTH AND STRUCTURAL LOADS MONITORING	
Pilatus PC-21 – A damage tolerant aircraft <i>Lukas Schmid</i>	1085
Introduction to service of an artificial neural network based fatigue monitoring system <i>Steve Reed, Brian McCoubrey and Andy Mountfort</i>	1093
Towards automated flight-maneuver-specific fatigue analysis <i>Juha Jylhä, Marja Ruotsalainen, Tuomo Salonen, Harri Janhunen, Tomi Viitanen, Juho Vihonen and Ari Visa</i>	1121
Service history analysis and teardown evidence – Key elements for structural usage monitoring of an ageing fleet <i>K.A. Lucas and M.J. Duffield</i>	1135
Development of fatigue life monitoring of RMAF fighter airplanes <i>Wahyu Kuntjoro, M. Suhaimi Ashari, M. Yazid Ahmad and Assanah M. Mydin</i>	1155

Research and development of impact damage detection system for airframe structures using optical fiber sensors <i>Hiroaki Tsutsui, Noriyoshi Hirano, Junichi Kimoto, Takahiko Akatsuka, Hirofumi Sashikuma, Nobuo Takeda and Naoyuki Tajima</i>	1165
Load factors (N/Z) / roll rate: First comparisons between design and in- flight recorded data on Eurofighter typhoon Italian fleet <i>Tommaso Giacobbe and Fabio Sardo</i>	1177
Development of a structural health monitoring system to evaluate de- bonding in composite adhesive structures <i>Hideki Soejima, Noritsugu Nakamura, Toshimichi Ogisu, Hiroshi Wakai, Yoji Okabe, Nobuo Takeda and Yoshihiro Koshioka</i>	1187
OLM: A hands-on approach <i>Stephen Willis</i>	1199
F-35 Joint strike fighter structural prognosis and health management: An overview <i>Timothy Fallon, Devinder Mahal and Iain Hebden</i>	1215
FATIGUE LIFE ENHANCEMENT METHODS AND REPAIR SOLUTIONS	
Bonded repair for fuselage damage: An overall benefit to commercial aviation <i>D. Furfari, H.J.M. Woerden, R. Benedictus and A. Kwakernaak</i>	1219
Fatigue & damage tolerance of hybrid materials & structures – Some myths, facts & fairytales <i>R.C. Alderliesten</i>	1245
High cycle fatigue of laser beam deposited Ti-6Al-4V and inconel 718 <i>E. Amsterdam and G.A. Kool</i>	1261
The variable expansion process – A new cost efficient method for cold working fastener holes in aluminium aircraft structures <i>Eggert D. Reese, Anthony L. Dowson and Timothy G.B. Jones</i>	1275
Stress measurements with x-ray diffractometry on aluminium alloys. Determination of the most optimized parameters of the measurement <i>Elżbieta Gadalińska, Jerzy Kaniowski and Andrzej Wojtas</i>	1285
Delamination growth at interfaces in hybrid materials and structures under various opening modes <i>G. Delgrange, R.C. Alderliesten and R. Benedictus</i>	1305

Developments in metal bonding
Jarkko J. Aakkula , Kari Lumppio, Olli Saarela and Tapani Haikola 1321

ENVIRONMENTAL EFFECTS

On separating the effect of corrosion on inter-lamellar fatigue on thin sheet
AA7079-T6
Sandeep R. Shah and S.A. Fawaz..... 1345

Authors Index..... 1365

PREFACE

While writing this preface for the Proceedings of the 25th Symposium – a silver jubilee! – of the International Committee on Aeronautical Fatigue (ICAF) I wish I already knew that it has been a great success and that everything went smoothly, all lecturers had shown up, the number of participants had been record-breakingly high, etc. But alas, owing to our decision to publish the Proceedings beforehand I can only *hope* that this will have been the case. What I do know, however, is that both the number and quality of the submitted papers is outstanding. It is therefore fair to state that ICAF continues to be regarded as an important platform for the exchange of information concerning aeronautical fatigue and structural integrity, as has been its aim since its foundation. The vitality of ICAF is emphasized by the fact that authors from 21 different countries have responded to our call for papers. This also indicates that ICAF has the potential to expand beyond its present status of 14 member nations. Poland, having become a full member of ICAF this year, has set a much appreciated example in this respect.

