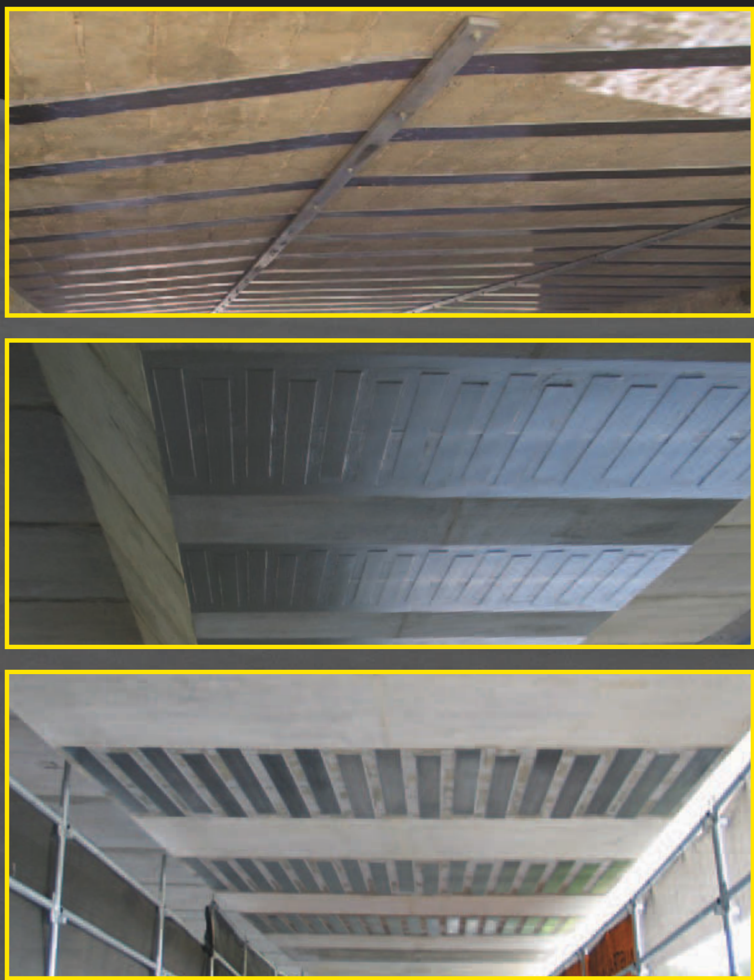
STANDARDS Australia

HB 305—2008

Design handbook for RC structures retrofitted with FRP and metal plates: beams and slabs



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Handbook

Design handbook for RC structures retrofitted with FRP and metal plates: beams and slabs

First published as HB 305—2008.

Published by Standards Australia GPO Box 476, Sydney, NSW 2001, Australia

ISBN 0 7337 8744 4

PREFACE

Rehabilitating, strengthening, repairing, upgrading and retrofitting (herein collectively referred to as *retrofitting*) reinforced concrete beams and slabs by adhesively bonding or mechanically fastening plates to their surfaces is advancing very rapidly and has reached the stage where the serviceability and ultimate behaviours of plated beams or slabs are understood (Blashko et al 1998, Concrete Society Technical Report No. 55 2004, fib bulletin 14 2001, Teng et al 2002, ACI 440.2R-02 2002, Oehlers and Seracino 2004, CNR-DT 200/04 2005). This behaviour, which encompasses flexure, transverse shear, bond and ductility, is described in the following Handbook. It is described in generic terms and can be applied to all forms of plating. This document uses the output from research on steel and fibre-reinforced polymer (FRP) plated structures, but it applies to plates of any material encourage current and future developments in this rapidly advancing retrofitting technique.

