FRP-Strengthened

Metallic Structures

Xiao-Ling
Zhao

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Preface

A significant number of metallic structures are aging. The conventional method of repairing or strengthening aging metallic structures often involves bulky and heavy plates that are difficult to fix and prone to corrosion, as well as to their own fatigue. Fibre-reinforced polymer (FRP) has great potential for strengthening metallic structures, such as bridges, buildings, offshore platforms, pipelines, and crane structures.

The existing knowledge of the carbon fibre-reinforced polymer (CFRP)–concrete composite system may not be applicable to the CFRP–steel system because of the distinct difference between their debonding mechanisms, alongside the unique failure modes for steel members and connections. Several design and practice guides on FRP strengthening of metallic structures have been published in the United Kingdom, the United States, Italy, and Japan. However, the following topics are not covered in detail: bond behaviour between FRP and steel, strengthening of compression members, strengthening of steel tubular members, strengthening against web crippling of steel sections, and strengthening for enhanced fatigue and seismic performance. This book contains not only descriptions and explanations of basic concepts and summarises the research performed to date on the FRP strengthening of metallic structures, but also provides some design recommendations. Comprehensive, topical references appear throughout the book. It is suitable for structural engineers, researchers, and university students who are interested in the FRP strengthening technique.

This book will provide a comprehensive treatment of the behaviour and design of FRP-strengthened metallic structures, especially steel structures, based on existing worldwide research. Chapters 1 and 2 outline the applications, existing design guidance, and special characteristics of FRP composites within the context of their use in the strengthening of metallic structures. Chapter 3 deals with the bond behaviour between FRP and metal. The strengthening of members is covered in Chapter 4 (bending), Chapter 5 (compression), and Chapter 6 (bearing forces). Chapter 7 provides a description of improvement of fatigue performance.

Chapter 4 is authored by Prof. Jin-Guang Teng at Hong Kong Polytechnic University and Dr. Dilum Fernando at the University of Queensland. I am appreciative of the comments from Prof. Jin-Guang Teng on the first three chapters; Dr. Yu (Barry) Bai at Monash University on Chapters 2 and 3; Prof. Dinar Camotim at Technical University of Lisbon, Prof. Amir Fam at Queen's University, and Prof. Amr Shaat at Ain Shams University on Chapter 5; Prof. Ben Young at the University of Hong Kong on Chapter 6; and Prof. Sing-Ping Chiew at Nanyang Technological University, Singapore, and Prof. Hitoshi Nakamura at Tokyo Metropolitan University on Chapter 7. I thank Dr. Mohamed Elchalakani at Higher Colleges of Technology, Dubai Men's College, for checking the design examples in Chapters 5 and 6.

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Notation

The following notation is used in this book. Where nondimensional ratios are involved, both the numerator and denominator are expressed in identical units. The dimensional units for length and stress in all expressions or equations are to be taken as millimetres and megapascals (N/mm^2), respectively, unless specifically noted otherwise. When more than one meaning is assigned to a symbol, the correct one will be evident from the context in which it is used. Some symbols are not listed here because they are only used in one section and are well defined in their local context.

A_{CFRP}	Area of the CFRP composites
A_{frp}	Cross-sectional area of the FRP laminate
$A_{eff,eq}$	Effective area of the equivalent steel section
$A_{eff,flange}$	Effective width of a flange in a lipped channel section
$A_{eff,lip}$	Effective width of a lip in a lipped channel section
$A_{eff,s}$	Effective area of a lipped channel section
$A_{eff,web}$	Effective width of web in a lipped channel section
A_{es}	Cross-sectional area of an equivalent steel section
A_s	Cross-sectional area of a steel section
A_t	Cross-sectional area of the equivalent section in the Shaat and Fam stub column model
A_1	Cross-sectional area of steel beam
C_{end}	Property (C_m) at final state (after the glass transition)
$C_{initial}$	Property (C_m) at initial state (ambient temperature)
C_m	Resin-dominated material property such as bending modulus, shear modulus, or shear strength
D_t	Transformed flexural rigidity
E_1	Modulus of elasticity of an isotropic plate
E_a	Modulus of elasticity of adhesive
E_{Al}	Modulus of elasticity of aluminium
E_c	Equivalent modulus of the composites
E_{CFRP}	Modulus of elasticity of CFRP
E_f	Modulus of elasticity of CFRP fibre

