Premier Reference Source

Computational Modeling of Masonry Structures Using the Discrete Element Method

Vasilis Sarhosis, Katalin Bagi, José V. Lemos, and Gabriele Milani

IGI Global
DISSEMINATOR OF KNOWLEDGE

Computational Modeling of Masonry Structures Using the Discrete Element Method

Vasilis Sarhosis
Newcastle University, UK

Katalin Bagi
Budapest University of Technology and Economics, Hungary

José V. Lemos
National Laboratory for Civil Engineering, Portugal

Gabriele Milani
Technical University in Milan, Italy

A volume in the Advances in Civil and Industrial Engineering (ACIE) Book Series

ENGINEERING SCIENCE REFERENCE
An Imprint of IGI Global

Published in the United States of America by
Engineering Science Reference (an imprint of IGI Global)
701 E. Chocolate Avenue
Hershey PA, USA 17033
Tel: 717-533-8845
Fax: 717-533-8661
E-mail: cust@igi-global.com
Web site: http://www.igi-global.com

Library of Congress Cataloging-in-Publication Data

Names: Sarhosis, Vasilis, 1981- editor.
Title: Computational modeling of masonry structures using the discrete element method / Vasilis Sarhosis, Katalin Bagi, J.V. Lemos, and Gabriele Milani, editors.
Description: Hershey PA : Engineering Science Reference, [2016] | Includes bibliographical references and index.
Identifiers: LCCN 2016003307| ISBN 9781522502319 (hardcover) | ISBN 9781522502326 (ebook)
Subjects: LCSH: Masonry--Data processing. | Brickwork--Mathematics. | Stone buildings--Mathematical models. | Discrete element method.
Classification: LCC TH1199 .C678 2016 | DDC 624.1/830113--dc23 LC record available at https://lccn.loc.gov/2016003307

This book is published in the IGI Global book series Advances in Civil and Industrial Engineering (ACIE) (ISSN: 2326-6139; eISSN: 2326-6155)

British Cataloguing in Publication Data
A Cataloguing in Publication record for this book is available from the British Library.

Advances in Civil and Industrial Engineering (ACIE) Book Series

ISSN: 2326-6139
EISSN: 2326-6155

Mission

Private and public sector infrastructures begin to age, or require change in the face of developing technologies, the fields of civil and industrial engineering have become increasingly important as a method to mitigate and manage these changes. As governments and the public at large begin to grapple with climate change and growing populations, civil engineering has become more interdisciplinary and the need for publications that discuss the rapid changes and advancements in the field have become more in-demand. Additionally, private corporations and companies are facing similar changes and challenges, with the pressure for new and innovative methods being placed on those involved in industrial engineering.

The **Advances in Civil and Industrial Engineering (ACIE) Book Series** aims to present research and methodology that will provide solutions and discussions to meet such needs. The latest methodologies, applications, tools, and analysis will be published through the books included in **ACIE** in order to keep the available research in civil and industrial engineering as current and timely as possible.

Coverage

- Engineering Economics
- Structural Engineering
- Urban Engineering
- Production Planning and Control
- Coastal Engineering
- Productivity
- Earthquake engineering
- Quality Engineering
- Hydraulic Engineering
- Construction Engineering

The Advances in Civil and Industrial Engineering (ACIE) Book Series (ISSN 2326-6139) is published by IGI Global, 701 E. Chocolate Avenue, Hershey, PA 17033-1240, USA, www.igi-global.com. This series is composed of titles available for purchase individually; each title is edited to be contextually exclusive from any other title within the series. For pricing and ordering information please visit http://www.igi-global.com/book-series/advances-civil-industrial-engineering/73673. Postmaster: Send all address changes to above address.

