Structural systems: behaviour and design

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'To the memory of my parents'

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> *"Πεπαιδευμένον γαρ εστιν*
> *επι τοσουτω το ακριβές επιζητειν*
> *όσον η του πράγματος φύσις επιδέχεται"*
> *Αριστοτέλης*
>
> *"Because it is the essence of education*
> *to seek as much accuracy*
> *as the nature of things allows"*
> *Aristoteles*

Preface

What a technically educated person (engineer, architect or constructor) understands today by the term 'structural design' is practically the same as what his fellow man meant 500 – or even more – years ago, namely a procedure based on the application of a particular item of knowledge, and because of which a structure will 'stand up' and not 'fall down', under whatever actions it may be exposed to during its life span.

However, what changed over the years and took the so-called 'structural theory' out of the realm of empiricism and intuition was the introduction of analysis in the assessment of structural behaviour and its elevation to an applied scientific field. Of course, the evolution of computational methods together with the wide availability of computer facilities played decisive roles in this.

Structural mechanics is now a highly demanding subject, not only from the point of view of its analytical treatment regarding structural behaviour but also with regard to its evaluation and practical application in structural design. Both of these directions have quite distinct characteristics.

The analytical approach always poses the question: *Given a structural configuration and a certain loading, what is the response and its corresponding deformations?* This is a problem governed by strict analytical conditions and requirements, establishing in this way the scientific character of the subject matter, but sometimes creating the illusion that the process of analysis is an end in itself. Of course, the solution to this problem is nowadays ensured, due to powerful numerical methods and the wide availability of personal computers.

On the other hand, the practical aspects focus on the application of load-carrying behaviour in the conceptual and working design of structures, by posing the essential question: *Given the physical environment and the prevailing service requirements, what structural system made of the appropriate materials will meet the necessary load-bearing requirements in an economical and aesthetically satisfactory way?* This problem does indeed constitute an end in itself.

It is the first approach which has become established, over the years, in education for many reasons, all of them hinging on the fact that it is this approach which ensures the appropriate 'scientific' profile. The second approach, although more realistic, seldom attracts the attention it deserves in the educational civil engineering curricula, a fact that the student unfortunately becomes aware of at a rather later stage, to his or her disappointment.

Indeed, the almost exclusive concentration on the computational aspect of structural mechanics dramatically deprives the young and inexperienced engineer from the physical perception of the load-carrying characteristics of a structural system, something which is not due solely to his or her lack of experience. The student concerned, being used to the study of complicated computational scenarios, tends to lack the mental clarity that permits the direct structural perception which is so often required either by the collaborating architect or the constructor on the building site.

In this book, an approach to the understanding of load-carrying mechanisms and the behaviour of a wide range of structural systems is presented, with subsequent application to relevant design decisions, which, relying in principle on physical comprehension, is carried out through simple analytical reasoning. However, despite the prevailing non-computer-oriented philosophy, it is recognised throughout this book that the computational procedure in the design office practice needs in every case to be underpinned by the appropriate computer software. A necessary condition, though, for the successful use of such software is the ability of the user to derive, even approximately, results based on a well-cultivated structural perception regarding the load-carrying action and the subsequent preliminary design, which should in any case precede any computer modelling and the corresponding computation: this is exactly what the present book aims at.

Thus, through the study of basic load-bearing actions and the behaviour of typical systems, such as simply supported and continuous beams, frames, arches, cable structures of any type, grids, plates, shells, rectilinear and curved thin-walled beams, and multi-storey systems, an attempt has been made to bring insights into these load-carrying characteristics that are necessary for their design and are usually overshadowed by a strictly analytical examination. In this respect, particular attention has been given to the use of reinforced and prestressed concrete, as well as to composite structures, in addition to the 'traditional' consideration of steel as the most 'convenient' material. Due attention has also been given to the plastic analysis and design of skeletal structures as well as to second-order theory and stability effects, with an emphasis on their practical and efficient use.