E_{frp}	Modulus of elasticity of FRP
$E_{L,c,cs}$	Young's modulus of the longitudinal carbon fibres in compression
$E_{L,t,cs}$	Young's modulus of the longitudinal carbon fibres in tension
E_{steel}	Modulus of elasticity of steel
$E_{T,c,cs}$	Young's modulus of the transverse carbon fibres in compression
$E_{T,t,cs}$	Young's modulus of the transverse carbon fibres in tension
F	Crack size–dependent correction factor
F_1	Ultimate bond strength under static load
$F_{1,d}$	Ultimate bond strength under static load for a bonded joint failing in debonding
F_2	Ultimate bond strength after a preset number of fatigue cycles
F_c	Force carried by CFRP composites
F_e	Correction factor for crack shape
F_g	Correction factor for stress gradient
F_h	Correction factor for eccentricity of crack against the central axis of the plate
F_s	Correction factor for surface crack or force carried by steel plate
F_t	Correction factor for finite thickness and width of plate
F_w	SIF reduction factor considering the influence of crack length and CFRP bond width
G_a	Shear modulus of adhesive
$G_a(T)$	Shear modulus of adhesive at a certain temperature T
G_f	Interfacial fracture energy defined by the area under the bond–slip curve
I_1	Second moment of area of steel beam
I_f	Second moment of area of CFRP composites
I_s	Second moment of area of a steel section
K_n	Normal stiffness of the adhesive layer
K_s	Stress intensity factor at crack tip or shear stiffness of the adhesive layer
$K_{s,max}$	Maximum stress intensity factor
$K_{s,min}$	Minimum stress intensity factor
L	Bond length or column length
L_e	Effective bond length
$L_e(T)$	Effective bond length at a certain temperature T
L_i	Distance of the ith strain gauge from the free end of the CFRP plate
$M_{b,rd}$	Inelastic lateral buckling moment
M_{cr}	Elastic lateral buckling moment
M_p	The plastic moment capacity per unit width

M_u	Ultimate moment carrying capacity
$M_{u,frp}$	In-plane moment capacity of the FRP-plated section assuming failure by FRP rupture
$M(x)$	Moment acting on the section at x distance from the plate end
M_x	Moment of the section when neutral axis depth is x
N	Number of fatigue cycles
$N_{c,E}$	Elastic global buckling capacity
$N_{c,D}$	Distortional buckling capacity
$N_{c,L}$	Local buckling capacity
N_{cr}	Elastic critical load for torsional buckling
N_D	Critical elastic distortional column buckling load
N_L	Critical elastic local column buckling load
$N_{s,T}$	Section capacity of T-section without FRP strengthening
$N_{y,s}$	Yield capacity of a CHS
$N(x)$	Axial force acting on the section at x distance from the plate end
P	Applied tensile load
P_a	Force in the adhesive
P_c	Force in the equivalent composites
P_f	Force in the FRP fibre
P_{max}	Maximum applied load in a fatigue test
P_n	Total peeling force to be resisted by an FRP end wrap
P_{ult}	Ultimate load carrying capacity or bond strength
$P_{ult}(T)$	Ultimate load carrying capacity at a certain temperature (T)
R	Tensile strain energy of the adhesive
R_b	Web bearing capacity
R_{bb}	Web bearing buckling capacity
R_{by}	Web bearing yield capacity
T	Average total thickness of the specimen at the joint or temperature
T_g	Glass transition temperature
$V(x)$	Shear force acting on the section at x distance from the plate end
a	Fatigue crack length
a_i	Initial size of crack
a_f	Final size of crack
b	Overall flange width of a metal section
b_b	Bearing load dispersion length
b_{CFRP}	Width of CFRP
b_c	Effective width of a concrete block in steel–concrete composite section
$b_{f,I}$	Width of an I-section flange i (i = 1, 2)
b_{flange}	Flange width of a lipped channel section

b_{frp}	Width of FRP laminate
b_{lip}	Lip width of a lipped channel section
b_s	Bearing length
b_{web}	Web width of a lipped channel section
d	Overall web depth of a metal section
$d_{eff,eq}$	Effective diameter of the equivalent steel section
d_{es}	Outside diameter of an equivalent CHS section
d_f	Flange depth of an LSB section
d_s	Outside diameter of a CHS
f_{cu}	Cube compressive strength of concrete
$f_{t,a}$	Tensile strength of adhesive
f_u	Ultimate tensile strength of metal
f_y	Tensile yield stress of metal
h_c	Height of the concrete block in a steel–concrete composite section
k	Effective length factor of columns
k_e	Effective buckling length factor defined in AS 4100
k_i	Factor used to define the level of strain in the ith layer with respect to the strain in the steel
k_n	Out-of-plane stiffness of adhesive
k_t	In-plane stiffness of adhesive in the transverse direction
k_u	In-plane stiffness of adhesive in the longitudinal direction
n	Number of CFRP layers on one side of the joint
n_{GFRP}	Number of GFRP sheets
n_L	Number of longitudinal FRP layers
n_T	Number of transverse FRP layers
r	Radius of gyration
r_{ext}	External corner radius of an RHS
r_i	Inner radius of a channel section
r_{int}	Internal corner radius of an RHS
r_t	Radius of gyration of a composite section
t	Wall thickness
t_a	Thickness of the adhesive between the steel plate and the first layer of CFRP
t_{a_layer}	Thickness of one layer of adhesive
t_{CFRP}	Thickness of CFRP sheet (including CFRP sheets and adhesive)
t_{CFRP_plate}	Thickness of one layer of CFRP plate
t_{CFRP_sheet}	Thickness of one layer of CFRP fibre sheet
t_{es}	Total thickness of steel and supplanted sections
$t_{es,cs}$	Thickness due to CFRP strengthening
t_f	Flange thickness of a metal section
t_{frp}	Thickness of the FRP laminate
$t_{L,cs}$	Thickness of the longitudinal carbon fibre sheet

