Plates and FEM

SOLID MECHANICS AND ITS APPLICATIONS

Volume 171

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Plates and FEM

Surprises and Pitfalls

Springer

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To Henny

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Preface

The Finite Element Method, shortly FEM, is a widely used computational tool in structural engineering. For basic design purposes it usually suffices to apply a linear-elastic analysis. Only for special structures and for forensic investigations the analyst need to apply more advanced features like plasticity and cracking to account for material nonlinearities, or nonlinear relations between strains and displacements for geometrical nonlinearity to account for buckling. Advanced analysis techniques may also be necessary if we have to judge the remaining structural capacity of aging structures. In this book we will abstain from such special cases and focus on everyday jobs. Our goal is the worldwide everyday use of linear-elastic analysis, and dimensioning on basis of these elastic computations. We cover steel and concrete structures, though attention to structural concrete prevails.

Structural engineers have access to powerful FEM packages and apply them intensively. Experience makes clear that often they do not understand the software that they are using. This book aims to be a bridge between the software world and structural engineering. Many problems are related to the correct input data and the proper interpretation and handling of output. The book is neither a text on the Finite Element Method, nor a user manual for the software packages. Rather it aims to be a guide to understanding and handling the results gained by such software.

We purposely restrict ourselves to structure types which frequently occur in practise. We consider shear walls and other two-dimensional structures loaded in their plane (*membrane state*), and we deal with floor and bridge structures loaded perpendicular to their plane (*bending state*). The content reflects the subject matter of continuing education courses in European countries, such as Belgium and the Netherlands.

The book is composed of four parts. In the first one we present an overview of the classical theory of plates in the membrane and bending state. This is considered necessary in order to better understand instructions to be given in later parts. For a few relevant examples which play an illustrative role exact solutions are presented. To some extent the presentation for plates in the membrane state diverges from classical text books. There all membrane problems are discussed on basis of the well-known Airy function. This theory can be considered as an application of the force method in which stress function is chosen as the statically dependent quantity. However, this method is completely opposite to the current displacement method (stiffness method) as applied in the finite element method. We consider this an unwanted discrepancy and anachronism, and therefore have chosen a displacement method for the membrane state as well. The degree of difficulty does not become higher, while there is now uniformity with the theory for the bending state. We resort to Airy's theory only for some well-known classical solutions. The problem of discrepancy and anachronism does not occur for plates in bending and transverse shear, because the relevant classical differential equations are already based on the displacement method. For this category another aspect needs attention, more than usually given in classical text books. Nowadays, explicit clarification is needed on the difference between thick plates (Mindlin–Reissner) and thin plates (Kirchhoff), because both options are offered in commercial software and surprising choices appear to have been made as default option or are made by users.

Before moving to the main body of the book we direct attention in Part 2 of the book to some instructive computational models of pre-FEM days. These are re-called for both plates in membrane state and plates in bending. It is believed that they are of great didactical value, particularly for plates in bending.

The contents of Part 3 of the book provide the impetus for publication. We intend to help the structural engineer in handling linear-elastic computational results in daily practice. This part starts with an overview of the stiffness method, as applied in commercial FEM packages. We review element types which are relevant to the subject matter of the book, discuss input options, and review output selection. We address the subject that results of the calculation are highly dependent on the structural engineer who performs the computation, and give hints how to avoid dependency on mesh fineness. We show how FE analysis can support application of the strut-and-tie design model and draw attention to several surprises and pitfalls. We are pleased with the contribution of Professor Paulo Lourenço of Minho University in Portugal on reinforcement design of plates in membrane state, bending-shear state or combined membrane-bending-shear state. We also review a couple of contemporary two-way slab systems, and consider options for calculating the deflection and crack-width in the serviceability state.

The final part of the book (Part 4) is another reason for publication: it deals with orthotropy as it occurs in bridge and floor systems. The focus for these orthotropic properties is on calculating correct input rigidity data, and determining whether computed plate moments and shear forces match code requirements. Noticing odd outcomes we observe a definite need for clarification of this subject matter. Orthotropic properties also render a service when structural engineers want to calculate deflections and crack-widths in the cracked serviceability state.

Acknowledgements

We happily acknowledge the support of Dr. Anton W.M. Kok, the spiritual father of the FE code *Kola*. We are indebted to Dr. Cox W.M. Sitters for brushing up the text and figures on theory, gratefully acknowledge the help of Dr. Pierre C.J. Hoogenboom in calculating examples, and highly value the writing hints of Professor Graham M.L. Gladwell of the University of Waterloo. We very much appreciated the contributions of software providers Nemetschek-Scia, Buildsoft, Technosoft and Matrix. The Structural Mechanics group of Civil Engineering in Delft University of Technology, PAO Foundation for Post Graduate Education, Delft Cluster organization on delta technology and infrastructural research, and Martens Group in the Netherlands have shown stimulating interest, facilitating a productive stay at the University of California in San Diego. We enjoyed the encouraging exchange of thoughts with Professors José Restrepo and Joel Conte. Particular thanks are due to publishing editor Nathalie Jacobs of Springer for her dedicated promotion, to Anneke Pot for assistance, and to Jolanda Karada for her great job in styling the book.