ICAF was formed in 1951 in response to the growing concerns regarding fatigue problems in metal aircraft structures. The stated aims of ICAF are to exchange information concerning aircraft structural fatigue and to encourage contacts between people active in this field. To this end a Conference and Symposium are organised every two years for attendance by representatives of industry, universities and institutes, regulatory agencies and operators throughout the world. The two-day Conference consists of reviews of aeronautical fatigue activities presented by the National Delegates of ICAF member nations. It is followed by the three-day Symposium that consists of specialist papers presented by authors with backgrounds and expertise in design, manufacturing, airworthiness regulations, operations and research.

The ICAF 2009 Conference and Symposium were held in the last week of May in Rotterdam, the Netherlands. ICAF 2009 was hosted by the National Aerospace Laboratory NLR (which celebrated its 90th anniversary in 2009 – another milestone!), under the auspices of the Netherlands Association of Aeronautical Engineers (NVvL), Delft University of Technology and Stork Fokker AESP B.V.

The theme of the 25th ICAF Symposium is “Bridging the gap between theory and operational practice”. This theme came to mind during a discussion with F-16 maintenance engineers of the Royal Netherlands Air Force. From their perspective it is not always clear why the fleet should go through a strict and often burdensome inspection programme during which cracks – fortunately – are only rarely found. In this light it is worth mentioning that the NATO Research & Technology Organisation has recently issued a report about future airframe structural lifing methodologies. This report attempts to reconcile the differences between the current damage tolerance requirements as specified by the US Air Force and the

safe life philosophy adhered to by the US Navy and helicopter manufacturers. In this report the focus is on risk-based methods that also account for operational damage findings.

A good theme should leave room for more topics than one. Judging by the submitted papers this is the case. In particular, a few authors have used this theme as a framework to describe the introduction of new materials and technologies into the latest generation of aircraft. Notable examples are the Airbus A380, Boeing 787, Joint Strike Fighter and NH90 helicopter. The latter three aircraft are especially important in their major use of composite structures, which are increasingly within the scope of ICAF. This is underscored by the 2009 Plantema Memorial Lecture, named in honour of the founder of ICAF, Dr. Frederick Plantema. The 2009 Lecture was given by M. Jean Rouchon, France's former National Delegate to ICAF, who recently retired as the head of the Technical Centre for Materials and Structures of the Centre d'Essais Aeronautique de Toulouse CEAT, and is now a private consultant. The title of the 2009 Plantema Memorial Lecture is "Fatigue and Damage-Tolerance Evaluation of Aircraft Structures – The Composite Materials Response". This special lecture was unavailable for publication in the ICAF Symposium Proceedings (this book). It has been decided to publish M. Rouchon's Plantema Memorial Lecture under the aegis of the organising committee as an NLR Technical Publication.

A new feature to ICAF was a session of three parallel workshops on the last morning of the 25th Symposium. These workshops were included to promote dissemination of a wealth of background knowledge and expertise that resides with senior workers. The workshops were led by Prof. Graham Clark (Aircraft Accident Investigation), Prof. Jaap Schijve (Fatigue Problems of Aircraft Structures) and M. Jean Rouchon (Composite Materials in the light of Damage/Fatigue Tolerance).

Delft University and the NLR recently established a biennial award for young and talented academics in the field of aeronautical fatigue. The award is named after Prof. Schijve, to celebrate his 80th birthday, and consists of a medal and prize. ICAF agreed to include presentation of the first Jaap Schijve Award on the last day of the 25th Symposium. It was felt that this would amply demonstrate that the subject of aeronautical fatigue is very much alive and well worth a career.

The Organizing Committee of ICAF 2009 consisted of Prof. Rinze Benedictus (Delft University of Technology), Marcel Bos (NLR), Tim Janssen (Stork Fokker AESP B.V.) and Henk van Leeuwen (NVvL). The Technical Committee consisted of Marcel Bos, Frank Grooteman and Dr. Russell Wanhill (NLR); Dr. René Alderliesten, Prof. Rinze Benedictus and Prof. Jaap Schijve (Delft University of Technology); Tim Janssen (Stork Fokker AESP B.V.); and Dr. Simon Barter (DSTO, Australia). The Conference Secretariat was provided by Ms. Gemma van der Windt (D&G Partners). Financial support for ICAF 2009 has been received from various organizations. MOOG, FTI and ACRA Control were the main

sponsors, partnered by Woodhead Publishing, Springer Science & Business Media and Emerald. The contribution by the City of Rotterdam is also gratefully acknowledged. I would like to thank these individuals and organizations, the authors, workshop leaders, National Delegates and all other persons who contributed to the success of ICAF 2009.

