Preface

Current Design Philosophy

Current codes of practice for the design of structures have been developed within the context of the limit-state philosophy: A structure or member is first designed so as to exhibit specified performance after attaining its load-carrying capacity, i.e. when its *ultimate limit state* is reached; the design is complemented or even revised during a process of checking whether the structure or member exhibits the desired behavioural characteristics under service conditions, i.e. at the *serviceability limit state*.

Anticipated Benefits

The adoption of the limit-state philosophy as the basis of current codes of practice for the design of concrete structures expresses the conviction that this philosophy is capable of leading to safer and more economical design solutions. After all, designing a structural concrete member to its ultimate limit state requires the assessment of the load-carrying capacity of the member and this provides a clearer indication of the margin of safety against collapse. At the same time, the high internal stresses which develop at the ultimate limit state result in a reduction of the member cross-section and the amount of reinforcement required to sustain internal actions. (Admittedly, the latter economy and, of course, safety itself are dependent on the actual safety factor adopted; nevertheless, the more accurate estimate of the true failure load provides an opportunity to reduce the uncertainties reflected in the factor of safety in comparison with, say, elastic design solutions).

Shortcomings

In contrast to the above expectations for more efficient design solutions, there have been instances of concrete structures which have been reported to have suffered unexpected types of damage under earthquake action, whereas a number of attempts to investigate experimentally whether or not the aims of limit-state philosophy for safety and economy are indeed achieved by current codes of practice have yielded conflicting results. Experimental evidence has been published that describes the behaviour of a wide range of structural concrete members (such as, for example, beams, columns, beam-column joints, walls, etc.) for which current methods for assessing structural performance yield predictions exhibiting excessive deviations from the true behaviour as established by experiment. In fact, in certain cases the predictions underestimate considerably the capabilities of a structure or member—indicating that there is still a long way to go in order to improve the economy of current design methods—while in other cases the predictions are clearly unsafe as they overestimate the ability of a structure or member to perform in a prescribed manner, in spite of the often excessive amount of reinforcement specified; and this provides an even more potent pointer to the fact that the rational and unified design methodology is still lacking in structural concrete. The lack of such a methodology is also reflected in the complexity and the segmented per structural element and performance requirement nature of the code specifications.

Need for Revision of Design Methods

As it will become apparent in the following chapter, the investigation of the causes of the above shortcomings led to the conclusion that the conflicting predictions are due to the inadequacy of the theoretical basis of the design methods which are used to implement the limit-state philosophy in practical design, rather than the unrealistic nature of the aims of the design philosophy as such. In fact, it was repeatedly shown that the fundamental assumptions of the design methods which describe the behaviour of concrete at both the material and structure levels were adopted as a result of misinterpretation of the available experimental information and/or use of concepts which, while working well for other materials (e.g. steel) or regimes (e.g. elastic behaviour), are not necessarily always suitable to concrete structures under ultimate-load conditions, i.e. at the ultimate limit state. Therefore, it becomes clear that the theoretical basis of current design methods requires an extensive revision if the methods are to consistently yield realistic predictions as a result of a rational and unified approach.

Proposed Revisions

Such a revision has been the subject of comprehensive research work carried out by Kotsovos and Pavlovic over the past three decades. This was done concurrently at two levels. One of these—the 'higher' level—was based on formal finite-element (FE) modelling of structural concrete with realistic material properties and behaviour as its cornerstone: a large part of the ensuing results are contained in the book by Kotsovos and Pavlovic, *Structural Concrete*, published in 1995; those obtained after 1995 are intended to be included in a new edition of the book. At the second—the 'lower', level an attempt was made to reproduce the essential results of complex numerical computations by means of much simpler calculations which would require no more effort than is the case with current code provisions. The latter approach was deemed necessary because, although the Kotsovos and Pavlovic's FE model has proved useful as a consultancy tool for the design, redesign, assessment and even upgrading of reinforced concrete structures, the fact remains that most design offices still rely on simplified calculation methods which, if not quite 'back-of-the-envelope' stuff, are quick, practically hand-based (or easily programmable), provide (or claim to provide) a physical feel for the problem, and, of course, conform to the simple methodology of code regulations.

