

# Designers' Guide to EN 1992-1-1:2023: Eurocode 2

Strengthening of Existing Concrete Structures with  
Carbon Fibre Reinforced Polymer (CFRP)



Kaloyana Kostova and Craig Giaccio

---

# **Designers' Guide to EN 1992-1-1:2023: Eurocode 2**

*This page intentionally left blank*

---

# **Designers' Guide to EN 1992-1-1:2023: Eurocode 2**

## **Strengthening of Existing Concrete Structures with Carbon Fibre Reinforced Polymer (CFRP)**

**Kaloyana Kostova and Craig Giaccio**

---

**Published by Emerald Publishing Limited**, Floor 5,  
Northspring, 21–23 Wellington Street, Leeds LS1 4DL.

ICE Publishing is an imprint of Emerald Publishing Limited

**Other ICE Publishing titles:**

*Concise Guide to Reinforced Concrete Design to Eurocode 2*  
Patrick Purcell. ISBN 978-0-72776-572-7

*ICE Handbook of Concrete Durability*

Edited by Marios Soutsos. ISBN 978-0-72776-375-4

*Fibre-reinforced Concretes for High-performance Structures*

Andreas Lampropoulos. ISBN 978-0-72776-556-7

A catalogue record for this book is available from the British Library

ISBN 978-1-83549-935-1

© Emerald Publishing Limited 2025

Permission to use the ICE Publishing logo and ICE name is granted under licence to Emerald from the Institution of Civil Engineers. The Institution of Civil Engineers has not approved or endorsed any of the content herein.

All rights, including translation, reserved. Except as permitted by the Copyright, Designs and Patents Act 1988, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying or otherwise, without the prior written permission of the publisher, Emerald Publishing Limited, Floor 5, Northspring, 21–23 Wellington Street, Leeds LS1 4DL.

This book is published on the understanding that the author is solely responsible for the statements made and opinions expressed in it and that its publication does not necessarily imply that such statements and/or opinions are or reflect the views or opinions of the publisher. While every effort has been made to ensure that the statements made and the opinions expressed in this publication provide a safe and accurate guide, no liability or responsibility can be accepted in this respect by the author or publisher.

While every reasonable effort has been undertaken by the author and the publisher to acknowledge copyright on material reproduced, if there has been an oversight please contact the publisher and we will endeavour to correct this upon a reprint.

Cover photo: Maksim Ladouski/Alamy Stock Photo

Commissioning Editor: Michael Fenton

Content Development Editor: Ryan Molyneux

Books Production Lead: Benn Linfield

Typeset by KnowledgeWorks Global Limited

Index created by Lyn Nesbitt-Smith

---

# Contents

	Preface	ix
	Acknowledgements	xi
	About the Authors	xiii
	List of Symbols	xv
	List of Figures	xxi
<b>1</b> .....	<b>Introduction to fibre reinforced polymer strengthening systems for concrete structures</b>	<b>1</b>
	<b>General</b>	<b>1</b>
	Strengthening applications covered by the standard	3
	Production methods	3
	Product specification	4
	Assessment for strengthening	5
<b>2</b> .....	<b>Materials</b>	<b>7</b>
	General	7
	Partial factors	7
	Material properties	8
	Mechanical properties	8
	Strength and stiffness	9
	Limitation on use	9
	Determination of cross-sectional area	10
	Surface tensile strength of concrete	12
	Durability considerations	12
	In service and application temperature	12
	Moisture	13
	Exposure to ultraviolet light (UV)	13
	Alkaline and acidic environments	13
	Saline environments	13
	Freeze-thaw	13
<b>3</b> .....	<b>Anchorage of adhesively bonded CFRP systems</b>	<b>15</b>
	Introduction	15
	Bond resistance of EBR systems	15
	Surface tensile resistance of concrete	15
	Anchorage resistance and length (refined method)	17
	Simplified method for determining anchorage resistance and length	19
	Intermediate crack debonding	19
	End cover separation	21
	Shear induced separation	23
	End anchorage (curtailment requirements) for a member strengthened in flexure	25
	Bond resistance of NSM systems	27

---

<b>4</b> .....	<b>Shear</b>	<b>31</b>
	Introduction	31
	Shear strengthening of members not requiring shear reinforcement	31
	Shear strengthening of members with shear reinforcement	31
	Shear resistance of member	32
	Design shear strength of strengthening system	35
	Effective strut angle	36
	Additional forces in the longitudinal reinforcement	36
	Spacing of CFRP strips	37
	Compatibility and deformation capacity	37
	Example EBR shear 1: Shear strengthening with EBR CFRP strips	38
	Example EBR shear 2: Shear strengthening with open EBR CF sheets	42
	Example EBR shear 3: Shear strengthening with closed EBR CF sheets	44
	Torsion, combined actions and punching shear	45
<b>5</b> .....	<b>Flexural design</b>	<b>47</b>
	Introduction	47
	Ultimate cross-sectional resistance	47
	Considerations for EBR CFRP systems	50
	Simplified method for determining intermediate crack debonding action effects	50
	Case study – review of results from a detailed intermediate crack debonding check of a member strengthened in flexure with an EBR CFRP system	52
	Considerations for NSM CFRP systems	53
	Moment redistribution	55
	Additional considerations for the accidental limit state	55
	Example flexural design 1	56
	Example flexural design 2	65
	Design with strut and tie models and stress fields	71
	Example strut and tie: Pier strengthening	71
<b>6</b> .....	<b>Columns</b>	<b>75</b>
	Introduction	75
	Confinement	75
	General formulation	78
	Circular columns	78
	Square or rectangular columns	79
	General constitutive model for concrete in compression confined with CFRP	80

