BetonKalender

Strengthening of Concrete Structures with Adhesively Bonded Reinforcement

Design and Dimensioning of CFRP Laminates and Steel Plates

Konrad Zilch, Roland Niedermeier, Wolfgang Finckh

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Coverphoto: Ludwig Freytag GmbH & Co. KG, Oldenburg, Germany

Coverdesign: Hans Baltzer, Berlin, Germany

The original German text is published in Beton-Kalender 2013, ISBN 978-3-433-03000-4 and titled "*Geklebte Verstärkung mit CFK-Lamellen und Stahllaschen*".

Library of Congress Card No.: applied for

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

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <http://dnb.d-nb.de>.

Print ISBN: 978-3-433-03086-8
ePDF ISBN: 978-3-433-60403-8
ePub ISBN: 978-3-433-60405-2
mobi ISBN: 978-3-433-60402-1
oBook ISBN: 978-3-433-60401-4

Typesetting: Thomson Digital, Noida, India

Printing and Binding: betz-druck GmbH, Darmstadt, Germany

Printed in the Federal Republic of Germany
Printed on acid-free paper

Editorial

The *Concrete Yearbook* is a very important source of information for engineers involved in the planning, design, analysis and construction of concrete structures. It is published on a yearly basis and offers chapters devoted to various, highly topical subjects. Every chapter provides extensive, up-to-date information written by renowned experts in the areas concerned. The subjects change every year and may return in later years for an updated treatment. This publication strategy guarantees that not only is the latest knowledge presented, but that the choice of topics itself meets readers' demands for up-to-date news.

For decades, the themes chosen have been treated in such a way that, on the one hand, the reader gets background information and, on the other, becomes familiar with the practical experience, methods and rules needed to put this knowledge into practice. For practising engineers, this is an optimum combination. In order to find adequate solutions for the wide scope of everyday or special problems, engineering practice requires knowledge of the rules and recommendations as well as an understanding of the theories or assumptions behind them.

During the history of the *Concrete Yearbook*, an interesting development has taken place. In the early editions, themes of interest were chosen on an ad hoc basis. Meanwhile, however, the building industry has gone through a remarkable evolution. Whereas in the past attention focused predominantly on matters concerning structural safety and serviceability, nowadays there is an increasing awareness of our responsibility with regard to society in a broader sense. This is reflected, for example, in the wish to avoid problems related to the limited durability of structures. Expensive repairs to structures have been, and unfortunately still are, necessary because in the past our awareness of the deterioration processes affecting concrete and reinforcing steel was inadequate. Therefore, structural design should now focus on building structures with sufficient reliability and serviceability for a specified period of time, without substantial maintenance costs. Moreover, we are confronted by a legacy of older structures that must be assessed with regard to their suitability to carry safely the increased loads often applied to them today. In this respect, several aspects of structural engineering have to be considered in an interrelated way, such as risk, functionality, serviceability, deterioration processes, strengthening techniques, monitoring, dismantlement, adaptability and recycling of structures and structural materials plus the introduction of modern high-performance materials. The significance of sustainability has also been recognized. This must be added to the awareness that design should focus not just on individual structures and their service lives, but on their function in a wider context as well, i.e. harmony with their environment, acceptance by society, responsible use of resources, low energy consumption and economy. Construction processes must also become cleaner, cause less environmental impact and pollution.

The editors of the *Concrete Yearbook* have clearly recognized these and other trends and now offer a selection of coherent subjects that reside under the common "umbrella" of a broader societal development of great relevance. In order to be able to cope with the corresponding challenges, the reader can find information on progress in technology, theoretical methods, new research findings, new ideas on design and construction, developments in production and assessment and conservation strategies. The current selection of topics and the way they are treated makes the *Concrete Yearbook* a splendid opportunity for engineers to find out about and stay abreast of developments in engineering knowledge, practical experience and concepts in the field of the design of concrete structures on an international level.

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Honorary president of the international concrete federation *fib*

Contents

1 Introduction

1.1 The reason behind this book

The main reason is the revised approach to the design of adhesively bonded strengthening measures for concrete members given in the guideline [1] (q.v. [2]) published by the Deutscher Ausschuss für Stahlbeton DAfStb (German Committee for Structural Concrete). This book explains the design rules of the DAfStb guideline, together with their background, and uses examples to illustrate their use. The scope of the explanations and background information provided here is mainly based on works that have already been published. However, some rules that so far have been dealt with in detail in committee meetings only are elaborated here for the first time.

