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Time-Dependent Behaviour and Design of Composite Steel-Concrete Structures

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International Association for Bridge and Structural Engineering (IABSE)

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18

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Editor
Gianluca Ranzi

State-of-the-art Review

International Association for Bridge and Structural Engineering (IABSE)

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Preface

Composite steel-concrete structures have been gaining popularity over the last decades throughout the world and are now widely used for building and bridge applications. This form of construction combines the advantages of the concrete and steel components to achieve enhanced structural performance.

This SED publication deals with the behaviour and design of composite structures relevant to a subset of the serviceability limit state requirements that is associated with the time-dependent behaviour of concrete caused by creep and shrinkage. Inadequate considerations for these structural aspects can lead to excessive deformations, displacements, and cracking. A state-of-the-art review is provided of the research carried out on the time-dependent response of composite structures and of the available service design specifications. European, Australian and New Zealand, and American design guidelines have been considered.

In the first part of the publication, the design framework recommended in the selected design specifications is outlined by providing an overview of the main service design requirements and by introducing the limit states of deflection and cracking that are significantly influenced by concrete time effects. An overview of the constitutive models commonly used to describe the time-dependent behaviour of the concrete is presented to provide the theoretical background and design models that are used throughout the book. Models considered range from the algebraic formulations, commonly recommended for routine design, to more sophisticated constitutive formulations suitable for advanced analysis.

The state-of-the-art review of research carried out over the last decades on the time-dependent behaviour of composite structures is reported in the central part of the book and it is arranged according to structural typologies, i.e. slabs, beams and columns. An extensive review of both experimental and modelling work related to concrete time effects, and how these affect the service response of composite members is provided.

The review of available design guidelines aims at presenting, in one publication, the similarities and differences of the recommended service design procedures influenced by concrete time effects. The comparison among design rules is organised in an objective manner to ensure that readers can form their own opinion. To support this process, the background information of these design rules is reported, when possible, in the preceding part on the state-of-the-art review of published research.

In the final part of the publication, selected case studies of buildings and bridges are provided to gain insight into the possible design approaches and rationale that are required when dealing with the time-dependent response of composite structures. The focus has been to discuss the key structural aspects of each case study that are significantly influenced by concrete time effects. Detailed calculations are outside of the scope of the book and have not been provided.

It is hoped that this SED will enhance the awareness of designers, academics, and students on the time-dependent response of composite structure and the most recent research advancements and standards' developments. To achieve this, the authors include design engineers and academics who have been involved in the service design and/or research on the time-dependent response of composite structures.

On behalf of the authors, I would like to thank Fabrizio Palmisano (Chief Reviewer), David Nethercot (External Reviewer), the Bulletin Editorial Board, Commission 3 *Structural Analysis and Evaluation* from which this initiative originated, and Ms. Brindarica Bose, who has been supporting the preparation of this SED from its conception to its publication.

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Gianluca Ranzi
April 2021

Table of Contents

Chapter 1

Introduction

Gianluca Ranzi[1], Raymond Ian Gilbert[1], Graziano Leoni[2], Luigino Dezi[2], Alejandro Pérez Caldentey[3], Javier Jordán[4], John Hewitt[1], Roberto Leon[5], Marion Rauch[6]

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This chapter presents the main concepts relevant to the design of composite steel-concrete structures for the serviceability limit state associated with the time-dependent effects of concrete caused by creep and shrinkage. After providing an overview of the verification of the serviceability limit state requirements, attention is given to the calculation of the service loads and their combinations. The key features associated with the limit states of deflection and concrete cracking are then introduced to provide a summary of how the service conditions can be incorporated into the design of a structure and its components. Finally, a classification of the different types of structures and their levels of sensitivity related to concrete time effects are presented. This classification is used to give insight into the available sets of recommended material models and analysis methodologies that can be used in design. The serviceability limit state requirements presented in this chapter have been outlined with reference to European, Australian and New Zealand, and American guidelines.