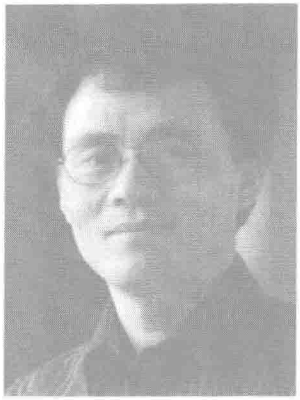
t_s	Wall thickness of a CHS or SHS or channel section
t_{steel}	Thickness of steel plate
$t_{T,cs}$	Thickness of the transverse carbon fibre sheet
t_w	Web thickness of a metal section
t_{we}	Equivalent web thickness
y_n	Neutral axis position
x	Neutral axis depth of an I-section (or plated I-section) from the top of the section
α	Fibre reinforcement factor
α_b	Section constant of compression members
α_c	Member slenderness reduction factor defined in AS 4100
α_g	Conversion degree of the glass transition
β_L	Modular ratio associated with the longitudinal fibres
β_T	Modular ratio related to the transverse fibres
χ	Strength reduction factor associated with global (flexural or flexural–torsional) buckling
Δ	Deformation under bearing load
ΔK_s	Range of stress intensity factor at the crack tip in a steel plate
ΔK_{th}	Threshold stress intensity factor below which fatigue crack does not propagate
$\Delta\sigma$	Stress range
δ_1	Initial slip in a bond–slip model
δ_2	Slip at the end of plateau in a bond–slip model
δ_f	Maximum slip in a bond–slip model
$\delta_{i+1/2}$	Slip at the middle point between the ith strain gauge and the i – 1th strain gauge
ε_c	Average strain of the composites
ε_{cc}	Compressive strain at the top of the concrete block
$\varepsilon_{CFRP,c}$	Average strain of CFRP
$\varepsilon_{c,i}$	Initial compressive strain
ε_{co}	Compressive strain of concrete at the first attainment of the peak axial stress
ε_{cr}	Average flexural buckling strain
ε_{cu}	Ultimate compressive strain of concrete
ε_{frp}	Average strain of the FRP laminate
ε_{frpl}	Limiting strain of the FRP laminate
$\varepsilon_{frp,I}$	Strain at intermediate debonding strength
ε_i	Reading of the ith strain gauge counted from the free end of the CFRP plate
ε_s	Average strain of the steel plate
$\varepsilon_{s,c}$	Strain at the top surface of the top (compression) flange of an I-section
$\varepsilon_{s,i}$	Strain at a depth of h_i from the top of an I-section

$\varepsilon_{s,t}$	Strain at the bottom surface of the bottom (tension) flange of an I-section
$\varepsilon_{t,i}$	Initial tensile strain
$\varepsilon_{u,CFRP}$	Ultimate tensile strain of CFRP composites
ϕ	Capacity factor
ϕ_x	Curvature of a beam with neutral axis depth x
γ_c	Material safety factor for concrete
γ_e	Adhesive elastic shear strain
$\gamma_e(T)$	Adhesive elastic shear strain at a certain temperature (T)
γ_{frp}	Partial safety factor for FRP composites
γ_{M1}	Partial safety factor for flexure
γ_p	Adhesive plastic shear strain
$\gamma_p(T)$	Adhesive plastic shear strain at a certain temperature (T)
γ_s	Material safety factor for steel
λ_{es}	Element slenderness for an equivalent CHS
λ_n	Modified compression member slenderness
λ_s	Element slenderness
λ_T	Nondimensional slenderness
ν	Poisson's ratio of steel
ν_a	Poisson's ratio of adhesive
ρ_c	Winter reduction factor in Bambach et al. stub column model
ρ_{es}	Winter reduction factor in modified EC3 model
ρ_f	Cross-sectional area ratio in Shaat and Fam column model
σ_c	Compressive stress of concrete
$\sigma_{cr,cs}$	Elastic buckling stress of a composite plate
σ_{ese}	Elastic buckling stress
σ_{frp}	Average stress of an FRP laminate
$\sigma_{frp,u}$	Ultimate strength of an FRP laminate
σ_{max}	Maximum value of the applied cyclic stress
σ_{min}	Minimum value of the applied cyclic stress
$\sigma_n(x)$	Interfacial normal stress at x distance from the plate end
σ_o	Nominal stress in steel plate
σ_{op}	Crack-opening stress
σ_s	Average stress over the steel section
$\sigma_{s,DB}$	Average stress at the nominal cross section of the steel plate for double-sided repair
$\sigma_{s,i}$	Steel stress at a depth of h_i from the top of an I-section
$\sigma_{s,SG}$	Average stress at the nominal cross section of the steel plate for single-sided repair
$\sigma_{s,y}$	Yield stress of an I-section beam
$\sigma_{y,c}$	Yield stress of corners in a cold-formed SHS
$\sigma_{y,s}$	Yield stress of a steel section
$\sigma_{y,c,eq}$	Equivalent yield stress for corners in a cold-formed SHS