---

	Eccentricity limit	81
	Slenderness	82
	Axial and bending (NM) interaction	83
	Columns confined and strengthened in flexure	83
	Example confinement 1: Strengthening of circular column with continuous wrapped system	86
	Example confinement 2: Strengthening of square column with continuous wrapped system	89
	Example confinement 3: Strengthening of circular column with discrete CFRP strips	92
<b>7</b> .....	<b>Serviceability</b>	<b>95</b>
	Introduction	95
	Stress limits	95
	Example EBR serviceability 1: Stress checks	99
	Example EBR serviceability 2: Concrete stress limits in a prestressed concrete slab	101
	Crack width	106
	Example EBR serviceability 3: Crack width	106
	Deflection control	109
	Example EBR serviceability 4: Deflection	109
<b>8</b> .....	<b>Fatigue</b>	<b>115</b>
	Introduction	115
	EBR CFRP systems	115
	Simplified fatigue design method for EBR CFRP systems	115
	Refined fatigue design method for EBR CFRP systems	117
	Determination of force difference	119
	Example EBR fatigue 1: Simplified method for fatigue evaluation	119
	Example EBR fatigue 2: Refined method for single stress range	123
	Example EBR fatigue 3: Refined method SN curve	124
<b>9</b> .....	<b>Detailing</b>	<b>129</b>
	Introduction	129
	Flexural strengthening with NSM	129
	Strengthening with EBR strips and sheets	132
	Flexural strengthening	132
	Multi-layered systems	132
	Orthogonal systems	133
	Shear strengthening	133
	Anchorage of fully wrapped systems	134
	Bending of prefabricated CFRP elements	135

---

<b>10</b> .....	<b>Considerations for execution</b>	<b>137</b>
	Introduction	137
	Adequacy of substrate for strengthening	137
	Surface preparation and installation considerations for EBR systems	138
	Surface preparation for NSM systems	140
	Fire performance	141
<b>11</b> .....	<b>References</b>	<b>143</b>
<b>Annex A</b> .....	<b>Flow chart for flexural design of a member</b>	<b>147</b>
<b>Annex B</b> .....	<b>Ultimate limit states design examples</b>	<b>151</b>
	Example flexural design B-1 (EBR CF sheets)	151
	Example flexural design B-2 (CFRP strips)	164
	Example flexural design B-3 (NSM CFRP)	174
<b>Annex C</b> .....	<b>Crack width calculation to fib Bulletin No. 90</b>	<b>181</b>
<b>Annex D</b> .....	<b>Determination of compression force and lever arm at a section using BS EN 1992-1-1:2023, Formula 8.4</b>	<b>185</b>
	Approach to determining solution	186
	Case 1: $\varepsilon_c \leq \varepsilon_{c2}$	187
	Derivation of compression force	187
	Derivation of the distance of the force from the outermost compression fibre	188
	Case 2: $\varepsilon_{c2} \leq \varepsilon_c \leq \varepsilon_{cu}$	189
	Derivation of compression force	189
	Derivation of the distance of the force from the outermost compression fibre	191
<b>Annex E</b> .....	<b>Determination of compression force and lever arm at a section using BS EN 1992-1-1:2023, Formula 5.6</b>	<b>195</b>
	Derivation of compression force	196
	Derivation of lever arm	198
	<b>Index</b>	<b>201</b>

---

# Preface

## Scope and field of application

The information contained in the informative Annex J of *BS EN 1992-1-1:2023* (BSI, 2023b) is intended to provide the designer with rules specific to the strengthening of structures with adhesively bonded carbon fibre reinforced polymer (CFRP) strengthening systems.

The standard covers the following adhesively bonded reinforcement (ABR).

- Externally bonded reinforcement (EBR) systems, including
  - prefabricated carbon fibre reinforced polymer (CFRP) strips
  - carbon fibre (CF) sheets or pre-impregnated laminates.
- Near surface mounted (NSM) systems comprising either
  - NSM CFRP strips
  - NSM CF bars
  - NSM CF rods.

In the vast majority of cases, the design rules for CFRP link to the provisions in *BS EN 1992-1-1:2023* as a whole to ensure consistency. Instances where this does not occur are acknowledged in this book, and an explanation provided for why this has occurred.

Strengthening of concrete structures with CFRP has become fairly common around the world. However, limitations on available testing results to cover all scenarios encountered in design became evident in the development of design rules contained in Annex J.

No provisions were given in the second generation Eurocode related to design of CFRP strengthening systems for fire resistance.

## Aim of this guide

The aim of this book is to provide practising design engineers and other code users with examples of the implementation of the provisions of *BS EN 1992-1-1:2023* pertaining to strengthening of concrete members with CFRP. It also aims to provide an understanding of some of the basic principles used in *BS EN 1992-1-1:2023* regarding strengthening of structures with CFRP systems.

The book is aimed at practising engineers who have a sound grasp of structural engineering principles, in particular the principles that apply to reinforced and prestressed concrete design. It does not set out to reproduce significant volumes of information pertaining to manufacturing methods of CFRP systems. It does, however, include pertinent information where required to support the basic understanding as to how the system works or why certain approaches were taken in the development

---

of the standard, as well as key points about the system and its execution that may influence design decisions.

In writing this book, the authors observed that some additional content could be provided to help designers implement the provisions in *BS EN 1992-1-1:2023*. They have sought to provide this additional content, in particular noting the source of where this has come from. This is intended to inform readers where additional content would support undertaking design, and provide the authors' opinion of how they would resolve any gaps. Designers and other code users are encouraged to make their own assessment of recommendations made in this book outside of the provisions of the standard, and to make their own informed decisions as to how to implement the provisions of the standard.

### **Layout of this guide**

The British Standard *BS EN 1992-1-1:2023* has a national foreword and 14 sections, together with 19 annexes. Annex J, which is the subject of this design guide, consists of 15 subsections numbered J.1 to J.15.

The layout of the guide is not aligned with the structure of *BS EN 1992-1-1:2023*. Instead, it uses Harvard referencing style and italics font to cite relevant parts of the code. Quotations from other sources, including other Eurocodes, and cross-references to sections, etc., of this guide, are in roman type. As the guide contains five annexes, it must be noted that none of them is aligned with a particular annex in *BS EN 1992-1-1:2023*.

When the standard is first introduced in a chapter, full in-text citation is used, i.e. *BS EN 1992-1-1:2023* (BSI, 2023b). When repeated, in-text citations are shortened to *BS EN 1992-1-1:2023*. Sections, clauses, expressions, figures and tables usually follow the code citation separated by a comma – for example

*BS EN 1992-1-1:2023*, J.5;

*BS EN 1992-1-1:2023*, J.11.1.2.5;

*BS EN 1992-1-1:2023*, Formulae 8.56 to 8.62;

*BS EN 1992-1-1:2023*, Figure J.3;

*BS EN 1992-1-1:2023*, Table 4.3.