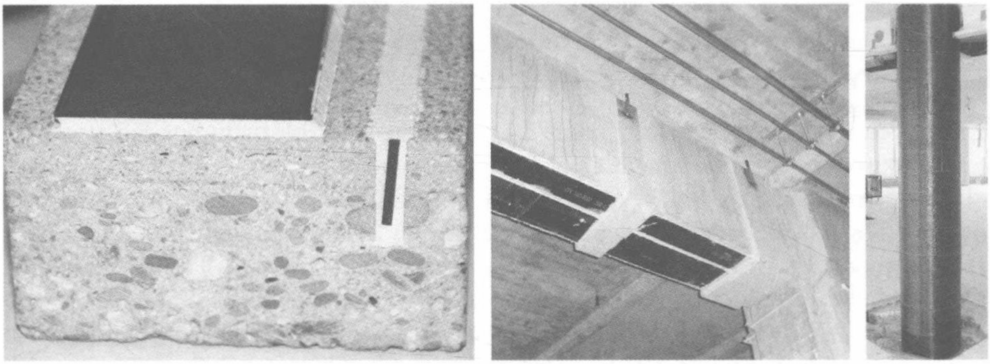
1.2 Strengthening with adhesively bonded reinforcement

The strengthening of concrete members means using constructional measures to restore or improve their load-carrying capacity, serviceability, durability or fatigue strength. The effects of strengthening measures can generally be described in quantitative terms and therefore analysed numerically. Besides numerous other methods (see [3, 4], for example), the subsequent strengthening of existing concrete members can be achieved by using adhesives to bond additional reinforcing elements onto or into those members. This topic of reinforcement bonded with adhesive has been the subject of many contributions to various editions of the *Beton-Kalender* in the past (see [5, 6]). However, design approaches for adhesively bonded reinforcement have continued to evolve (see [7, 8]) and the new DAfStb guideline [1, 2] on this subject revises those design methods and adapts them to our current state of knowledge. In principle, the DAfStb guideline together with a corresponding system approval allows the following concrete member strengthening measures to be carried out:

- Flexural strengthening with externally bonded (surface-mounted) CFRP strips, CF sheets and steel plates
- Flexural strengthening with CFRP strips bonded in slots (near-surface-mounted reinforcement)
- Shear strengthening with externally bonded CF sheets and steel plates
- Column strengthening with CF sheets as confining reinforcement.

Figure 1.1 provides an overview of these methods. The term 'adhesively bonded' is used in this book as universal expression comprising both methods 'externally bonded' and 'near-surface-mounted'.

Strengthening of Concrete Structures with Adhesively Bonded Reinforcement: Design and Dimensioning of CFRP Laminates and Steel Plates. First Edition. Konrad Zilch, Roland Niedermeier, and Wolfgang Finckh.



(a) (b) (c)

Fig. 1.1 (a) Externally bonded and near-surface-mounted CFRP strips; (b) flexural strengthening with externally bonded CFRP strips together with shear strengthening in the form of externally bonded steel plates (photo: Laumer Bautechnik GmbH); (c) column strengthening with CF sheets as confining reinforcement (photo: Laumer Bautechnik GmbH)

2 DAfStb guideline

2.1 The reasons for drawing up a guideline

In the past, the product systems as well as the design and installation of adhesively bonded reinforcement were regulated in Germany by national technical approvals and individual approvals. Such approvals contained provisions covering the materials, the design of the strengthening measures, the work on site and the monitoring of products. There were several reasons why it was deemed necessary to revise the design approaches of the earlier approvals.

One of those reasons was the harmonization of standards across Europe, leading to national standards and regulations being successively adapted to the European standards. These developments also render it necessary to adapt the former national approvals to the new generation of standards.

Furthermore, the results of numerous research projects carried out in recent years had only been partly incorporated in the older regulations, which therefore no longer matched the current state of knowledge. Therefore, industry, the building authorities and the German Research Foundation (DFG) made substantial funds available for researching adhesively bonded reinforcement. That led to many scientific projects in the German-speaking countries and adhesively bonded reinforcement gradually becoming a standard method in the building industry. Consequently, all the groups involved regarded the preparation of a universal guideline as indispensable.