Free Software

For the majority of the Finite Element Analyses in this book we applied the program *KolaLight*, which was developed for teaching purposes by Anton W.M. Kok, former Associate Professor in the Structural Mechanics Group of the Faculty of Civil Engineering and Geosciences (CiTG) in Delft University of Technology in the Netherlands. The reader can freely download the program and documentation from internet. The link is

http://www.mechanics.citg.tudelft.nl/kolalight

We also offer a free program *RCShell* for the application of the theory for reinforcement design on the basis of linear-elastic analysis as discussed in Chapter 16. The author of the program is Paulo B. Lourenço, Professor in the Masonry and Historical Constructions Group, Department of Civil Engineering, University of Minho, Guimarães, Portugal. The links to the menu and fortran files are

http://www.civil.uminho.pt/masonry/Software/RCShell.zip (menu)
http://www.civil.uminho.pt/masonry/Software/Reinforcement.zip (fortran)

Conversion of SI Units to Imperial Units

1 SI unit = C USCS units

$\frac{1}{C}$ SI units = 1 USCS unit

SI Unit	***C***	***1/C***	***Imperial***
Area			
1 m^2	10.76	0.0929	ft^2
1 mm^2	1.55×10^{-3}	645	in^2
Distributed line load			
1 N/m	0.0685	1.46	lbf/ft
1 kN/m	0.0306	32.7	tonf/ft
1 N/m	5.71×10^{-3}	175	lb/in
1 kN/m	2.55×10^{-3}	392	tonf/in
Distributed area load			
1 N/m^2	0.0209	47.9	lbf/ft^2
1 kN/m^2	0.0933	10.7	$tonf/ft^2$
$1N/m^2$	0.145×10^{-3}	6.89×10^3	lbf/in^2
$1kN/m^2$	64.7×10^{-6}	15.5×10^3	$tonf/in^2$
Force			
1 N	0.225	4.45	lbf
1 kN	0.100	9.96	tonf
Length			
1 m	3.28	0.305	ft
1 mm	0.0394	25.4	in

SI Unit	***C***	***1/C***	***Imperial***
Moment. Torque			
1 N·m	0.738	1.36	lbf·ft
1 N·m	8.85	0.113	lbf·in
1 kN·m	0.329	3.04	tonf·ft
1 kN·m	3.95	0.253	tonf·in
Moment in plate			
1 N·m/m	0.225	4.45	lbf·ft/ft
1 N·m/m	0.225	4.45	lbf·in/in
1 kN·m/m	0.100	9.96	tonf·ft/ft
1 kN·m/m	0.100	9.96	tonf·in/in
Shear force in plate			
1 N/m	0.0685	14.6	lbf/ft
1 kN/m	0.0305	32.8	tonf/ft
1 N/m	5.71×10^{-3}	175	lbf/in
1 kN/m	2.55×10^{-3}	392	tonf/in
Moment of inertia (second moment of area)			
1 mm^4	2.40×10^{-6}	0.416×10^{6}	in^4
1 m^4	2.40×10^{6}	0.416×10^{-6}	in^4
Pressure, Stress			
1 Pa	0.0209	47.9	lbf/ft^2
1 Pa	0.145×10^{-3}	6890	lbf/in^2
1 MPa	20.9×10^{3}	47.9 lbf/ft^2	
1 MPa	0.145×10^{-3}	7.20	lbf/in^2
1 MPa	93.3	0.0107	$tonf/ft^2$
1 MPa	0.648	1.54	$tonf/in^2$
Section modulus. Volume			
1 mm^3	0.0610×10^{-3}	16.4×10^{3}	in^4
1 m^3	0.0610×10^{6}	16.4×10^{-6}	in^4

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SI Unit	***C***	***1/C***	***US CS***
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1 m^2	10.76	0.0929	ft^2
1 mm^2	1.55×10^{-3}	645	in^2
Distributed line load			
1 N/m	0.0685	1.46	lb/ft
1 kN/m	0.0685	14.6	k/ft
1 N/m	5.71×10^{-3}	175	lb/in
1 kN/m	5.71×10^{-3}	175	k/in
Distributed area load			
1 N/m^2	0.0209	147.9	lb/ft^2
1 kN/m^2	0.0209	47.9	k/ft^2
1 N/m^2	0.145×10^{-3}	6.89×10^3	lb/in^2
1 kN/m^2	0.145×10^{-3}	6.89×10^3	k/in^2
Force			
1 N	0.225	4.45	lb
1 kN	0.225	4.45	k
Length			
1 m	3.28	0.305	ft
1 mm	0.0394	25.4	in

SI Unit	***C***	***1/C***	***US CS***
Moment. Torque			
1 N·m	0.738	1.36	ft-lb
1 N·m	8.85	0.113	in-lb
1 kN·m	0.738	1.36	ft-k
1 kN·m	8.85	0.113	in-k
Moment in plate			
1 N·m/m	0.225	4.45	ft-lb/ft
1 N·m/m	0.225	4.45	in-lb/in
1 kN·m/m	0.225	4.45	ft-k/ft
1 kN·m/m	0.225	4.45	in-k/in
Shear force in plate			
1 N/m	0.0685	14.6	lb/ft
1 kN/m	0.0685	14.6	k/ft
1 N/m	5.71×10^{-3}	175	lb/in
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Moment of inertia (second moment of area)			
1 mm^4	2.40×10^{-6}	0.416×10^{6}	in^4
1 m^4	2.40×10^{6}	0.416×10^{-6}	in^4
Pressure. Stress			
1 Pa	0.0209	47.9	psf
1 Pa	0.145×10^{-3}	6890	psi
1 MPa	20.9	0.0479	ksf
1 MPa	0.145	6.89	ksi
Section Modulus. Volume			
1 mm^3	0.0610×10^{-3}	16.4×10^{3}	in^4
1 m^3	0.0610×10^{6}	16.4×10^{-6}	in^4