Alternatively, the cross-reference may be described as part of the code – for example, Section 3 of *BS EN 1992-1-1:2023*.

---

## Acknowledgements

The authors would like to acknowledge the contribution of Professor Antony Darby from the University of Bath, UK. Professor Darby has provided valuable insight into the background on a number of areas in this book and supported the authors by reviewing this material. His contribution has been very valuable.

The authors would like to acknowledge and thank Concrete Repairs Limited for providing a selection of photos for use in this book. This has enabled the authors to provide what, in their view, is a well-balanced combination of theoretical descriptions and real photographic descriptions of the material, applications and unique considerations that apply for strengthening concrete structures with CFRP.

Craig would like to extend his gratitude to his family for their unwavering support, patience and encouragement throughout the development of this work. Without their understanding during long hours of research and writing, completing this book would not have been possible. Craig's wife's constant belief in his work and steadfast support has been a source of strength. His daughter's curiosity and enthusiasm has reminded him of the importance of perseverance and advancing knowledge.

*This page intentionally left blank*

---

## About the Authors

Dr Kaloyana Kostova PhD CEng FICE is a Fellow of the Institution of Civil Engineers with practical and research experience in the field of structural engineering. She holds a PhD in Civil Engineering from the University of Bath where her studies were focused on the use of fibre-reinforced polymer (FRP) reinforcement in structural concrete cast in fabric formwork.

In 2017 Kaloyana joined the Eurocode development project team working on the addition of new items in the next generation of EN 1992-1-1, including FRP strengthening of reinforced concrete structures, use of FRP embedded reinforcement, stainless steel reinforcement, assessment of existing structures and steel fibre reinforced concrete (SFRC). She continued her involvement in the development of standards as a co-opted member of the B/525/2 committee on 'Structural use of concrete', a member of the ISO/TC 071/SC 06 committee on 'Non-traditional reinforcing materials for concrete' and a member of fib Task Group 5.1 on 'FRP reinforcement for concrete structures'. She also has a strong interest in research on fire safety and durability of FRP composites as key questions in the adoption of these materials.

In 2021 Kaloyana joined the National Composites Centre (NCC) in the UK, where she leads a structural analysis team delivering innovative FRP composites design for different sectors, including construction, wind, hydrogen, aerospace and marine. Prior to her deep dive in exploitation of composites at NCC, Kaloyana spent most of her career as a bridge designer working for Tony Gee and Partners and, earlier, for Scott Wilson. Her experience varied from bridge investigations, assessments and strengthening schemes to new bridge designs, including FRP strengthening of existing structures and new FRP composite bridges.

Kaloyana first explored FRP composites for their potential as a reinforcing material for concrete during her PhD studies under a Leverhulme Trust grant on 'A new form of architecture for concrete structures'. She developed an optimisation tool for structural analysis of concrete formed using an innovative flexible formwork system and reinforced with various types of FRP due to their flexibility and light weight, as well as offering a novel end anchorage for FRP bars. She also had an early experience in design and construction of buildings, following her graduation from the University of Architecture, Civil Engineering and Geodesy in Bulgaria.

Kaloyana is actively involved in developing capabilities within industry, dissemination of knowledge and improving regulations, as well as creating methods and technologies aimed at shaping the future of engineering.

---

Dr Craig Giaccio BE Civil (Hons), PhD (Eng), FICE, FIEAust, CPEng, NER, APEC Engineer, IntPE(Aus) is a chartered civil engineer with over 27 years of experience that spans design delivery of major infrastructure projects through to development of codes and standards for structural engineering. Craig is a Fellow of the Institution of Civil Engineers and the Institution of Engineers Australia. He is presently a Technical Director at Hewson Consulting, UK.

He is currently Deputy Chair of the B525/2 committee and the National Annex Group responsible for preparing the National Annex and Published Document for *BS EN 1992-1-1:2023*. This commission follows a previous commission where he led a project team developing material for the new concrete design standard. He is also an active member of fib Task Group T5.1 on fibre reinforced polymer reinforcement.

Craig has played a key role in the delivery of an array of structural and civil engineering projects. This includes major infrastructure projects such as Queensferry Bridge and HS2. He has additionally undertaken a significant number of commissions involved in assessment and remediation of aging concrete structures in the UK and Australia.

Additionally, Craig has a track record of supporting the development of the profession. He was the Chief Editor of the *ICE Bridge Engineering Journal* from 2017 to 2023, and reviews technical submissions for the *ACI Structural Journal* and the *Australian Journal of Structural Engineering*.

---

## List of Symbols

Where possible, symbols have been adopted from BS EN 1992-1-1:2023 (BSI, 2023b). In some instances, additional symbols have been used for descriptive purposes as outlined below.

$A_{equiv}$	Equivalent effective area of tension steel of a member strengthened with CFRP with the CFRP transformed into an equivalent steel layer and all tension reinforcement layers combined as a single layer
$A_{f,eff}$	Transformed CFRP area to steel
$A_{f,1}$	Area of a single CFRP sheet
$A_{sc,i}$	Area of compression steel of the $i^{th}$ layer of tension reinforcement with $i = 1$ corresponding to the layer of compression reinforcement with the highest compression stress for members in flexure
$A_{st,i}$	Area of tension steel of the $i^{th}$ layer of tension reinforcement with $i = 1$ corresponding to the layer of tension reinforcement with the highest tension stress for members in flexure
$F_c$	Compression force in concrete
$F_{ct}$	Tension force in concrete
$F_{equiv}$	Combined tension components of the cross section
$F_f, F_{fEd}$	Force in the CFRP reinforcement
$F_{fEd,max}$	Force in the CFRP reinforcement generated by the lower value of fatigue loading
$F_{fEd,min}$	Force in the CFRP reinforcement generated by the upper value of fatigue loading
$F_s$	Force in the steel reinforcement
$F_{st}$	Design force in the CFRP shear stirrup resisting end cover separation
$\Delta F_{fEd,max}$	Maximum value of $\Delta F_{fEd,fat}$ between two cracks under the fatigue load combination being considered