$\sigma_{y,s,eq}$	Equivalent yield stress for flat faces in a cold-formed SHS
$\tau(x)$	Interfacial shear stress at x distance from the plate end
$\tau_{i+1/2}$	Shear stress at the middle point between the ith strain gauge and the i – 1th strain gauge
τ_f	Maximum shear stress in a bond–slip model
$\tau_f(T)$	Maximum shear stress in a bond–slip model at a certain temperature (T)
ξ	Proportioning factor
AA	Aluminium Association
ACFM	Alternating current field measurement (method)
ACPD	Alternating current potential drop (method)
AISC	American Institute of Steel Construction
AISI	American Iron and Steel Institute
ASI	Australian Steel Institute
AS/NZS	Australian/New Zealand Standard
ASTM	American Society for Testing and Materials
BEM	Boundary element method
CCT	Centre-cracked tensile (steel plates)
CFRP	Carbon fibre-reinforced polymer
CHS	Circular hollow section
CIRIA	Construction Industry Research and Information Association
CSA	Canadian Standards Association
DB	Double-sided (repair)
DMTA	Dynamic mechanical thermal analysis
DSC	Differential scanning calorimetry
DSM	Direct stress method
EC3	Eurocode 3
FEM	Finite element method
FRP	Fibre-reinforced polymer
GFRP	Glass fibre-reinforced polymer
GPa	Gigapascal (kN/mm^2)
HAZ	Heat-affected zone
HM	High modulus
ICE	Institution of Civil Engineers
IIFC	International Institute for FRP in Construction
JSSC	Japan Society of Steel Construction
kN	KiloNewton
LEFM	Linear elastic fracture mechanics
LSB	LiteSteel beam
MPa	Megapascal (N/mm^2)
m	Metre
mm	Millimetre
RHS	Rectangular hollow section
SG	Single-sided (repair)

SHS	Square hollow section
SIF	Stress intensity factor
TMA	Thermomechanical analysis
TRB	Transportation Research Board
UHM	Ultra-high modulus
UV	Ultraviolet

Author



Dr. Xiao-Ling Zhao obtained his BE and ME from Shanghai JiaoTong University, China, in 1984 and 1987, respectively. He received his PhD in 1992 and his Doctor of Engineering (higher doctorate) in 2012 from the University of Sydney. He also received an MBA (executive), jointly awarded by the University of Sydney and the University of New South Wales in 2007. After two years of postdoctoral research at the University of Sydney, Dr. Zhao joined Monash University in December 1994 as an assistant lecturer. He was appointed chair of structural engineering at Monash University in November 2001.

Dr. Zhao's research interests include tubular structures and FRP strengthening of structures. He has published 7 books, 5 edited special issues in international journals, and 180 Science Citation Index journal papers. He is a member of the editorial board for three international journals. Dr. Zhao has a strong history of attracting research funds through competitive grants and industry funding with a total of $10 million, including 17 Australian Research Council Grants. He has supervised 22 PhD students to completion.

Dr. Zhao's research excellence is demonstrated by the prestigious fellowships awarded by the Royal Academy of Engineering (UK), the Swiss National Science Foundation, the Alexander von Humboldt Foundation, the Japan Society for Promotion of Science, the Chinese "1000-talent" program, the Institute of Engineers Australia's Engineering Excellence Award, and the International Institute of Welding (IIW) Thomas Medal and Kurobane Lecture award.

Dr. Zhao has chaired the International Institute of FRP for Construction (IIFC) working group on FRP-strengthened metallic structures since 2005. He has chaired the IIW (International Institute of Welding) subcommission XV-E on Tubular Structures since 2002. He chaired the Australian/New Zealand Standards Committee CS/23 from 1998 to 2002. He was elected to the Fellows of American Society of Civil Engineers (ASCE), Engineers Australia (IEAust), and International Institute of FRP for Construction (IIFC). Dr. Zhao was head of the Department of Civil Engineering at Monash University, Australia, from 2008 to 2011.