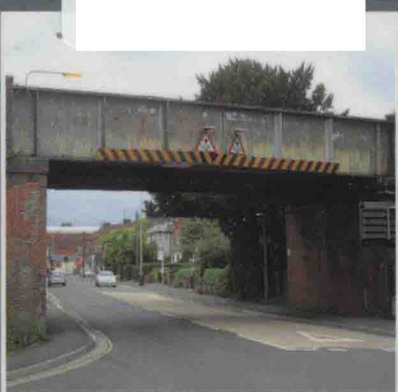
Woodhead Publishing Series in Civil and Structural Engineering



Rehabilitation of Metallic Civil Infrastructure using Fiber-reinforced Polymer (FRP) Composites

Edited by Vistasp M. Karbhari

WP
WOODHEAD PUBLISHING

Woodhead Publishing Series in Civil and Structural Engineering: Number 51

Rehabilitation of Metallic Civil Infrastructure using Fiber-reinforced Polymer (FRP) Composites

Edited by
Vistasp M. Karbhari

ELSEVIER

AMSTERDAM • BOSTON • CAMBRIDGE • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Woodhead Publishing is an imprint of Elsevier

WP
WOODHEAD PUBLISHING

Woodhead Publishing is an imprint of Elsevier
80 High Street, Sawston, Cambridge, CB22 3HJ, UK
225 Wyman Street, Waltham, MA 02451, USA
Langford Lane, Kidlington, OX5 1GB, UK

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Control Number: 2014931605

ISBN 978-0-85709-653-1 (print)
ISBN 978-0-85709-665-4 (online)

For information on all Woodhead Publishing publications visit our website at http://store.elsevier.com/

Typeset by Toppan Best-set Premedia Limited

Printed and bound in the United Kingdom

Rehabilitation of Metallic Civil Infrastructure using Fiber-reinforced Polymer (FRP) Composites

Related titles:

Eco-efficient construction and building materials
(ISBN 978-0-85709-767-5)

Advanced fibre-reinforced polymer (FRP) composites for structural applications
(ISBN 978-0-85709-418-6)

Developments in fiber-reinforced polymer (FRP) composites for civil engineering
(ISBN 978-0-85709-234-2)

This book is dedicated to Professor Len Hollaway, a pioneer in the field, who sadly died before this book was completed.

Contributor contact details

(* = main contact)

Editor and Chapter 1

Vistasp M. Karbhari
University of Texas at Arlington
Campus Box 19125
701 South Nedderman Drive
Arlington
TX 76019-0125, USA

E-mail: vkarbhari@uta.edu

Chapter 2

Alan A. Baker
Advanced Composite Structures Australia Pty Ltd (ACS-A)
1/320 Lorimer St
Port Melbourne
Victoria 3207, Australia

and

Aerospace Division
Defence Science and Technology Organisation
506 Lorimer Street
Fishermans Bend
Victoria 3207, Australia

E-mail: alan.baker@dsto.defence.gov.au; a.baker@acs-aus.com

Chapter 3

Reza Haghani
Department of Civil and Environmental Engineering
Chalmers University of Technology
Sven Hultinsgata 8
412 98 Gothenburg, Sweden

Email: reza.haghani@chalmers.se

Chapter 4

Mina Dawood
Department of Civil and Environmental Engineering
University of Houston
N107 Engineering Bldg 1
Houston
TX 77204-4003, USA

Email: mmdawood@uh.edu

Chapter 5

Kent A. Harries
Department of Civil and Environmental Engineering
University of Pittsburgh
742 Benedum Hall
Pittsburgh
PA 15261, USA

E-mail: kharries@pitt.edu

Chapter 6

Mike R. Bambach
Transport and Road Safety Research (TARS)
Old Main Building (K15)
University of New South Wales
Sydney, NSW 2052, Australia

E-mail: m.bambach@unsw.edu.au

Chapter 7

Fabio Matta*
Department of Civil and Environmental Engineering
University of South Carolina
300 Main Street
Room C210
Columbia
SC 29208, USA

E-mail: fmatta@sc.edu

Mina Dawood
Department of Civil and Environmental Engineering
University of Houston
N107 Engineering Bldg 1
Houston
TX 77204-4003, USA

Email: mmdawood@uh.edu

Chapter 8

Chris P. Pantelides
Civil and Environmental Engineering Department
University of Utah
110 South Central Campus Drive
Room 2000
Salt Lake City
UT 84112, USA

E-mail: c.pantelides@utah.edu

Chapter 9

Jun Deng*
School of Civil and Transportation Engineering
Guangdong University of Technology
No. 100 Waihuan Xi Road
Guangzhou Higher Education Mega Center
Guangzhou, 510006, China

Email: jdeng@gdut.edu.cn

Marcus M. K. Lee
Department of Civil and Construction Engineering
Curtin University Sarawak
CDT 250
98009 Miri, Sarawak, Malaysia

Email: marcus.lee@curtin.edu.my

Chapter 10

Pierluigi Colombi* and G. Fava
Department of Architecture, Built Environment and Construction Engineering ABC
Technical University of Milan (Politecnico di Milano)
Pizza L. da Vinci, 32
20133 Milan, Italy