---

$\Delta F_{fk,B}$	Bond resistance between cracks
$I_{cr,post}$	Post-strengthening cracked second moment of area (moment of inertia)
$I_{cr,pre}$	Pre-strengthening cracked second moment of area (moment of inertia)
$M_{Ed,shift}$	Design value of the applied bending moment after applying the shift rule
$M_{Ed,SLS}$	Design value of the applied bending moment at SLS
$M_{Ed,str}$	Design value of the applied bending moment at strengthening
$M_p$	Prestressing bending moment
$M_{post}$	Additional applied bending moment after strengthening (equal to the difference of the total applied moment and the moment applied at strengthening)
$M_{Rd,pre}$	Design value of bending moment resistance of the unstrengthened reinforced or prestressed concrete member
$\Delta M_{Ed}$	Applied bending moment difference between cracks
$N_{Rd,pre}$	Design value of axial resistance of the unstrengthened reinforced or prestressed concrete member
$T_g$	Glass transition temperature
$a_{\delta,post}$	Total deflection generated by the additional applied bending moment after strengthening $M_{post}$
$a_{I,post}, a_{II,post}$	Value of $a_{\delta,post}$ calculated for uncracked and fully cracked conditions, respectively
$a_{\delta,pre}$	Total deflection generated by the applied bending moment at strengthening $M_{Ed,str}$
$a_{I,pre}, a_{II,pre}$	Value of $a_{\delta,pre}$ calculated for uncracked and fully cracked conditions, respectively

---

$d_{equiv}$	Equivalent effective depth of a member strengthened with CFRP strengthening with the CFRP transformed into an equivalent steel layer and all tension reinforcement layers combined as a single layer
$d_f$	Effective depth of CFRP reinforcement
$d_{fv}$	Effective depth of CFRP strengthening, measured from the top of CFRP shear strengthening to the steel tension reinforcement
$d_{sc,i}$	Effective depth of compression steel of the $i^{th}$ layer of tension reinforcement with $i=1$ corresponding to the layer of compression reinforcement with the highest compression stress for members in flexure
$d_{st,i}$	Effective depth of compression steel of the $i^{th}$ layer of tension reinforcement with $i=1$ corresponding to the layer of tension reinforcement with the highest tension stress for members in flexure
$d_{st}$	Effective depth of total steel reinforcement in tension
$f_{bfk,max}$	Characteristic maximum resistance of an end anchorage
$f_{bfRd}^*$	Adhesive bond resistance component of the intermediate crack resistance to be used for simplified fatigue design method
$\Delta f_f$	Stress change in CFRP under the fatigue load combination
$\Delta f_{fRd, fat2}$	Fatigue stress in the CFRP system subject to $N^*$ stress cycles
$h_f$	Height of shear strengthening
$h_{max}$	Maximum distance from centre of gravity to extreme concrete fibre
$k_1$	Concrete strength reduction factor
$k_2$	Factor for the depth of resultant compression force
$n_s$	Factor depending on the configuration of the CFRP shear strengthening system (fully wrapped or open)

---

$n$	Total number of CFRP stirrups crossing a crack
$m$	Number of CFRP stirrups crossing a crack with anchorage length less than characteristic maximum value of effective bond length
$p_f$	Bonded perimeter of the EBR CFRP system
$q_{Ed,SLS}$	Applied UDL at SLS
$q_{Ed,str}$	Applied UDL at strengthening
$s$	Slip of the CFRP reinforcement or spacing of steel shear reinforcement
$s_{f1k}$	Slip of the CFRP reinforcement at maximum bond stress
$s_{f,max}$	Maximum spacing of individual CFRP strips
$z_m$	Lever arm between tension and compression forces in a member subject to flexure for use with the simplified method for determining internal forces and stresses for intermediate crack debonding checks
$a_{fE}$	Distance between the end of the CFRP strengthening and the nearest point of zero moment (including a point of contraflexure in a hogging zone)
$\beta$	Angle of inclination of a CFRP shear strengthening relative to an axis perpendicular to the span of the member being strengthened
$\varepsilon_{bot}$	Strain in concrete at the outermost tension fibre
$\varepsilon_{cu,c}$	Ultimate compression strain of concrete confined with CFRP, which has value of 0.006 unless more accurate information is available
$\varepsilon_{c2,c}$	Compressive strain concrete, at which the bilinear stress strain curve for concrete confined with CFRP changes gradient, taken as 0.00175
$\varepsilon_{c,post}$	Strain in concrete generated by the additional applied bending moment after strengthening $M_{post}$

---

$\varepsilon_{c,pre}$	Strain in concrete generated by the applied bending moment at strengthening $M_{Ed,str}$
$\varepsilon_{equiv}$	Equivalent strain in tension reinforcement of a member strengthened with CFRP, with the CFRP transformed into an equivalent steel layer and all tension reinforcement layers combined as a single layer
$\varepsilon_f$	Strain in CFRP reinforcement
$\varepsilon_{h,rupt}$	Hoop rupture strain of CFRP confining reinforcement
$\varepsilon_{top}$	Strain in concrete at the outermost compression fibre
$\varepsilon_{sc,i}$	Strain in the $i^{th}$ layer of compression reinforcement with $i=1$ corresponding to the layer of compression reinforcement with the highest compression stress for members in flexure
$\varepsilon_{st,i}$	Strain in the $i^{th}$ layer of tension reinforcement with $i=1$ corresponding to the layer of tension reinforcement with the highest tension stress for members in flexure
$\varepsilon_0$	Strain at the soffit of a reinforced or prestressed concrete member at the time of strengthening (also called CFRP pre-strain)
$\kappa_h$	Factor determining the contribution of clamping force to the intermediate crack debonding resistance
$\lambda_{crit}$	Limiting slenderness for isolated members below which second order effects may be neglected for CFRP strengthened columns
$\sigma_{equiv}$	Equivalent stress in tension reinforcement of a member strengthened with CFRP, with the CFRP transformed into an equivalent steel layer and all tension reinforcement layers combined as a single layer
$\sigma_f$	Stress in the CFRP reinforcement
$\sigma_{c,post}$	Stress in concrete generated by the additional applied bending moment after strengthening $M_{post}$