This Handbook covers the retrofitting of both reinforced concrete beams and reinforced concrete slabs. It is the intention of the authors to eventually expand the document to include columns, joints and frames. The plating technique described can be applied to any type of plate (such as steel or FRP) and any cross-sectional shape of plate that can be attached to any surface of a reinforced concrete beam or slab at any inclination, such as longitudinal plates, transverse plates or inclined plates. These plates can be externally bonded to the concrete surface, near-surface mounted, in which a plate is adhesively bonded within a groove formed within or cut into the concrete cover, or bolted to the concrete surface. They can also be used in both reinforced concrete and prestressed concrete beams to increase the flexural capacity, the flexural ductility when the plate is applied to compression regions, the stirrup component of the transverse shear capacity and the concrete component of the transverse shear capacity.

Plated reinforced concrete structures are a relatively new and unique form of structure, which has similar failure mechanisms and behaviours as in both reinforced concrete structures and composite steel and concrete structures (Oehlers and Bradford 1995, 1999); however, plated structures also have many new failure mechanisms (Teng et al 2002, Oehlers and Seracino 2004) that are not covered in reinforced concrete and composite design manuals. As with all new forms of structures and because plating is a very efficient retrofitting technique, plating is being used in practice concurrently with the development of design rules. Hence, it is not possible at this stage of development of the technique to formulate prescriptive design rules that cover all situations. This should not hinder the application of plating but it does require a deep understanding of the behaviour of plated structures (Oehlers and Seracino 2004) to ensure a safe design. This in turn requires an understanding of the behaviour of both reinforced concrete structures and composite steel and concrete structures (Oehlers and Bradford 1995).

This Handbook consists of *Guidelines* and *Commentary* to *Guidelines*. The *Handbook* covers the generic and fundamental behaviour of both plated beams and plated slabs and it is these behaviours that have to be designed for. The more advanced design rules that quantify the fundamental behaviours in the *Handbook* are given in the *Commentary*. The *Commentary* is only meant to assist in the design and the designer is free to use any other approach that has been shown to be correct and safe and which satisfies the generic and fundamental principles outlined in the *Handbook*. It is recognised that design rules are improving and developing rapidly. In the long run, it is the intention of the authors to gradually transfer information from the *Commentary* to the *handbook* as design rules become established.

The Handbook includes a Commentary to the text (set in a box), the designation of which aligns with the clause numbering of the 'Handbook', is preceded by a 'C' and set in bold font. For ease of cross-referencing, additional subject headings in the Commentary are numbered in hierarchical order to follow initial numbering, preceded by a 'C' and set in light font.

In this document the term beam is used collectively to encompass all flexural members, both beams and slabs. The background and fundamental principles governing much of the *Handbook* is given in Oehlers and Bradford (1995 and 1999) and Oehlers and Seracino (2004).

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CONTENTS

STANDARDS AUSTRALIA

Australian Handbook

Design handbook for RC structures retrofitted with FRP and metal plates: beams and slabs

1 INTRODUCTION

This *Handbook* sets out the generic and fundamental behaviours that need to be designed for in plated beams and slabs. Current state-of-the-art design rules are given in the *Commentary* (shown boxed).

This Handbook covers both *plated beams and slabs*, which from herein will be referred to collectively as *beams or plated beams*, including the bonding of plates of any material (such as steel or FRP), of any shape, of any geometry, of any inclination (such as longitudinal, transverse or inclined plates) to any surface of a reinforced concrete (RC) beam. The plates can be bonded with adhesives or bolted, or both adhesively bonded and bolted. The plates can be designed to either yield or remain elastic at failure. They need to be designed to resist flexural deformations and shear deformations at both ultimate and serviceability limit states, as well as for ductility such as required for moment redistribution.

Types of plates that can be used for retrofitting are first described in Section 2, followed in Section 3 by methods of analysis and the resulting axial forces, moments and shear forces that are unique to composite plated RC beams, in particular the bond stress resultants that have to be designed for. Section 4 covers the design of adhesively bonded plates for all debonding mechanisms and Section 5 covers the design of bolted plates. Having now designed the bond, Section 6 ensures that the concrete surrounding the bonded plate, that is the adhesively bonded or bolted plate, does not fail. The position of the bolts has now been determined so that Section 7 can be used to ensure that local plate buckling does not occur. In Section 8, overall design approaches for adhesively bonded longitudinal plates is covered. Ductility of plated members is described in Section 9 and design safety factors in Section 10.