1.1 Background

Composite steel-concrete structures are widely used throughout the world for building and bridge applications. One of the distinguishing features of this form of construction is that the advantages of concrete and steel are combined to achieve stiffer and stronger structural solutions than those exhibited by the two materials working independently. The ability of the concrete and steel components to work together is commonly referred to as composite action and the force transfer mechanisms at the basis of this behaviour depend on the type of the structural component under consideration, such as a slab, column or beam, and the type of connectors used to tie the two materials together. For example, the composite action in composite beams is usually provided by means of mechanical devices, typically in the form of shear connectors, or in composite slabs by a mechanical interlock produced at the concrete and steel interface by embossments or indentations on the profiled steel sheeting. The peculiarities of the composite action exhibited by each structural component are briefly introduced in the corresponding chap-

Chapter 2

Time-dependent behaviour of concrete

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This chapter provides an introduction to the constitutive models commonly specified in design guidelines to describe the time-dependent behaviour of concrete and that can be used for the time-dependent analysis of composite structures. These formulations range from the simplest algebraic methods, such as the Effective Modulus Method that is widely recommended in design guidelines, to more sophisticated approaches that can account for creep and shrinkage effects in advanced modelling. The last part of the chapter provides a brief overview of multi-physics modelling that could be useful in predicting the concrete time-dependent response for composite construction.

2.1 Introduction

The time-dependent behaviour of composite steel-concrete structures is characterised by creep and shrinkage effects in the concrete components. This chapter provides an overview of, and an introduction to, the available constitutive models that range from the algebraic formulations, commonly recommended for routine design in the European, and Australian and New Zealand composite guidelines (EN 1994-1-1 [1], EN 1994-2 [2], AS/NZS 2327 [3], AS/NZS 5100.6 [4]), to more sophisticated constitutive representations suitable for advanced analysis. An introduction to multi-physics modelling is provided at the end of the chapter to highlight its advantages in predicting the long-term response of concrete. The purpose of this chapter is to present the theoretical background and design models that will be used in the following chapters when considering the time-dependent behaviour of composite structures.

The mathematical representations and derivations will be kept to a minimum. Further details on concrete time effects can be found in specialised textbooks, e.g. [5], [6] and [7], or in the references cited thereinafter.

Chapter 3

State-of-the-art review on the time-dependent behaviour of composite steel-concrete slabs

Gianluca Ranzi[1], Raymond Ian Gilbert[1]

1 Australia

This chapter presents a state-of-the-art review of work published to date on the time-dependent response of composite steel-concrete slabs. The key components of this form of construction are introduced in the first part of the chapter, followed by a review of the time-dependent behaviour of the concrete and how it affects the in-service response of composite slabs. Throughout the chapter, particular attention is given to recent experimental and modelling work related to concrete time effects, and how these affect the in-service response of composite slabs, including the development of non-uniform shrinkage gradients that have been recently shown to occur in composite floors due to the inability of the concrete to dry from its underside because of the presence of the profiled steel sheeting.

3.1 Introduction

Composite steel-concrete slabs are widely used for building applications and consist of reinforced or post-tensioned concrete slabs cast on profiled steel sheeting. A typical layout of this form of construction is illustrated in Fig 3.1. The key components consist of profiled steel sheeting, concrete slab, steel reinforcement, and, in the case of post-tensioned floors, prestressing ducts and strands. Composite slabs are widely used in steel framed construction, while post-tensioned composite slabs have found wide applicability in concrete structures.

It is common practice to classify profiles of steel sheeting according to their geometry. The most common geometries are depicted in Fig 3.2 and include re-entrant trough profiles, clipped-pan profiles and open trough profiles (EN 1994-1-1 [1], AS/NZS 2327 [2]). The profiled steel sheeting may have different patterns of embossments or indentations on its surface to improve the bond between the steel and the concrete.