---

$\sigma_{c,pre}$	Stress in concrete generated by the applied bending moment at strengthening $M_{Ed,str}$
$\sigma_{s,post}$	Stress in steel generated by the additional applied bending moment after strengthening $M_{post}$
$\sigma_{s,pre}$	Stress in steel generated by the applied bending moment at strengthening $M_{Ed,str}$
$\sigma_{sc,i}$	Strain in the $i^{th}$ layer of compression reinforcement with $i=1$ corresponding to the layer of compression reinforcement with the highest compression stress for members in flexure
$\sigma_{st,i}$	Strain in the $i^{th}$ layer of tension reinforcement with $i=1$ corresponding to the layer of tension reinforcement with the highest tension stress for members in flexure
$\tau_b(s)$	Bond-slip law describing the relationship between the shear stress between the CFRP and concrete substrate and the slip required to generate this shear stress
$x_{post}$	Depth of the neutral axis corresponding to the additional applied bending moment after strengthening $M_{post}$
$x_{pre}$	Depth of the neutral axis corresponding to the applied bending moment at strengthening $M_{Ed,str}$

---

# List of Figures

Figure 1.1	Illustration of beams strengthened in flexure with strengthening systems covered in Annex J (Adapted from <i>BS EN 1992-1-1:2023</i> )	2
Figure 1.2	Illustration of shear strengthening with deep embedded FRP strengthening method	2
Figure 1.3	CFRP strengthening systems covered by <i>BS EN 1992-1-1:2023</i>	3
Figure 2.1	Typical stress-strain diagram for the CFRP material	8
Figure 2.2	Illustration of potential sources of moisture ingress (Adapted from fib Bulletin No. 90 (fib, 2019))	13
Figure 3.1	EBR CFRP failure mechanisms	16
Figure 3.2	Pull-off testing (Photographs courtesy of Concrete Repairs Limited UK)	16
Figure 3.3	Definition of concrete casting positions for determining $k_{c,surf}$	17
Figure 3.4	General form of bond-slip relationship for EBR CFRP systems (Reproduced from fib Bulletin No. 90 (fib, 2019) using characteristic values)	18
Figure 3.5	Illustration of an element of concrete strengthened with EBR CFRP between cracks	19
Figure 3.6	End cover separation failure mode	21
Figure 3.7	Illustration of force system causing end cover separation	22
Figure 3.8	Illustration of vertical component of force to be resisted by additional stirrup for end cover separation	23
Figure 3.9	Illustration of vertical dislocation at shear cracks	24
Figure 3.10	Curtailement of EBR CFRP systems	26
Figure 3.11	Definition of inner shear lever arm (Taken from <i>BS EN 1992-1-1:2023</i> , Figure 8.9)	26
Figure 4.1	Types of EBR CFRP shear strengthening covered by <i>BS EN 1992-1-1:2023</i> (Reproduced from <i>BS EN 1992-1-1:2023</i> )	32
Figure 4.2	Terminology for shear strengthening with EBR CFRP strips (Reproduced and modified from <i>BS EN 1992-1-1:2023</i> )	35
Figure 4.3	Beam details for EBR shear strengthening example 1	38
Figure 4.4	Beam details for EBR shear strengthening example 2	43
Figure 4.5	Beam details for EBR shear strengthening example 3	44

---

Figure 5.1	Illustration of superposition required to determine strain in cross section of member subjected to flexure	48
Figure 5.2	Force balance in a doubly reinforced cross section strengthened in flexure with EBR CFRP (Adapted from fib Bulletin No. 90 (fib, 2019))	49
Figure 5.3	Flexural strengthening zones for EBR CFRP systems	52
Figure 5.4	Case study of a beam strengthened in flexure to identify areas where intermediate crack debonding governs	54
Figure 5.5	Cross-sectional information for example flexural design 1 – all dimensions are in mm unless stated otherwise	56
Figure 5.6	Cross-sectional information for example flexural design 2 – all dimensions are in mm unless stated otherwise	65
Figure 5.7	Applied and resistance bending moments including shift diagram for example flexural design 2	66
Figure 5.8	Force in CFRP and end anchorage resistance for example flexural design 2	67
Figure 5.9	Force in CFRP and steel (a) and force difference in CFRP (b) for example flexural design 2	68
Figure 5.10	Example strut and tie strengthening of bridge pier CFRP NSM strengthening details – all dimensions are in mm unless stated otherwise	71
Figure 6.1	Illustration of full height column wrapping with CFRP (Photo courtesy of Concrete Repairs Limited (UK))	76
Figure 6.2	Definition of geometric symbols for confinement provisions (Copied from <i>BS EN 1992-1-1:2023</i> , Figure J.2)	77
Figure 6.3	Confinement mechanism and illustration of strengthening with CFRP strips (Adapted from TR55 (Concrete Society, 2013))	77
Figure 6.4	Example stress-strain diagram for a concrete member confined by CFRP strengthening	81
Figure 6.5	Flow chart for developing column curve using provisions of <i>BS EN 1992-1-1:2023</i>	85
Figure 6.6	Example confinement 1 circular column with continuous wrapped system strengthening – all dimensions are in mm unless stated otherwise	86
Figure 6.7	Example confinement 1 concrete: (a) concrete stress-strain curves, (b) NM interaction curve for the strengthened section	88