Titles in this Series

For a list of additional titles in this series, please visit: www.igi-global.com

Advanced Research on Nanotechnology for Civil Engineering Applications
Anwar Khitab (Mirpur University of Science and Technology, Pakistan) and Waqas Anwar (Mirpur University of Science and Technology, Pakistan)
Engineering Science Reference • copyright 2016 • 339pp • H/C (ISBN: 9781522503446) • US $195.00 (our price)

Emerging Challenges and Opportunities of High Speed Rail Development on Business and Society
Raj Selladurai (Indiana University Northwest, USA) Peggy Daniels Lee (Kelley School of Business, Indiana University, USA) and George VandeWerken (Providence Bank, USA)
Engineering Science Reference • copyright 2016 • 289pp • H/C (ISBN: 9781522501022) • US $210.00 (our price)

Advanced Manufacturing Techniques Using Laser Material Processing
Esther Titilayo Akinlabi (Univeristy of Johannesburg, South Africa) Rasheedat Modupe Mahamood (University of Johannesburg, South Africa & University of Ilorin, Nigeria) and Stephen Akinwale Akinlabi (University of Johannesburg, South Africa)
Engineering Science Reference • copyright 2016 • 288pp • H/C (ISBN: 9781522503293) • US $175.00 (our price)

Handbook of Research on Applied E-Learning in Engineering and Architecture Education
David Fonseca (La Salle Campus Barcelona, Universitat Ramon Llull, Spain) and Ernest Redondo (Universitat Politècnica de Catalunya, BarcelonaTech, Spain)
Engineering Science Reference • copyright 2016 • 569pp • H/C (ISBN: 9781466688032) • US $310.00 (our price)

Emerging Design Solutions in Structural Health Monitoring Systems
Diego Alexander Tibaduiza Burgos (Universidad Santo Tomás, Colombia) Luis Eduardo Mujica (Universitat Politecnica de Catalunya, Spain) and Jose Rodellar (Universitat Politecnica de Catalunya, Spain)
Engineering Science Reference • copyright 2015 • 337pp • H/C (ISBN: 9781466684904) • US $235.00 (our price)

Robotics, Automation, and Control in Industrial and Service Settings
Zongwei Luo (South University of Science and Technology of China, China)
Engineering Science Reference • copyright 2015 • 337pp • H/C (ISBN: 9781466686939) • US $215.00 (our price)

Using Decision Support Systems for Transportation Planning Efficiency
Ebru V. Ocalir-Akunal (Gazi University, Turkey)
Engineering Science Reference • copyright 2016 • 475pp • H/C (ISBN: 9781466686489) • US $215.00 (our price)

IGI GLOBAL
DISSEMINATOR OF KNOWLEDGE
www.igi-global.com

701 E. Chocolate Ave., Hershey, PA 17033
Order online at www.igi-global.com or call 717-533-8845 x100
To place a standing order for titles released in this series, contact: cust@igi-global.com
Mon-Fri 8:00 am - 5:00 pm (est) or fax 24 hours a day 717-533-8661

Preface

Masonry is a combination of units such as stones, bricks or blocks usually laid in a cementitious or lime mortar. It is probably the oldest material used in construction and has proven to be both simple to build and durable. Over the years, existing masonry constructions have inevitably suffered damage with time. Earthquakes, soil settlements, material degradation and lack of maintenance are the main reasons for that. Careful and periodic assessment of such structures is necessary in order to evaluate their structural capacity and safety levels. However, performing the structural analysis of masonry construction is not an easy task.

Masonry is a material which is characterised by high non-linearity and discontinuity; it is the dry or mortar joints in a masonry structure which act as planes of weakness. When subjected to very low levels of stress, masonry behaves approximately in a linear elastic manner. This becomes increasingly non-linear after the formation of cracks and the subsequent redistribution of stress through the uncracked material as the structure approaches collapse. The behaviour of masonry is complicated further by the inherent variations in the constituent materials, variations in workmanship, the effects of deterioration caused by weathering processes and the development of other defects during the life of the masonry structure.

Accurate structural analysis is needed is needed to understand the behaviour of these many different forms of masonry constructions and avoid erroneous or defective conclusions. In particular it is important to understand the pre- and post-cracking behaviour to inform decisions concerning the maintenance needs, management of safety risks, assessment of levels of safety and the need for repair or strengthening. As experimental research is prohibitively expensive, it is fundamentally important to have available a computational model that can be used to predict the in-service and near-collapse behaviour with sufficient reliability.