In conclusion, I would like to direct the attention of the reader to the contents of this book. It includes 77 selected papers on a broad range of structural fatigue topics that include airworthiness, advanced materials and innovative structural concepts, full-scale fatigue testing, life extension and management of ageing fleets, structural health and structural loads monitoring, inspection techniques and maintenance, fatigue crack growth and life prediction methods, fatigue life enhancement methods and repair solutions, environmental effects, probabilistic modelling and risk analysis. I think the papers are an excellent read for anyone with an interest in aeronautical fatigue and aircraft structural integrity, from both a scientific and practical point of view. I hope you enjoy this book as much as I do.

Marcel Bos
Chairman of the ICAF 2009 Organizing Committee
National Aerospace Laboratory NLR

ICAF GENERAL SECRETARY

Dr. Anders F. Blom

Defence & Security, Systems and Technology
Swedish Defence Research Agency (FOI)
SE-164 90 Stockholm, Sweden
anders.blom@foi.se

NATIONAL DELEGATES

AUSTRALIA

Prof. Graham Clark

School of Aerospace
Mechanical and Manufacturing
Engineering
RMIT University, PO Box 71
Bundoora VIC 3083, Australia
graham.clark@rmit.edu.au

FINLAND

Dr. Aslak Siljander

VTT Technical Research Centre of
Finland
Machines and Vehicles
P. O. Box 1000
FI-02044 VTT, Finland
aslak.siljander@vtt.fi

GERMANY

Dr. Claudio Dalle Donne

EADS Innovation Works
81663 München, Germany
claudio.dalledonne@eads.net

ITALY

Prof. Luigi Lazzeri

Università di Pisa
Department of Aerospace Engineering
Via G. Caruso, 8
56122 Pisa, Italy
aero.lazzeri@ing.unipi.it

CANADA

Jerzy P. Komorowski

Institute for Aerospace Research
National Research Council Canada
1200 Montreal Road, Bldg. M-3
Ottawa, Ontario K1A 0R6, Canada
jerzy.komorowski@nrc-cnrc.gc.ca

FRANCE

Dr. Thierry Ansart

Structures Division
Toulouse Aeronautical Test Center (CEAT)
BP 93123, 47 rue Saint Jean
31131 Balma, France
thierry.ansart@dga.defense.gouv.fr

ISRAEL

Abraham Brot

Israel Aircraft Industries
Dept 4441, Engineering Div.
Ben-Gurion Airport 70100, Israel
abrot@iai.co.il

JAPAN

Dr. Hiroyuki Terada (retiring)

hterada@dance.ocn.ne.jp

Prof. Nobuo Takeda (as of May 2009)

Graduate School of Frontier Sciences
The University of Tokyo
Mail Box 302, 5-1-5 Kashiwanoha,
Kashiwa-shi, Chiba 277-8561, Japan
takeda@smart.k.u-tokyo.ac.jp

POLAND

Dr. Antoni Niepokólczycki
NET Institute
Institute of Aviation
Al. Krakowska 110/114
02-256 Warsaw, Poland
antekn@ilot.edu.pl

SWITZERLAND

Dr. Michel Guillaume
RUAG Aerospace
P.O. Box 301
CH-6032 Emmen, Switzerland
michel.guillaume@ruag.com

UNITED KINGDOM

Dr. John E. Moon
Airworthiness & Structural Integrity
QinetiQ, Building A7, Room 2043
Cody Technology Park, Ively Road
Farnborough, Hants, GU14 OLX, UK
jemoon@qinetiq.com

SWEDEN

Hans Ansell
Saab Aerosystems
Saab AB
SE-581 88 Linköping, Sweden
hans.ansell@saab.se

THE NETHERLANDS

Marcel J. Bos
National Aerospace Laboratory (NLR)
P.O. Box 153
NL-8300 AD Emmeloord, The Netherlands
bosm@nlr.nl

UNITED STATES OF AMERICA

Dr. Ravinder Chona
Structural Sciences Center
US Air Force Research Laboratory (AFRL /
RBSM)
Wright-Patterson Air Force Base
Ohio, USA
ravi.chona@wpafb.af.mil