---

Figure 6.8	Example confinement 2 rectangular column with continuous wrapped system strengthening – all dimensions are in mm unless stated otherwise	89
Figure 6.9	Example confinement 2: (a) concrete stress-strain curves, (b) NM interaction curve for the strengthened section	92
Figure 6.10	Example confinement 3: (a) concrete stress-strain curves, (b) NM interaction curve for the strengthened section	93
Figure 7.1	Arbitrary section for flexural strengthening	96
Figure 7.2	Stress superposition at serviceability limit state	97
Figure 7.3	Example post-tensioned slab original details – all dimensions are in mm unless stated otherwise	102
Figure 7.4	Stress distribution at SLS – post-tensioned slab	104
Figure 7.5	Stress distribution at strengthening – post-tensioned slab	105
Figure 7.6	Strain distribution after strengthening – post-tensioned slab	105
Figure 7.7	Strengthened beam for calculating deflection	110
Figure 8.1	CFRP fatigue stress range under a combination of actions	116
Figure 8.2	Strengthened beam for calculating SN curve	119
Figure 8.3	SN curve for EBR fatigue example 3	128
Figure 9.1	Illustration of the NSM system and the interaction with steel reinforcement (Image courtesy of Concrete Repairs Limited UK)	130
Figure 9.2	Symbols describing geometry of the NSM slot and clearances (Reproduced from <i>BS EN 1992-1-1:2023</i> and amended)	131
Figure 9.3	Termination of multi-layered EBR CFRP	134
Figure 9.4	Wrapping a concrete column with multiple plies	134
Figure 10.1	Removal of deteriorated concrete pre-strengthening (Photo courtesy of Concrete Repairs Limited UK)	138
Figure 12.1	General flow chart for analysis of CFRP strengthened sections	148
Figure 12.2	Layer-by-layer calculation of forces in concrete	148
Figure 12.3	Flow chart for finding pre-strain in concrete	149
Figure 12.4	Strain profiles before and after strengthening including the additional moment	149
Figure 12.5	Flow chart for finding strengthened moment capacity when concrete fails in compression first	150
Figure 13.1	T-beam cross section and loading configuration – all dimensions are in mm unless stated otherwise	151

---

Figure 13.2	T-beam strain distribution at strengthening all dimensions are in mm	155
Figure 13.3	T-beam strain distribution at ULS for CFRP rupture – CF sheets strengthening all dimensions are in mm	156
Figure 13.4	Applied and resistance bending moments including shift diagram	158
Figure 13.5	Force in CFRP and end anchorage resistance – CF sheets strengthening	160
Figure 13.6	Stress in reinforcement (a) and force difference in CFRP (b) - CF sheet strengthening	161
Figure 13.7	Strain distribution at ULS for CFRP rupture – CFRP strips strengthening all dimensions are in mm	166
Figure 13.8	Force in CFRP and end anchorage resistance – CFRP strips strengthening	167
Figure 13.9	Force in CFRP and steel (a) and force difference in CFRP (b) – CFRP strips	168
Figure 13.10	End shear stirrup to prevent end cover separation – CFRP strips strengthening all dimensions are in mm	171
Figure 13.11	Strain distribution at ULS for CFRP rupture – NSM strengthening all dimensions are in mm	177
Figure 13.12	Applied and resistance bending moments including shift diagram – NSM strengthening	177
Figure 13.13	Force in CFRP and end anchorage resistance – NSM strengthening separation	178
Figure 13.14	End shear stirrup to prevent end cover separation – NSM strengthening all dimensions are in mm	180
Figure 14.1	Flow chart summarising the crack width calculation provided in fib Bulletin No. 90 (fib, 2019)	181
Figure 15.1	Arbitrary rectangular cross section	185
Figure 15.2	Stresses and strains in compression region for case 2	189

Kaloyana Kostova and Craig Giaccio

ISBN 978-1-83549-935-1

<https://doi.org/10.1108/978-1-83549-934-420251001>

Emerald Publishing Limited: All rights reserved

# Chapter 1

## Introduction to fibre reinforced polymer strengthening systems for concrete structures

### General

Fibre reinforced polymer (FRP) strengthening of concrete structures has become more commonly used over the last couple of decades. FRP strengthening systems rely on high-strength tension fibres contained within a fibre/polymer matrix to provide additional tensile strength to concrete structural members subjected to flexure, shear and torsion, or to confine concrete columns to increase compression resistance. Commonly used FRP strengthening systems comprise either carbon, aramid, glass or basalt fibres. Efficient use of FRP material is achieved by aligning fibres with the tension forces that are resisted in a structure being strengthened or those that arise from confining effects.

FRP strengthening systems obtain their structural properties from the fibres that are embedded within a polymer matrix. The surrounding polymer matrix binds the fibres together and facilitates load share between them. The surrounding polymer material can also provide resilience against accidental impacts as well as protection from environmental conditions such as ultraviolet (UV) light. There are a variety of systems on the market, some have uni-directional fibres and some have multidirectional fibres.

FRP strengthening is commonly achieved by adhering an FRP fabric or plate to the exterior surface or notching the surface to embed a bar or rod, as shown in [Figure 1.1](#). Other systems that are used with some frequency include embedding FRP bars or rods within concrete members or fixing prestressed FRP to external surfaces of a concrete member fastened to a concrete surface with mechanical anchors. An illustration of the deep embedment technique is shown in [Figure 1.2](#). The systems shown in [Figure 1.1](#) are the only systems covered by *BS EN 1992-1-1:2023* (BSI, 2023b).

FRP strengthening continues to become more popular with time because it has a higher tensile strength than steel. This means that the weight of structural components used for strengthening is lower than it would be with steel, bringing installation benefits and adding relatively little dead load to a structure. FRP is also a very light and easy-to-transport solution compared to solutions such as steel plate strengthening.

It has disbenefits on cost. Material costs are generally higher than steel. Labour costs of surface preparation are additional to this. Therefore, the selection of the system needs to carefully consider all aspects of installation prior to ensuring its economic viability.

Figure 1.1 Illustration of beams strengthened in flexure with strengthening systems covered in Annex J (Adapted from BS EN 1992-1-1:2023)