The selection of the most appropriate method to use depends on, among other factors, the structure under analysis; the level of accuracy and simplicity desired; the knowledge of the input properties in the model and the experimental data available; the amount of financial resources; time requirements and the experience of the modeller. It should also be expected that different methods should lead to different results depending on the adequacy of the approach and the information available. Preferably, the approach selected to model masonry should provide the desired information in a reliable manner within an acceptable degree of accuracy and with least cost.

Engineering modelling of masonry structures is often based on continuum representations, using appropriate constitutive models, which provide an adequate solution for many practical cases. However, such models does not represent accurately the mechanical behaviour of masonry components. Over the last two decades, discontinuous models are applied with increasing frequency; since they intended at simulating the mechanical behaviour of masonry structures more accurately in a simplified micro modeling manner.

The present book focuses on the discrete element modelling of masonry structures, a designation that covers a variety of representations of a structure as a system of blocks (rigid or deformable) or particles. The possibility of frequent changes in the connectivity and the type of contact as well as marked non-linearity induced by the inability of the masonry joints to withstand tension makes the Discrete Element Method (DEM) a suitable approach for solving problems involving discontinuities as is the case with low bond strength masonry. Models based on the discrete element approach solve the equations of motion using a time stepping scheme and contact forces are obtained by means of the concept of joint stiffness, an approach related to the penalty methods. The resultant out of balance forces and motion parameters are calculated at each integration time step. Material deformability, complex contact interaction laws as well as failure and fracture criterial at the interfaces can be assigned. More recent implementations allow for an increased block deformability and block fracturing, comprising a combined discrete/finite element approach.

A review is presented of the main models based on the discrete element method and the available related numerical techniques that have been proposed for the analysis of masonry. The essential assumptions adopted by these models and numerical implementation issues are discussed. Differences between available models are illustrated by applications to various masonry problems including static and dynamic analysis of masonry arch bridges, walls, vaults, domes and ancient colonnades.

This book is composed of 17 chapters authored/co-authored by 25 outstanding researchers from 11 countries (Canada, France, Greece, Hungary, Iran,Italy, Mexico, Norway, Portugal, UK, USA), which were reviewed by 60 referees.

In Chapter 1, a review on the mechanical behaviour of masonry is presented. The aim is to establish a base of knowledge and understanding of masonry that will underpin its mechanical characteristics and will inform the decisions towards the selection of the computational tool used which are going to be described in the following chapters. Initially, a brief description of the factors that influence the mechanical response of masonry and the variation of the material properties are discussed. The review then considers the possible causes of cracking in masonry and the different failure modes that may occur during loading. Principal findings from the review are summarised at the end of the chapter.

In Chapter 2, a review of the available methods and their challenges to simulate the mechanical behavior of masonry structures are presented. Different micro-modeling computational options are considered and compared with regard to their ability to define the initial state of the structure, realism in simulation, computer efficiency and data availability for their application to model low bond strength masonry structures. It is highlighted that different computational approaches should lead to different results and these will depend on the adequacy of the approach used and the information available. From the results analysis it is also highlighted that a realistic analysis and assessment of existing masonry structures using numerical methods of analysis is not a straight forward task even under full knowledge of current conditions and materials.

In Chapter 3, the "distinct element method" is introduced. The distinct element method was proposed by Peter Cundall in 1971 for the analysis of rock slopes by means of rigid block or circular particle models. This method led to the UDEC and 3DEC codes, presently in wide use in rock engineering. Their application to masonry structures started in the 90's, as researchers found that they were also excellent tools to approach the highly nonlinear behavior of masonry, in particular the collapse processes of stone block structures under static or seismic loads. This chapter reviews the essential assumptions of UDEC and 3DEC, relating them to other methods and codes, and stressing the features that make them suitable for masonry analysis. Rigid and deformable blocks, contact mechanics, contact detection, and solution algorithms are examined. Key issues in the modelling of masonry are addressed, including: irregular block models; determination of collapse loads; large displacement analysis; computational efficiency issues in dynamic analysis. Practical examples taken from the published literature illustrate these issues.