E-mail: pierluigi.colombi@polimi.it

Chapter 11

Ron Barrett-Gonzalez*
Aerospace Engineering Department
2120 Learned Hall
The University of Kansas
Lawrence
KS 66045, USA

E-mail: adaptivebarrett@yahoo.com

Stanley Rolfe, Adolfo Matamoros and Caroline Bennett
Department of Civil, Architectural and Environmental Engineering
2150 Learned Hall
The University of Kansas
Lawrence
KS 66045, USA

E-mail: srolfe@ku.edu; amatamor@ku.edu; crb@ku.edu

Chapter 13

Alessio Pipinato
University of Padova
Department of Civil and Environmental Engineering
via Marzolo 9
35131 Padova, Italy

E-mail: alessio.pipinato@dicea.unipd.it

Chapter 14

Stuart Moy
Formerly of School of Civil Engineering and the Environment
University of Southampton
18 Leigh Road
Highfield
Southampton
SO17 1EF, UK

E-mail: ssjm@soton.ac.uk; S.S.Moy@soton.ac.uk

Woodhead Publishing Series in Civil and Structural Engineering

1 **Finite element techniques in structural mechanics**
C. T. F. Ross
2 **Finite element programs in structural engineering and continuum mechanics**
C. T. F. Ross
3 **Macro-engineering**
F. P. Davidson, E. G. Frankl and C. L. Meador
4 **Macro-engineering and the earth**
U. W. Kitzinger and E. G. Frankel
5 **Strengthening of reinforced concrete structures**
Edited by L. C. Hollaway and M. Leeming
6 **Analysis of engineering structures**
B. Bedenik and C. B. Besant
7 **Mechanics of solids**
C. T. F. Ross
8 **Plasticity for engineers**
C. R. Calladine
9 **Elastic beams and frames**
J. D. Renton
10 **Introduction to structures**
W. R. Spillers
11 **Applied elasticity**
J. D. Renton
12 **Durability of engineering structures**
J. Bijen
13 **Advanced polymer composites for structural applications in construction**
Edited by L. C. Hollaway
14 **Corrosion in reinforced concrete structures**
Edited by H. Böhni
15 **The deformation and processing of structural materials**
Edited by Z. X. Guo
16 **Inspection and monitoring techniques for bridges and civil structures**
Edited by G. Fu
17 **Advanced civil infrastructure materials**
Edited by H. Wu

18 **Analysis and design of plated structures Volume 1: Stability**
Edited by E. Shanmugam and C. M. Wang
19 **Analysis and design of plated structures Volume 2: Dynamics**
Edited by E. Shanmugam and C. M. Wang
20 **Multiscale materials modelling**
Edited by Z. X. Guo
21 **Durability of concrete and cement composites**
Edited by C. L. Page and M. M. Page
22 **Durability of composites for civil structural applications**
Edited by V. M. Karbhari
23 **Design and optimization of metal structures**
J. Farkas and K. Jarmai
24 **Developments in the formulation and reinforcement of concrete**
Edited by S. Mindess
25 **Strengthening and rehabilitation of civil infrastructures using fibre-reinforced polymer (FRP) composites**
Edited by L. C. Hollaway and J. C. Teng
26 **Condition assessment of aged structures**
Edited by J. K. Paik and R. M. Melchers
27 **Sustainability of construction materials**
J. Khatib
28 **Structural dynamics of earthquake engineering**
S. Rajasekaran
29 **Geopolymers: Structures, processing, properties and industrial applications**
Edited by J. L. Provis and J. S. J. van Deventer
30 **Structural health monitoring of civil infrastructure systems**
Edited by V. M. Karbhari and F. Ansari
31 **Architectural glass to resist seismic and extreme climatic events**
Edited by R. A. Behr
32 **Failure, distress and repair of concrete structures**
Edited by N. Delatte
33 **Blast protection of civil infrastructures and vehicles using composites**
Edited by N. Uddin
34 **Non-destructive evaluation of reinforced concrete structures Volume 1: Deterioration processes**
Edited by C. Maierhofer, H.-W. Reinhardt and G. Dobmann
35 **Non-destructive evaluation of reinforced concrete structures Volume 2: Non-destructive testing methods**
Edited by C. Maierhofer, H.-W. Reinhardt and G. Dobmann
36 **Service life estimation and extension of civil engineering structures**
Edited by V. M. Karbhari and L. S. Lee
37 **Building decorative materials**
Edited by Y. Li and S. Ren
38 **Building materials in civil engineering**
Edited by H. Zhang
39 **Polymer modified bitumen**
Edited by T. McNally