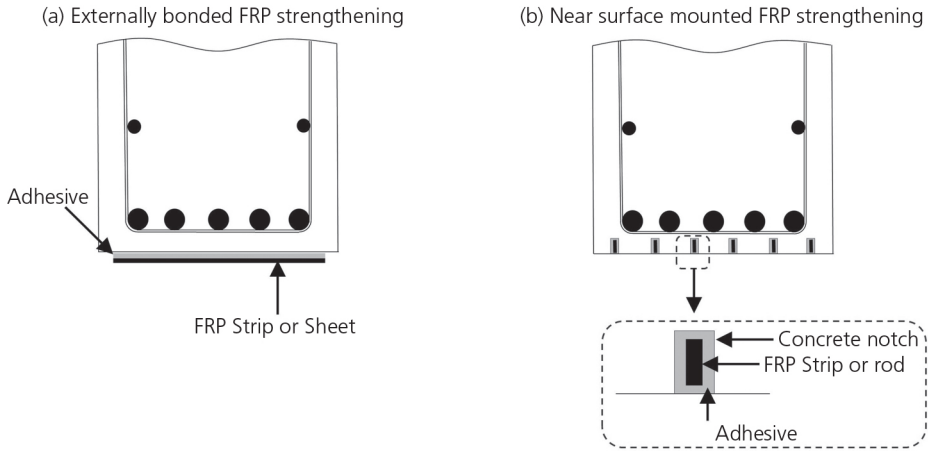
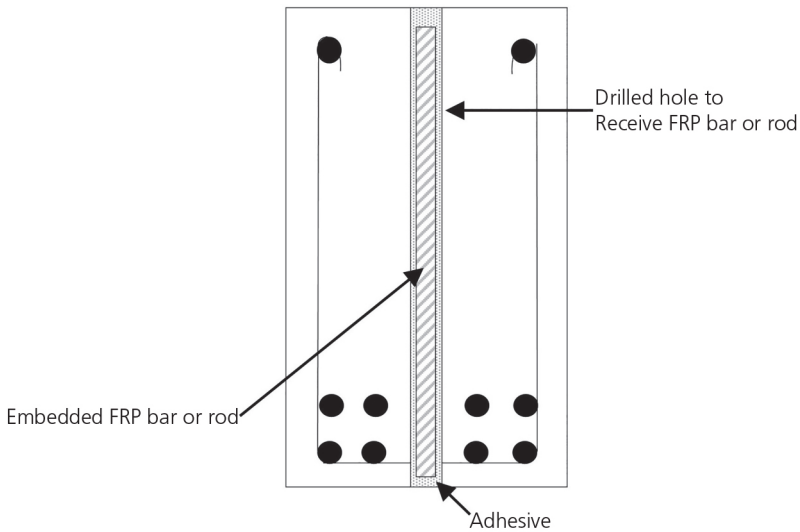
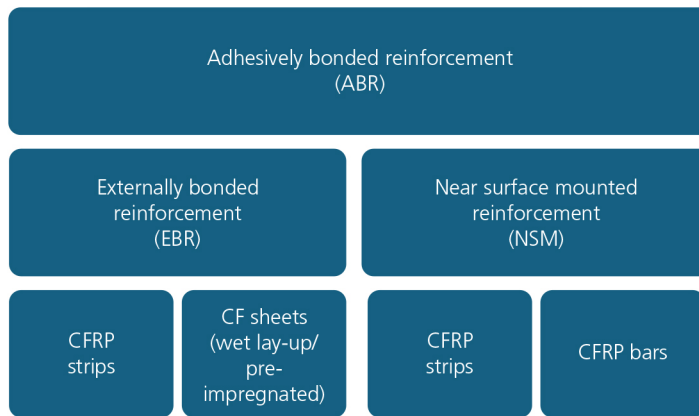


Figure 1.2 Illustration of shear strengthening with deep embedded FRP strengthening method



Standardisation in *BS EN 1992-1-1:2023* was undertaken only for carbon fibre reinforced polymer (CFRP) strengthening. This was simply because this application was the only FRP strengthening system that had a large enough database of necessary information to cover all aspects addressed in the code. Other strengthening systems commonly available on the market are glass fibre or aramid fibre reinforced polymer (GFRP and AFRP) strengthening systems.

Figure 1.3 CFRP strengthening systems covered by *BS EN 1992-1-1:2023*



### Strengthening applications covered by the standard

All CFRP strengthening systems covered in *BS EN 1992-1-1:2023* are adhesively bonded reinforcing (ABR) systems which are not prestressed. This standard covers the following ABR systems.

- Externally bonded reinforcement (EBR) systems which include CFRP bars, sheets and strips, bonded to the external surface of concrete with adhesive that provides bond to the surface as illustrated in Figure 1.1a.
- Near surface mounted (NSM) systems which are strengthening systems that require a slot to be cut into the concrete cover of the strengthened structure, into which a bar or strip is bonded as illustrated in Figure 1.1b.

Figure 1.3 outlines the terminology used in *BS EN 1992-1-1:2023* for CFRP strengthening.

### Production methods

Al-Mahaidi and Kalfat (2018) explain that carbon fibres are created from a precursor material which is used to create filament yarns. The precursor material is commonly polyacrylonitrile, with also rayon or petroleum pitch being used. The filaments are taken through a heating and oxidation process to create the fibres which are then coated to protect them from damage. These fibres are then woven into fabrics or pultruded into laminates (strips) or bars.

There are various production and installation methods available to produce a strengthening system from the bare fibres. Production of the CFRP strengthening material from the bare fibres varies. The systems covered by *BS EN 1992-1-1:2023* (BSI, 2023b) are listed below along with a brief summary of how they are produced.

- CFRP EBR sheets.
  - Wet lay-up sheets – this is a system where a dry fibre matrix (either uni- or multidirectional) is impregnated with compatible saturating resin on site. The resin, along with compatible primers, adhere the CFRP matrix to the strengthened surface of the structure.

This is a popular method of applying CFRP, owing to its flexibility, and can be used in a wide variety of applications, including systems that require wrapping around corners (e.g. shear strengthening and column confinement).

- Pre-impregnated sheets – in this system, a dry fibre matrix is pre-impregnated with resin prior to transport to site. The fibre matrix is partially cured ahead of installation. On site, additional resin may be added when the sheets are installed, and heating may be required to cure the resin. The benefit of the system is that it can be faster and easier to install and provide shorter curing times.
- CFRP EBR or NSM strips.
  - EBR strips are pre-cured offsite, with the resin to bind fibres together being applied in a controlled factory environment. These systems can be formed to a variety of shapes. The pultrusion method is often used to produce these strips. The pultrusion process undertakes the following steps
    - The fibres are first fed through a preforming guide to achieve the required fibre orientation.
    - The reinforced fibres then undergo resin impregnation in a ‘wet-out’ bath of polymer.
    - The reinforced fibres with the resin are then passed through a heated die. In this process the fibres begin to solidify.
    - Near the end of the heating process the resin temperature will become higher than the die, and a separation process begins where the cured profile can be removed from the die, leaving the strips.
- CFRP NSM bars or rods.
  - Round bars are often manufactured using the pultrusion process described above.
  - Bars and plates are also manufactured using the pultrusion process described above.