Compressive-Force Path Method

The alternative methodology at this level, which stems from the Kotsovos and Pavlovic's work and is the subject of their book *Ultimate Limit-State Design of Concrete Structures*, published in 1999, and which provided the basis for a new, improved design approach for the implementation of the limit-state philosophy into the practical design of concrete structures, involves, on the one hand, the identification of the regions of a structural member or structure at its ultimate limit state through which the external load is transmitted from its point of application to the supports, and, on the other hand, the strengthening of these regions so as to impart to the member or structure desired values of load-carrying capacity and ductility. As most of the above regions enclose the trajectories of internal compressive actions, the new methodology has been termed the 'compressive-force path' (CFP) method. In contrast to the methods implemented in current codes of practice, the proposed methodology is fully compatible with the behaviour of concrete (as described by valid experimental information) at both the material and structure levels capable of producing design solutions that have been found to satisfy the code performance requirements in all cases investigated.

It may also be of interest to note that, although the CFP method might appear, at first sight, to be a rather unorthodox way of designing structural concrete, it is easy, with hindsight, to see that it conforms largely to the classical design of masonry structures by Greek and Roman Engineers. These tended to rely greatly on arch action—later expressed (and extended) through the Byzantine dome and the Gothic vaulting. Now, such a mechanism of load transfer may seem largely irrelevant for a beam exhibiting an elastic response. However, for a cracked reinforced concrete girder close to failure the parallel with an arch-and-tie system reveals striking similarities between the time-honoured concept of a compressive arch and the newly proposed CFP method.

Revised Compressive-Force Path Method

Since the publication of the book by Kotsovos and Pavlovic in 1999, the first of the authors has focused his efforts into generalising the CFP method so as to extend its application into the whole range of practical cases covered by current codes of practice for the design of RC structures, earthquake-resistant RC structures inclusive. This was achieved by replacing the failure criteria with simple expressions which were derived from first principles without the need for calibration through the use of experimental data on structural concrete behaviour. The implementation of these criteria into the CFP method not only simplified the assessment of the strength characteristics of structural concrete, but also led to a drastic revision of the method and extended its use into the whole range of structural elements of common RC structures.

Present Book

The aim of the present book, therefore, is to introduce to designers the revised version of the '*Compressive-Force Path*' *Method*. Such an introduction not only includes the description of its underlying theoretical concepts and their application in practice but, also, presents the causes which led to the need for a new design methodology for the implementation of the limit-state philosophy into practical structural design together with evidence—both experimental and analytical—supporting its validity.

The book is divided into eight chapters. Chapter 1 presents in a unified form and discusses all available information on the conflict between the concepts underlying current code provisions and the causes of the observed and/or measured structural behaviour. The information presented in Chap. 1 is summarised in Chap. 2 so as to form the theoretical basis of the proposed design methodology. The latter forms the subject of Chaps. 3–7 which concentrate not only on its description but, also, on its implementation into practical design and the presentation of evidence of its validity.

More specifically, Chap. 3 presents the physical model which underlies the application of the methodology for the design of simply supported beams, together with failure criteria capable of providing a realistic prediction of the load-carrying capacity for all types of behaviour characterising such beams. The physical model and the failure criteria presented in Chap. 3 are used for the development of the design method discussed in Chap. 4; this method is extended so as to apply for punching, as described in Chap. 5, and for any structural concrete configuration comprising beam, column or wall elements, as described in Chap. 6. Chapter 7 demonstrates that the proposed methodology is also applicable to the design earthquake-resistant RC structures without the need of the modifications normally required by the methods adopted by current codes for the design of RC structures under normal loading conditions. Finally, the presentation of typical examples of the application of the proposed method in design forms the subject of Chap. 8.

The author is fully aware, of course, that code tenets cannot be ignored by the majority of designers, not only because of legal implications but, more positively, many guidelines accumulate vast practical experience regarding the detailing of a wide range of reinforced concrete structures. Nevertheless, there are clearly problems for which code guidelines are less successful, and such difficulties need to be addressed. The present book is intended to address such problems. Ultimately, however, it is up to the experienced engineer, as well as the young graduate or student well acquainted with present-day code rules, to decide whether or not ideas contained in this book do, in fact, provide a rational alternative to the design of structural concrete members.

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