2.2 Preparatory work

In order to produce a universal guideline reflecting the current level of knowledge, the German Committee for Structural Concrete (DAfStb) first commissioned a report on the current situation [7] to document and collate national and international knowledge. A database of test results containing almost all the experimental studies carried out nationally and internationally was also set up and compared with the established models and the guidelines available elsewhere in the world. During the drafting of the report it became apparent that the knowledge necessary to produce an effective guideline was lacking in some areas. Therefore, under the direction of the DAfStb, a research project was initiated in which all the groups interested took part. The research work was carried out by the technical universities in Munich and Brunswick, both of which had been working continually on adhesively bonded reinforcement for more than 20 years. The project was financed by the owners of the approvals (Bilfinger Berger AG, Laumer Bautechnik GmbH, Ludwig Freytag GmbH & Co. KG, MC-Bauchemie Müller GmbH & Co. KG, S&P Clever Reinforcement Company AG, Sika Deutschland GmbH, Stocretec GmbH), the Federal Institute for Research on Building, Urban Affairs & Spatial Development (BBSR) plus a number of associations and consulting engineers. Issues surrounding the bond strength under static loads [9] and dynamic loads [10] plus the shear strength [11] were successfully clarified during this project.

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2.3 Work on the guideline

A subcommittee set up by the DAfStb began drafting the guideline as the research work progressed. In accordance with DIN 820-1 [12], the groups involved (building authorities, industry, research centres, official bodies, trade associations) were all represented equally on the subcommittee. Within a year, a draft version had been prepared. The draft, incorporating the results of research projects but also the experiences of the members of the subcommittee, appeared in March 2011 as a paper for discussion and was announced and presented to the industry in numerous publications [13–19]. Comments and objections could be filed by mid-September 2011. A meeting to discuss and decide on objections was subsequently held. Following its notification by the European Union, the finished guideline became available in the summer of 2012. It can be purchased from Beuth Verlag. The DAfStb guideline [2] is also available in English.

2.4 The structure and content of the guideline

2.4.1 General

The DAfStb guideline covering the strengthening of concrete members with adhesively bonded reinforcement [1, 2] provides rules for design and detailing, the application of national technical approvals for strengthening systems, execution and additional rules for planning strengthening measures employing adhesively bonded reinforcement.

The guideline is divided into four parts. The first part covers the design and detailing of strengthening measures using reinforcement bonded with adhesive. This part of the guideline supplements DIN EN 1992-1-1 [20] with its associated National Annex [21] by providing the additional requirements necessary for adhesively bonded reinforcement. The second part of the guideline, together with the system approvals, describes the products and systems used for strengthening measures with adhesively bonded reinforcement. The third part covers the execution, and also contains advice on installing the specified strengthening measures. The fourth part of the guideline contains additional rules for planning strengthening measures.

2.4.2 Design and detailing

As mentioned above, the first part of the DAfStb guideline supplements DIN EN 1992-1-1 [20] and its associated National Annex [21]. Its structure corresponds exactly to that of DIN EN 1992-1-1, and there are additional provisions for materials, durability, ultimate limit state, serviceability limit state, reinforcing principles and detailing.

Chapters 3, 5 and 7 of this book describe the design and detailing provisions for different strengthening measures and the background to these.

2.4.3 Products and systems

The second part of the DAfStb guideline covers the application of system approvals for strengthening measures employing adhesively bonded reinforcement. Strengthening must be carried out with an approved strengthening system using strengthening products to DIN EN 1504-1 [22]. A strengthening system consists of various properly matched construction products whose usability as components in a strengthening system must be verified within the scope of a national technical approval for the strengthening system.

The main elements of such a strengthening system are:

- the strengthening elements made from carbon fibre materials (CFRP strips or CF sheets) or steel flats/angles,
- the adhesive,
- a primer based on epoxy resin as a component for protecting steel parts against corrosion, and
- a repair mortar based on epoxy resin which includes a bonding agent.

2.4.4 Execution

The third part of the DAfStb guideline deals with the work on site. It contains advice and provisions for carrying out the strengthening measures. For example, it provides information on the pretreatment of members and the associated inspections to be carried out. In addition, it specifies the requirements to be met by contractors who carry out strengthening measures.