40 **Understanding the rheology of concrete**
Edited by N. Roussel
41 **Toxicity of building materials**
Edited by F. Pacheco-Torgal, S. Jalali and A. Fucic
42 **Eco-efficient concrete**
Edited by F. Pacheco-Torgal, S. Jalali, J. Labrincha and V. M. John
43 **Nanotechnology in eco-efficient construction**
Edited by F. Pacheco-Torgal, M. V. Diamanti, A. Nazari and C. Goran-Granqvist
44 **Handbook of seismic risk analysis and management of civil infrastructure systems**
Edited by F. Tesfamariam and K. Goda
45 **Developments in fiber-reinforced polymer (FRP) composites for civil engineering**
Edited by N. Uddin
46 **Advanced fibre-reinforced polymer (FRP) composites for structural applications**
Edited by J. Bai
47 **Handbook of recycled concrete and demolition waste**
Edited by F. Pacheco-Torgal, V. W. Y. Tam, J. A. Labrincha, Y. Ding and J. de Brito
48 **Understanding the tensile properties of concrete**
Edited by J. Weerheijm
49 **Eco-efficient construction and building materials: Life cycle assessment (LCA), eco-labelling and case studies**
Edited by F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha and A. de Magalhães
50 **Advanced composites in bridge construction and repair**
Edited by J. Kim
51 **Rehabilitation of metallic civil infrastructure using fiber-reinforced polymer (FRP) composites**
Edited by V. M. Karbhari
52 **Rehabilitation of pipelines using fiber-reinforced polymer (FRP) composites**
Edited by V. Karbhari
53 **Transport properties of concrete: Measurement and application**
P. A. Claisse

Preface

Worldwide, civil infrastructure is facing challenges of critical dimensions. On the one hand, the demands placed on infrastructure components and systems are increasing due to higher densities of population in urban areas and greater need for the faster and more efficient conveyance of goods and service from one point to another while, on the other hand, our existing infrastructure is aging (with a significant portion either beyond its service life or close to it) or functionally deficient in that it is unable to meet the demands currently being placed on it because of design limitations. As with all structures, the materials used in construction also deteriorate over time further increasing the limitations and causing concerns not just in terms of functionality of use, but also in terms of safety.

Among all infrastructure systems, those related to transportation infrastructure, especially roadways and networks, have drawn significant attention over the past two decades. In the US alone, the American Society of Civil Engineers in its 2013 Report Card for America's Infrastructure[1] stated that 'Over two hundred million trips are taken daily across deficient bridges in the nation's 102 largest metropolitan regions. In total, one in nine of the nation's bridges is rated as structurally deficient, while the average age of the nation's 607 380 bridges is currently 42 years. The Federal Highway Administration (FHWA) estimates that to eliminate the nation's bridge backlog by 2028, we would need to invest $20.5 billion annually, while only $12.8 billion is being spent currently.' The state of bridges and allied transportation infrastructure in Europe is no different, and is perhaps worse in South East Asia where tremendous construction activity took place in the early part of the latter half of the last century.

While significant attention has been paid to the challenges related to the rehabilitation of structural concrete used in bridges and affiliated infrastructure components and systems, attention has not been as focused on metallic and steel components although in many cases these are both

[1]ASCE 2013 Report Card for America's Infrastructure, http://www.infrastructurereportcard.org/a/#p/home.

more prevalent and older in age. While traditional methods of repair, such as bolting and riveting of additional strengthening sections and welding of others, can be used, they all suffer from two primary deficiencies in that the rehabilitation itself adds significant weight to the already under-capacity component or system, and that the technique is either not as reliable as needed, or takes too long (resulting in elongated periods of closure) or in itself causes further distress albeit in terms of different performance metrics (such as the addition of deleterious residual stresses initiated by welding).

Fiber-reinforced polymer (FRP) composites provide significant opportunities for the rehabilitation of metallic infrastructure components and systems and have attracted significant attention recently due to the ease of use in the field, light weight and ability to match both configuration and performance characteristics. It should be noted that, although the application of FRP composites to civil infrastructure is relatively new, the materials have a long, and successful, history of use in the naval/marine and aerospace sectors, where they have been used extensively both for the purpose of rapid repair in the field and for the extension of service life. There is, thus, a significant body of knowledge that is available for use in civil infrastructure based on application in other areas and it behooves us to take advantage of this rather than 'reinventing the wheel.'

Based on the increasing need for the development of a rapid, low weight technique for the rehabilitation of metallic infrastructure, especially as related to bridge components and systems, there has been a significant interest in the fields of research and field application of FRP materials for the rehabilitation of metallic components and systems. In a large number of cases, the FRP composites have been based on carbon fiber reinforcements due to the need for stiffness matching but, in some cases, the use of glass fibers can provide significant advantages. This volume provides an introduction to the overall topic, focusing on specific areas of interest and application, and should thus be considered as providing a synopsis of the topic rather than a comprehensive overview. For ease of reference and use it is divided into four parts.

Part I consists of a general introduction to materials and systems aspects (Chapter 1), a summary of the use of FRP for rehabilitation in the aerospace sector (Chapter 2), adhesive bonding (Chapter 3), and issues related to durability (Chapter 4). Chapter 2, specifically, provides a broad overview of the use of FRP composites in repair of metallic airframe components, an area that is now considered mature with a long history of successful use in the field. It is hoped that the inclusion of this chapter will serve two primary purposes – first to show that the technique can be implemented successfully even in areas where factors of safety are significantly lower than those in civil infrastructure, and second to assist in cross-fertilization between areas