In this form of construction, the profiled steel sheeting is used as permanent formwork and, once the concrete hardens, the slab becomes composite and the sheeting acts as

Chapter 4

State-of-the-art review on the time-dependent behaviour of composite steel-concrete beams

Gianluca Ranzi[1], Graziano Leoni[2], Raymond Ian Gilbert[1], Luigino Dezi[2], Riccardo Zandonini[2]

1 Australia, 2 Italy

This chapter provides an overview of the work carried out to date on the long-term behaviour of composite steel-concrete beams. In the first part of the chapter, a description of the components forming a composite member is presented. This is followed by an outline of the main kinematic concepts, such as full and partial shear interaction, that influence the structural response of this form of construction due to the flexibility of the shear connection provided between the concrete and steel components. The review of the work performed on the time-dependent behaviour of concrete and its influence on the long-term structural response of composite beams for building and bridge applications is then presented. The modelling and experimental work considered in the review highlights the importance of considering concrete time effects, when predicting the in-service response of composite beams.

4.1 Introduction

Composite steel-concrete beams are widely used for building and bridge applications. Typical composite beams used for building applications combine steel beams with solid or composite slabs, as illustrated in Figs. 4.1a and 4.1b, respectively. In this case, the depth of the steel beam is usually of the same order or a few times larger than the thickness of the concrete slab. Typical composite beam arrangements for bridge applications are depicted in Figs. 4.2a and 4.2b for a twin-girder deck and a box girder, respectively. The depth of the steel section of composite bridges is usually about one order of magnitude larger than the concrete slab thickness.

Composite beams represent an economical structural solution. This form of construction is particularly efficient in positive (sagging) moment regions in which the concrete is mainly in compression and the steel is in tension. In such an arrangement, the coupling of

Chapter 5

State-of-the-art review on the time-dependent behaviour of composite steel-concrete columns

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1 China, 2 Australia

This chapter presents a state-of-the-art review of the time-dependent behaviour of composite columns. The first part of the chapter outlines the available typologies and advantages of composite columns. This is followed by an overview of the time-dependent response of concrete (specific to composite columns) and an introduction to concrete confinement. The main part of the chapter is devoted to the state-of-the-art review on how concrete time effects influence the long-term and ultimate behaviour of concrete-filled steel tube (CFST) columns, and on the combined effects produced by sustained loading and chloride corrosion on CFST columns. The review then deals with the long-term behaviour of concrete-filled double skin tube (CFDST) and encased composite columns. The final parts of the chapter provide a review of the time-dependent differential axial shortening (DAS) in vertical components of multi-storey buildings and on the long-term response of arch bridges.

5.1 Introduction

Composite steel-concrete columns represent an efficient structural typology in which steel and concrete components can be combined in different arrangements depending on their geometry and relative positioning, as illustrated for selected cases in Fig. 5.1.

The first type of composite column adopted in construction consisted of the fully concrete-encased steel section depicted in Fig. 5.1a and this was specified for its ability to enhance the performance of the steel section in terms of structural stiffness and fire protection. With the use of the partially concrete-encased steel column of Fig. 5.1b, it was possible to reduce the concrete volume and the amount of formwork being specified for the casting operations.

In the case of a concrete-filled steel tube (CFST) column, the steel section acts as permanent formwork during concrete casting and the member becomes composite once the

Chapter 6

Design specifications for the time-dependent behaviour of composite steel-concrete structures

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This chapter deals with the long-term behaviour of composite members and structures used for building and bridge applications and provides a review of the relevant international serviceability limit state design methodologies, with particular focus given to the European, Australian and New Zealand, and American specifications. The first part of the chapter introduces the deflection limit requirements specified in design procedures for satisfying the serviceability limit state conditions. This is followed by a review of the design procedures recommended in the specifications for composite slabs, beams, and columns. Particular attention is devoted to reviewing design methodologies for the calculation of the displacements, for detailing, and for control of concrete cracking.

6.1 Introduction

This chapter provides a review of international guidelines for the service design of composite members and structures for building and bridge applications with particular attention given to European standards EN 1994-1-1 [1] and EN 1994-2 [2], Australian and New Zealand specifications AS/NZS 2327 [3] and AS/NZS 5100.6 [4], and American standards. In the United States, the design of composite steel-concrete construction is covered by a number of standards. For example, the design of composite floors is covered in ANSI/SDI C-2017 [5], while more general provisions dealing with composite steel/concrete construction are given in AASHTO [6] and ANSI/AISC 360-16 [7]. ACI-318-19 [8] deals only with composite construction involving different concrete elements.