2.4.5 Planning

The fourth part of the DAfStb guideline contains supplementary regulations for planning strengthening measures. It includes definitions of the requirements to be satisfied by the member being strengthened. There are also recommendations regarding the scope of the planning and the measures required to determine the actual condition of the member to be strengthened. In addition, all design and construction work must take into account the DAfStb's guideline on the maintenance of reinforced concrete [23].

2.5 Safety concept

As with DIN EN 1992-1-1 [20] and its associated National Annex [21], the DAfStb guideline is based on the safety concept of DIN EN 1990 [24] together with its National Annex [25].

The guideline specifies partial safety factors for externally bonded reinforcement, which are given in Table 2.1. A distinction is made between the partial safety factors for the strength of the bonded reinforcement and those for the bond of the bonded reinforcement.

The partial safety factors for the strength of externally bonded reinforcement were chosen according to the *fib* recommendations [26]. The partial safety factor proposed in [26] for CFRP strips has also been evaluated statistically by Blaschko [27] and used in the design rules of earlier approvals [28, 29].

The partial safety factors for the bond of reinforcement attached with adhesive depend on the mode of failure. In the case of near-surface-mounted reinforcement and when bonding steel to steel or CFRP to CFRP, it is generally the adhesive that governs a bond failure, and the safety factor for the adhesive according to [27] is used, as it was already the case in the earlier approvals (see [29], for example).

Table 2.1 Partial safety factors for adhesively bonded reinforcement for the ultimate limit state.

Design situation	CFRP strips	CF sheets	Bond of externally bonded reinforcement	Bond of near-surface-mounted reinforcement	Bond of steel on steel or CFRP on CFRP
Designation	γ_{LL}	γ_{LG}	γ_{BA}	γ_{BE}	γ_{BG}
Persistent and transient	1.2	1.35	1.5	1.3	1.3
Accidental	1.05	1.1	1.2	1.05	1.05

A bond failure with externally bonded reinforcement (steel plates, CFRP strips, CF sheets) entails a failure in the layer of concrete near the surface. For this reason, when it comes to the bond of externally bonded reinforcement, the DAfStb guideline uses the partial safety factors for concrete failure according to [20], as in the earlier approvals [28]. According to [30], using such a global partial safety factor for the bond of externally bonded reinforcement – instead of individual partial safety factors for every variable in the design equations – resulted in the smallest deviations in the level of safety when comparing various sample calculations.

2.6 Applications

2.6.1 Member to be strengthened

The DAfStb guideline can be applied to concrete members complying with DIN EN 1992-1-1 [20, 21]. The design approaches of the guideline were prepared based on the theories of mechanics and calibrated and validated by means of tests on normal-weight concretes of strength classes C12/15 to C50/60. Therefore, the design approaches of the guideline should not be applied to other construction materials without carrying out additional investigations. In order to keep within the range of experience of the experimental studies available, the guideline specifies the following exceptions:

- The DAfStb guideline cannot be used for strengthening lightweight concrete.
- The DAfStb guideline only covers the strengthening of normal-weight concretes of strength classes C12/15 to C50/60.

Furthermore, the guideline [1, 2] cannot be applied to components made from steel fibre-reinforced concrete or autoclaved aerated concrete. So extending DIN EN 1992-1-1 [20] by means of the DAfStb guideline on steel fibre-reinforced concrete [31] and combining this with the DAfStb guideline on the strengthening of concrete members with externally bonded reinforcement [1, 2] is not permitted.

The DAfStb guideline on the strengthening of concrete members with adhesively bonded reinforcement [1, 2] can only be used to design strengthening for concrete components. It cannot be used to design strengthening measures for masonry components (see [32], for example), timber components (see [33], for example), steel components (see [34], for example) or composite components, nor does it cover combinations with other methods of strengthening.

2.6.2 Strengthening systems

The DAfStb guideline [1, 2] covers strengthening systems incorporating adhesively bonded reinforcement. German construction law requires that the strengthening system being used must have been granted a national technical approval.