In Chapter 4, the discontinuous deformation analysis (DDA) with polyhedral elements is presented. The basic degrees of freedom and the element behaviour are introduced. Also, the contact behaviour, the quantities in the equations of motion, and the time integration scheme are presented. A short comparison is given between DDA and 3DEC. Finally, applications of DDA to predict the mechanical behaviour masonry are shown.

In Chapter 5, the basic concepts of the Non-Smooth Contact Dynamics method are presented. For the sake of simplicity, detailed theoretical description is given only for the case of rigid elements; fundaments of modelling with deformable elements are then shortly summarized. Questionable features of NSCD such as non-uniqueness of the solution are emphasized. Finally, different applications of the Contact Dynamics method in the analysis of masonry structures are introduced.

In Chapter 6, the main processes of the combined finite-discrete element method are discussed including contact detection, contact interaction, fracture and fragmentation algorithms, calculation of deformations, parallelization and the time integration of the equations of motion. Different modelling approaches and examples connected to the structural analysis of masonry structures are mentioned which were found in the literature. Afterwards a brief comparison is made between FEM/DEM and other techniques belonging to the DEM.

In Chapter 7, the application of circular particle models to masonry structures is addressed. The potential of these techniques appears significant, due to their proven ability to simulate fracture processes through random particle assemblies representing quasi-brittle materials at the grain scale. The chapter presents the fundamentals of the numerical approach and reviews some previous applications to masonry. The capabilities of the model are exemplified by simple tests involving a few irregular blocks formed by particles. Examples of an irregular stone masonry wall specimen under compression and in-plane shear are also presented, considering failure processes through the joints and the stones.

In Chapter 8, the numerical modelling of masonry dams using the Discrete Element Method is presented. The chapter begins with a review of the history of masonry dams and their behaviour. A numerical tool based on the Discrete Element Method developed specifically for the structural assessment of masonry dams is then presented. The mechanical calculations performed by the tool are discussed in detail, together with the approach used for the modelling of passive anchors and the modules for seismic analysis and hydro-mechanical analysis. Structural and hydraulic analyses of a diverse set of existing masonry dams conducted using the tool are then presented. The Discrete Element Method is shown to be capable of reproducing the structural behaviour of masonry dams and identifying their likely failure mechanisms as required for structural safety evaluations.

In Chapter 9, the different aspects of simplified micro-modeling strategies including the Discrete Element Method (DEM) for modeling masonry-infilled frames are investigated. Masonry infill panels are represented by individual bricks and blocks separated by zero thickness interfaces representing mortar joints. A thorough overview of the different DEM studies performed on concrete and brick masonry-infilled frames are presented. The essential assumptions adopted by these models and numerical implementation issues are discussed outlined. Also, the advantages and disadvantages of modeling masonry infilled frames using the discrete element method are discussed. This 'discontinuum' approach, an alternative to modeling masonry as a homogenized continuum, is particularly suited for studying the mechanical behavior and interaction between of the individual brick/blocks and their interaction with the framed structure.

In Chapter 10, the effect of past drum dislocations on the vulnerability of classical columns and presents a performance-based framework for their seismic risk assessment. The vulnerability is numerically calculated through response estimations using detailed three-dimensional models based on the Discrete Element Method. Conditional limit-state probabilities are calculated and appropriate performance criteria are suggested. The proposed methodology is able to pinpoint cases where past damage affects the vulnerability of such structures

In Chapter 11, the most important structural components of historic unreinforced masonry buildings are considered. Gothic buttresses, arches of different shapes, and multidrum columns are analysed with the help of UDEC. Extensive parameter studies for the various types of structures are conducted, considering different geometric shapes and mechanical properties. The output of numerical simulations is compared with available analytical solutions. Modeling of dynamic problems is also addressed. The influence of stiffness, friction and damping parameters is assessed for the different types of masonry structures.