However, it has been deemed an absolute necessity to consider in advance and in some detail the handling of plane skeletal statically determinate and indeterminate structures in two respective chapters. Moreover, the dynamic behaviour of discrete-mass structures has been examined in the penultimate chapter, where not only the response of multi-storey systems to earthquake but also that of beams and plates to human-induced dynamic actions as well as to machine operation is discussed.

Of course, complete consideration of structural design must also include the foundation problem. Thus, the final chapter is dedicated to this issue, dealing primarily with the behaviour and design of shallow foundations, but also with soil–structure interaction and, to a lesser extent, the pile foundations.

It is hoped that, through the systematic examination of the above subjects, the basic elements of structural perception are emphasised which permit the safe preliminary design and dimensioning of any structure, such as a bridge, building, roofing of a large space etc. These elements constitute the basis of not only appropriate computer modelling but also of the deliberate acceptance – or not – of the numerical results produced by software, which is a very important issue.

This book follows a strictly progressive path in the presentation of various subjects. Thus, later chapter build only on previously examined concepts, and some basic knowledge of elementary mechanics is considered a prerequisite.

As is well known – since the first century BC, from the Roman architect Vitruvius – a successful structural concept requires the satisfaction of four characteristic properties, namely *technical safety*, *functionality*, *economy* and *aesthetic quality*. Technical safety means that the available strength should be greater than the resulting response; functionality means, structurally, the control of different deformational characteristics, annoying vibrations included; economy means the successful selection of the structural and foundation system, as well as of the appropriate construction method; and aesthetic quality means the achievement of structural elegance.

While the first two criteria are the subject of a knowledgeable technical analysis, successfully meeting the last two requires, on the part of the engineer, ingenuity, creativity and aesthetic judgment – properties not acquired by studying the prevailing design characteristics of the structural systems but are nevertheless prerequisites. Thus, although the successful design of a structure is based on the technical and aesthetic talent of the engineer, the knowledge of the structural principles put forward in this book are an essential basis for any such endeavour.

This book is aimed at everyone engaged in the study of structural analysis and design, either as a student, a practising engineer, or even as an architect seeking for a more profound structural understanding of bridge or building engineering. I hope that this books proves useful and achieves its goals.

Finally, I would like to express my gratitude to Thomas Telford Ltd for undertaking the publication of this edition of this book and the excellent collaboration with the editorial team, whose authoritative and knowledgeable direction under Matthew Lane has led to an entirely satisfactory result.

L.T. Stavridis
Athens, June 2010

Foreword

In the process of designing, engineers have to consider the different alternatives for structures, aiming generally towards an optimum of functional performance, resistance, durability and also towards a minimum of costs. In the dialogue with architects, the overall design as well as the suitable structural elements are looked for. Hence, the engineer has to master the art of structural design, has to understand the behaviour and the functions of beams, frames, plates, shells etc. Engineering knowledge is more than the ability to analyse a structure. It enables engineers to propose structural systems and also to determine a first estimation of the overall and sectional dimensions needed.

A computer aided numerical analysis can be applied only after the design is chosen. It is a complementary tool, especially helpful to obtain results for dimensioning the structure and for parameter variations. For checking and validating computer results it is needed to apply engineering judgement, plausibility considerations and e.g. simple equilibrium checks.

An engineer is a good engineer when he or she – even on vacation – does not only admire structures like bridges, towers, buildings, but when he or she is visualising the flow of forces, the structural elements for tension and those for compression, perhaps even imaging moment diagrams. This is rather easy where 'form follows function' (L.H. Sullivan) as for instance in suspension bridges, yet difficult for more complex structures such as thin shell structures.