Externally bonded reinforcement assumes that an adhesive, based on an epoxy resin, is used to attach reinforcing elements in the form of steel or carbon fibre (CF) materials to a concrete substrate from which all intrinsic substances (cement laitance) and foreign matter (plaster, render, paint) have been removed using suitable methods. An externally bonded strengthening solution therefore assumes that a compact tension member, linear elastic in the area of the stress–strain curve considered, is attached to the concrete with the help of a high-strength adhesive. Owing to this high-strength adhesive and the compact form of the reinforcing element, a concrete failure is always assumed in the case of the debonding of externally bonded reinforcement. For these reasons, the design approaches cannot be directly transferred to other forms of strengthening, e.g. upgrading with textile-reinforced concrete (see [35], for example). Most of the experiments carried out and practical experience gained so far in Germany has involved strengthening with steel plates and CFRP strips. Considerable experience has been gained with externally bonded CF sheets, too. However, there can be much greater differences between different CF sheet products than is the case with CFRP strips or steel plates. Therefore, the DAfStb guideline only specifies bond values for CFRP strips or steel plates. Owing to the mechanics background to the design equations, it is readily possible, however, to transfer the design approaches to CF sheets as well by adapting or verifying the bond values given in the guideline. These bond values are included in the national technical approvals for CF sheets.

When it comes to near-surface-mounted reinforcement (i.e. reinforcement bonded in slots), it is assumed that reinforcing elements in the form of prefabricated CFRP strips are bonded with an epoxy resin adhesive in slots sawn or milled in the concrete cover. It is not possible to use steel elements instead of CFRP slots in such cases because assuring adequate corrosion protection is awkward. Likewise, it is not possible to apply the design approaches to other types of reinforcement, e.g. round bars, because of the dissimilar bond behaviour.

Besides conventional bonding, it is also possible to use appropriate equipment to attach prestressed CFRP strips (see [36–38], for example). However, owing to the numerous unanswered questions about prestressed bonded reinforcement, the DAfStb guideline [1, 2] does not include any design approaches for this form of strengthening.

2.6.3 Ambient conditions

As the acceptable environmental conditions depend heavily on the properties of the strengthening system, the DAfStb guideline [1, 2] provides only general advice on this aspect. The permissible ambient conditions, such as exposure classes and other environmental influences, are – like the ensuing protective measures – regulated in the national technical approvals for the strengthening systems.

Generally, without additional protective measures, externally bonded reinforcement may only be used for exposure classes X0, XC1 or XC3 to DIN EN 1992-1-1 Table 4.1. In addition, the members in the region of the bonded reinforcement may not be exposed to strong UV radiation (direct sunshine or indirect sunshine reflected off snow or water) or alternating or permanent saturation.

One special aspect of bonded strengthening systems is their sensitivity to elevated temperatures. Cold-curing epoxy resin adhesives are normally used for retrofitted strengthening measures. These thermosetting polymers are amorphous and very stable below a certain temperature. However, at higher temperatures the crystalline phase gradually breaks up and the adhesive loses its strength over the glass transition range. The guideline therefore specifies that no loads may be allocated to the externally bonded reinforcement once the start of the glass-liquid transition (minus a safety margin) has been reached. This temperature is denoted T_f and owing to its dependence on the particular product is noted in the associated national technical approval. Without heat treatment, this figure lies between 40 and 60 °C for the epoxy resin adhesives currently on the market. According to the current state of knowledge, it is also known that the glass transition temperature essentially depends on the temperature during bonding and curing and during any further hardening involving intensive heating. It was observed in [39], for example, that a static glass transition temperature is not acceptable as a thermal serviceability limit because it is heavily dependent on the curing conditions. Therefore, care should be taken to ensure that when bonding at the bottom end of the service temperature range, no abrupt rise in temperature to the top end of the glass transition range can take place.

2.6.4 Fire protection

As described in the preceding section, adhesively bonded reinforcement is especially sensitive to elevated temperatures. Fire protection should therefore be paid special attention. Basically, the options are either carrying out a structural fire analysis without taking into account the bonded reinforcement or protecting the bonded reinforcement against heat by applying a suitable protective system. Examples of structural fire analyses for members with bonded reinforcement can be found in [40], for example.

A structural fire analysis, ignoring the adhesively bonded reinforcement, can be carried out according to DIN EN 1992-1-2 [41] in conjunction with its National Annex [42]. However, this is generally associated with the degree of strengthening being limited to some extent. In addition, through using an approved fire protection system to protect the internal reinforcement it is often possible to verify that the member has an adequate load-carrying capacity in the event of a fire even in the case of failure of the bonded reinforcement.

The other possibility is to protect the adhesively bonded reinforcement with a fire protection system that is approved for that particular reinforcement. At the time of drawing up the DAfStb guideline, however, no systems for protecting bonded