C1 INTRODUCTION

The fundamental principles governing the behaviour of plated beams are described in this *Handbook*. Although many aspects of the behaviours are broadly understood, some have not been quantified, some are in the process of being quantified and are the subject of current research, and some have already been the subject of intensive research leading to established design rules. It may be some time before all aspects of the behaviours are quantified to a satisfactory level but this should not prevent nor severely restrict the use of plating. The designer needs to understand and bear in mind the fundamental principles described in this *Handbook*, design where possible for potential limit states and, where the behaviour is not fully understood, use conservative approaches. It is only with a real understanding of the fundamentals that the designer can confidently produce safe conservative designs, especially where the behaviour has not been fully quantified.

This *Commentary* follows the structure of the *Guidelines*. It is written on the assumption that the reader has an understanding of the behaviour of reinforced concrete structures, composite steel and concrete structures (Oehlers and Bradford 1995 and 1999) as well as some understanding of plated structures (Oehlers and Seracino 2004). It is not meant to be a “handbook” and, in particular, it is not meant to be a prescriptive criterion that can be routinely followed. *Commentary* to the *Guidelines* contain what the authors believe is the most advanced current research available. It is intended that, as design approaches become established, the text the *Commentary* will be integrated in the *Guidelines*.

Wherever possible, characteristic values are given, which can be used directly for design in conjunction with appropriate capacity reduction factors.

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2 BONDED PLATES

Plates can be made from any material, as long as the mechanical properties are known, and can be of any thickness. Commonly used plate materials are steel, carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP); however, the *Handbook* can, in theory, be applied to any type of plate material provided the mechanical properties are known. Fibre reinforced polymer (FRP) plates generally have linear elastic properties, prior to brittle fracture of the plate; the Young's modulus depends on the concentration of the fibre, and the fracture strain depends on the strain capacity of the fibre. FRP plates may be pultruded, in which case the fibres are generally in one direction, or they can be formed in the wet lay-up procedure using several layers in which case the fibres can be in any number of directions. Adhesively bonded plates tend to be thin in order to inhibit premature debonding. Whereas bolted plates tend to be thick with bi-directional fibres to inhibit plate buckling, bearing failure of the bolt shear connector and plate splitting.

It is assumed that the plate material properties are guaranteed by the plate manufacturer, for example, it is assumed that delamination within the FRP plate will not occur. Design should allow for fracture, creep and debonding of the plate as well as for temperature variations, fire, glass transition points, durability and the effects of ultra-violet radiation.

C2 BONDED PLATES

It is recommended that the designer have sufficient data from the manufacturer of the plate material to ensure that plate delamination does not occur under service conditions, and to ensure that the adhesive and FRP plate can maintain their assumed strength under service conditions. The adhesive bond should have a strength several times greater than the tensile strength of the concrete to ensure that debonding failure always occurs within the concrete medium. Furthermore, all necessary measures relevant to surface preparation and practical application should be carried out under quality control procedures.

C2.1 Design strength of FRP plates

Provisions from the ACI 440.2R-02 (2002) handbook for treatment of the long-term behaviour of FRP are recommended for use in subsequent calculations in this design *Handbook*, and are now summarised. The characteristic short-term properties of FRP reported by the manufacturer, namely, characteristic strength f_{fu}^* and elongation at rupture ε_{fu}^*, are corrected (reduced) by an environmental-reduction factor C_E which accounts for long-term exposure of different types of fibres in various environments. Equations C2.1(1) and C2.1(2) give the rupture strength f_{rup} and rupture strain ε_{rup} of FRP that can be used in design, while Table C2.1 lists the environmental-reduction factors for a range of environmental conditions and fibre types.

$$f_{rup} = C_E f_{fu}^* \qquad \text{. . . C2.1(1)}$$

$$\varepsilon_{rup} = C_E \varepsilon_{fu}^* \qquad \text{. . . C2.1(2)}$$