The book of Professor Stavridis *Structural systems: behaviour and design* follows the above issues very consistently, making a remarkable contribution to this rather rarely encountered book genre. It is an excellent textbook, especially for Civil Engineering students and young professionals. It covers the principal approaches to determine states of equilibrium and to calculate the deformations. For statically indeterminate structures, alternative methods are demonstrated using either forces or deformations as unknowns. In explaining the structural behaviour of beams, frames, plates, shells, thin-walled elements, pre-stressed concrete, foundation elements and dynamically incited systems, basic concepts and directly applicable approaches are presented that allow an estimation of crucial quantities for the design of a very wide range of structures, including bridges, buildings, roofing of larger spaces and foundations. Many graphic figures help to visualise the underlying mechanics. Thus, the main objective is very well achieved: to promote structural understanding as a complementary tool to computer analyses, to make students and readers fit for the art of designing.

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Foreword

Methods of structural analysis have experienced an explosive growth during the last 40 years. But it was the advent of powerful personal computers, along with the evolution of numerical tools (based mainly on the finite element method) and the parallel development of numerous reliable, comprehensive, commercially available computer software, that have enabled the engineer to tackle very complex structural systems. As a consequence, in today's design offices, analysis of even some rather simple systems is performed (especially by the younger generation of engineers) with the use of such computer codes. Classical as well modern methods of structural analysis (based on the principles of virtual work, compatibility of deformations, matrix analysis) are rather rarely invoked in everyday practice. Yet, these theoretical tools often constitute the major (if not the only) part of the curriculum in civil engineering schools.

Several problems may arise from this state of affairs. First, the danger of the '*black-box syndrome*': when a sophisticated code is used without the analyst having the ability to check if the results are indeed reasonable and to spot any errors in the physical meaning of his/her implicit assumptions and on how these assumptions are materialised in the model. Second, there is little if any training to help the young engineer develop a deeper understanding of how structural systems behave, let alone to sharpen his/her physical intuition; such understanding and intuition are necessary especially in the conception and preliminary design stages. Indeed, conceptual clarity and physical insight are rarely mentioned as key objectives of structural analysis courses.

The book by Professor Leonidas Stavridis offers a much needed addition to classical computational structural analysis: a physical approach is developed in which a structural system is decomposed into elements whose behaviour to the applied loads is easily computed '*from the basics*'. Starting in the first chapters with fundamental concepts and applications, the step-by-step exposition becomes progressively more advanced. Structural analysis blends naturally with mechanics of materials – the latter include reinforced and pre-stressed concrete, steel and composites. The in-depth analysis of standard structural systems (such as simply and multi-supported beams, frames, arches, cabled beams) is followed by the exposition of some more advanced topics such as buckling, plates and shells, thin-walled and box girders, grids and curved beams, laterally-loaded multi-story frames and shear walls.

It is amazing how the analysis of such complex systems is made so simple, clearly understandable even to a non-specialist civil engineer, as the present writer. This is accomplished to a large extent thanks to the numerous illustrative figures (sketches) which go far beyond the usual 'formalistic' figures of most available textbooks: they are imaginative, vivid, self-explanatory. What a difference they make when trying to comprehend difficult topics! For instance, the chapter on 'Shells' contains 51 elaborate figures, most of which comprise several sketches while a few of them are a whole page long. The 3D nature of cylindrical, spherical, paraboloid, and conical shells is elucidated with the help of ingeniously-selected isometric views and numerous cross-sections, so that the reader feels that this is a rather simple subject.

As an engineer with special interest in soil–foundation–structure interaction I was particularly happy with the comprehensive treatment of foundations. Viewed mainly from a structural engineer's viewpoint, the pertinent chapter deals not only with some classical deformation-settlement and stress-distribution problems, but also with the interplay between foundation stiffness and structure distress.

I believe this book will prove invaluable to both students and active engineers in helping them not only to absorb a huge volume of material but (more significantly) to cultivate '*engineering intuition*' and develop insight into the physics of structural analysis. For students, in particular, all this will offer the motivation for further study and the desire to later apply in real-life projects both the material and the methodology developed in the book.

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