Chapter 7

Case studies considering the influence of the time-dependent behaviour of concrete on the serviceability limit state design of composite steel-concrete buildings

Alejandro Pérez Caldentey[1], John Hewitt[2], John van Rooyen[2], Graziano Leoni[3], Gianluca Ranzi[2], Raymond Ian Gilbert[2]

1 USA/Spain, 2 Australia, 3 Italy

This chapter presents a number of case studies that deal with the service design of composite steel-concrete buildings associated with the time-dependent behaviour of the concrete. The particular focus of this chapter is to outline key design aspects that need to be accounted for in design and that are influenced by concrete time effects. The first case study provides an overview of the design considerations related to the time-dependent column shortening in typical multi-storey buildings by considering the layout of the Intesa Sanpaolo Headquarters in Turin as reference. The second case study focuses on a composite floor of a commercial building constructed in Australia and it provides an overview of the conceptual design used to select the steel beam framing arrangement to support the composite floor system while accounting for concrete cracking and time effects. The third case study deals with the Quay Quarter Tower that has been designed for the repurposing of an existing 50-year-old building in Australia while accounting for the time-dependent interaction between the existing and the new concrete components of the building.

7.1 Introduction

This chapter provides three case studies that highlight key design aspects associated with the service response of composite steel-concrete buildings produced by the time-dependent behaviour of the concrete. For this purpose, real building projects have been used as reference. It is outside the scope of this chapter to describe the steps involved in the

Chapter 8

Case studies considering the influence of the time-dependent behaviour of concrete on the serviceability limit state design of composite steel-concrete bridges

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1 USA/Spain, 2 Italy, 3 Spain, 4 Australia

This chapter introduces three case studies that describe how aspects related to the serviceability limit state design associated with the time-dependent behaviour of concrete can be considered in a design situation. The first case study considers the Oxec II Bridge in Guatemala. It provides an overview of the stress verification of the steel section of the composite bridge and accounts for concrete time effects to capture the stress redistribution that occurs between the concrete and the steel components. The second case study deals with the Yalquincha Viaduct in Chile and provides an overview of the type of long-term analyses that can be carried out when considering the influence of different cross-sectional arrangements on the time-dependent response of the bridge. The last case study focusses on the Serra Cazzola Viaduct in Italy and highlights the opportunities available to designers in exploiting optimised casting sequences to reduce the time-dependent stresses induced in the concrete and, therefore, mitigate the likelihood of concrete cracking.

8.1 Introduction

This chapter illustrates how aspects related to the time-dependent response of concrete have been dealt with in the serviceability limit state design of composite steel-concrete bridges. For this purpose, three case studies are considered.

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Time-Dependent Behaviour and Design of Composite Steel-Concrete Structures

Steel-concrete composite structures are widely used throughout the world for buildings and bridges. A distinguishing feature of this form of construction is the combination of concrete and steel components to achieve enhanced structural performance.

The time-dependent response of concrete and its influence on the service behaviour and design of composite structures are the main focus of this SED. For the first time, a publication combines a state-of-the-art review of the research with the available design specifications of Europe, Australia and New Zealand, and USA. This publication intends to enhance the awareness of the service response of composite structures and of the latest research and standards' developments. It is aimed at designers and researchers alike.

The review of research available in open literature is provided and arranged according to structural typologies, i. e. slabs, beams, and columns. It serves as background information for current service design rules and provides insight into the most recent research advancements. The review of available design guidelines presents the similarities and differences of the recommended service design procedures influenced by concrete time effects. Selected case studies of building and bridge projects show possible design approaches and the rationale required when dealing with the time-dependent response and design of composite structures.

The authors of this publication are design engineers and academics involved in the service design and research on the time-dependent response of composite structures.

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