## Product specification

At the time of producing this standard, there was no harmonised EN standard to cover the production of the CFRP strengthening material. However, European Assessment Documents (EADs) were being prepared for the European Organisation for Technical Approvals (EOTA), which will enable European Technical Assessments (ETAs) to be produced. These will provide a basis on which suppliers can obtain certification of their product under the European Construction Directive (CE marking).

The intention of the drafting group who produced Annex J was to ensure that it would enable use of these ETAs when they become available. This was achieved by including statements referring to ‘production data’ or ‘more accurate information’ in the annex.

Additionally, these ETAs are likely to cover systems not included in the standard, such as deep embedded bars for shear strengthening, or externally prestressed systems.

At the time of writing this book, EAD 160086-00-0301 – Kits for the strengthening of concrete elements by externally bonded CFRP strips (EOTA, 2019) was not yet granted and, therefore, was not available.

ETAs provide manufacturers with a route to producing a CE mark for a product that is not covered by a harmonised European standard. It is the European Union (EU) Construction Products Regulations (CPR) that enables this route. A product that complies with an ETA can, therefore, be used

throughout the European Union and any other country that utilises the EU CPR. Use of these documents in a country outside of the jurisdiction of the EU CPR may need confirmation of its validity for use or agreement to its use as part of a project specification.

### **Assessment for strengthening**

Assessment of a structure for strengthening may be undertaken for a variety of reasons. As stated in TR55 (Concrete Society, 2013), this can include a change in load regime (e.g. change of use for a building or changes in bridge loading standards), to cater for changes in standards since a structure was constructed, to add reinforcement to an under-designed structure or one not constructed correctly, to address concerns regarding observed deterioration, or to add reinforcement for alterations (e.g. around holes cut into floor slabs in buildings to enable services or stairs to be added).

*BS EN 1992-1-1:2023* includes a new Annex I dedicated to the assessment of concrete structures. The annex includes the following items

- methods to enable determination of characteristic material properties for assessment to avoid conservative properties being used
- adjusting partial material factors where testing is used to determine material properties
- deterioration
- calculating bond and anchorage lengths of plain bars in a way that is consistent with the method for ribbed bars
- dealing with detailing that doesn't conform to the current standard
- more rigorous assessment provisions for assessment of shear resistances of members without shear reinforcing using Critical Shear Crack Theory (Muttoni and Fernandez Ruiz, 2008)
- using the beneficial effect of compression concrete flanges to increase shear strength, shown in various sources—as illustrated in Giaccio (2003).

The methods in this annex should be exhausted prior to implementing strengthening to ensure sustainable and cost-effective solutions are developed and unnecessary strengthening is avoided.

*This page intentionally left blank*

Kaloyana Kostova and Craig Giaccio

ISBN 978-1-83549-935-1

<https://doi.org/10.1108/978-1-83549-934-420251002>

Emerald Publishing Limited: All rights reserved

## Chapter 2

# Materials

### General

As stated earlier, the design rules in Annex J of *BS EN 1992-1-1:2023* (BSI, 2023b) were written when harmonised European standards for production and execution were not available, so flexibility was needed in the provisions.

The intent of Annex J is to enable planned development of European Assessment Documents (EADs) to be used (normally cited as *relevant product standards* or *more accurate information available from tests data*) in an effort to ensure that future developments are not prevented by standardisation in *BS EN 1992-1-1:2023*. ISO 10406-1:2015 (ISO, 2015a), ISO 10406-2:2015 (ISO, 2015b) and ISO 10406-3:2019 (ISO, 2019b) provide methods to obtain some relevant design properties, and these have been referenced when available. BS EN 2561:1996 (BSI, 1996) and ISO 527 (ISO, 2019a) also provide methods to determine properties for FRP systems.

The code only caters for strengthening systems and approaches where sufficient databases exist to substantiate code based on the reliability required in the Eurocode standards. This precludes various systems described throughout this book which are in use. These could potentially be covered under future EADs or ETAs.

### Partial factors

Provided that all provisions in this standard are complied with, failure mechanisms for the CFRP system arise from either rupture of the CFRP material or bond failure at the interface between the CFRP system and the concrete. Two sets of partial factors for resistance differentiate between the possible mechanisms of failure. These are provided in [Table 2.1](#).

**Table 2.1** Partial factors for CFRP systems

Design situation / limit state	Tensile strength		Bond strength
	CFRP strips and bars	In situ lay-up CF sheets	
Designation	$\gamma_f$		$\gamma_{BA}$
Persistent and transient	1.30	1.40	1.50
Accidental	1.1	1.15	1.15
Serviceability	1.00	1.00	1.00
Fatigue	1.30	1.40	1.50

In situ lay-up CF sheets generally have higher partial factors than CFRP bars and strips. This, in part, reflects the fact that they are impregnated with resin to bond the carbon fibres together on site, hence do not have factory controls on geometry of the complete CFRP product and, therefore, have more variability in resistance.

### Material properties

CFRP is a non-ductile linear elastic material which generally has a higher tensile strength compared with ordinary reinforcement steel. Its modulus of elasticity depends on how it is produced and can vary significantly for different systems. The modulus of elasticity of CFRP is also generally low as a ratio to yield strength when compared to ordinary reinforcing steel. A typical stress-strain diagram is shown in Figure 2.1 which illustrates a typical commercially available system alongside ordinary reinforcement (with post yield hardening not considered).

### Mechanical properties

The characteristic short-term tensile strength of CFRP,  $f_{fuk}$ , will depend on the CFRP strengthening system used and the supplier that produces it. This property should be obtained from a supplier. The material is prone to reductions in strength over time, owing to effects of the environment (such as being in an alkaline environment or exposure to high or low temperatures) and creep under sustained loading. The design value of the tensile strength  $f_{fud}$ , therefore, needs to be factored to account for such strength reductions, as is shown in Equation 2.1.

$$f_{fud} = \frac{\eta_f f_{fuk}}{\gamma_f} \tag{2.1}$$

Where

$\eta_f$  is the reduction applied to the short-term tensile strength to account for environmental conditions and produce the design tensile strength.

$\gamma_f$  is the partial material factor given in Table 2.1.

Figure 2.1 Typical stress-strain diagram for the CFRP material