In Chapter 12, an overview of the major contributions for the analysis of limit stability of masonry arches during the last three decades is presented, together with the later developments of limit analysis. The solution of arch problems with DEM is addressed, and the numerical models are validated against analytical solutions of collapse loads for arches under gravity and lateral loading. An application of DEM to the safety assessment of an ancient tunnel structure is presented.

In Chapter 13, two engineering applications of the Distinct Element Method to the analysis of historic masonries are presented. In particular, the software UDEC, which implements DEM in a variety of engineering problems, is here used to analyse the Águas Livres aqueduct in Lisbon (Portugal) and multi-leaf masonry arch-tympana carrying systems of a basilica in Como (Italy). The second example analyses the arch-tympana carrying systems of a church in Italy. They present an unusual building technology, relying into a multiple-leaf arch, and a tympanum, made by a mixture of bad quality mortar and small stones. Again the structure is discretized into distinct elements and the load carrying capacity under dynamic excitation is evaluated, discussing the role played by the infill.

In Chapter 14, the feasibility of the utilization of a combined Finite Element/Discrete Element (FEM/DEM) approach to investigate the behaviour of masonry arch bridges is assessed. In particular, the Chapter proposes and discusses a possible approach to FEM/DEM modelling of two existing masonry arch bridges. Attention is paid to the assessment of the load carrying capacity of the structures by means of a suitable coupled FEM/DEM 2D approach.

In Chapter 15, the analysis of unreinforced masonry structures which are comprised of a finite number of distinct, interacting blocks that have length scales relatively comparable with the structure of interest, is concerned using the Discrete Finite Element Method (DFEM) developed by the author. DFEM is based on the finite element method incorporating contact elements: blocks are considered as solid sub-domains and contact elements are used to model block interactions such as sliding or separation.

In Chapter 16, a Semi-Discrete Model (SDM) is proposed for the study of freestanding blocks, in which the block is considered as a mass element supported by springs and dashpots, in the spirit of deformable contacts between rigid blocks. The advantages of the proposed model with respect to a full discrete model are discussed in further detail. The proposed model is able to reproduce the six motion states of the rigid bodies: rest, slide, rotation, slide-rotation, translation-jump and rotation-jump.

In Chapter 17, through some illustrative examples, the applicability of the Discrete Finite Element Method (DFEM) to the analysis of unreinforced masonry structures such as rock pillars, open rock slopes, underground openings, tunnels, fault propagations, and fault-structure interactions is examined and discussed. In the numerical study, the behaviour of contacts and blocks is assumed to be elasto-plastic or elastic. The Mohr-Coulomb yield criterion, representing material behaviour of contacts, is implemented in the developed codes for DFEM. The secant stiffness method together with the updated Lagrangian scheme is employed to deal with non-linear behaviour. The constant strain triangular element with two degrees of freedoms at each node, formed by properly joining the corners and contact nodes of an individual block, is adopted for finite element meshing of the blocks.

It is hoped that this book tool will be used by civil, architectural and mechanical engineering students, lecturers, researchers, asset managers, consultants and engineers to understand the different numerical approaches based on the discrete element method to be used for the structural assessment of masonry structures in their care.

Vasilis Sarhosis
Newcastle University, UK

Katalin Bagi
Budapest University of Technology and Economics, Hungary

José V. Lemos
Laboratório Nacional de Engenharia Civil, Portugal

Gabriele Milani
Politecnico di Milano, Italy
December 15, 2015

Table of Contents

Detailed Table of Contents

In this chapter, a review on the mechanical behaviour of masonry is presented. The aim is to establish a base of knowledge and understanding of masonry that will underpin its mechanical characteristics and will inform the decisions towards the selection of the computational tool used which are going to be described in the following chapters. Initially, a brief description of the factors that influence the mechanical response of masonry and the variation of the material properties are discussed. The review then considers the possible causes of cracking in masonry and the different failure modes that may occur during loading. Principal findings from the review are summarised at the end of the chapter.

In this chapter, a review of the available methods and their challenges to simulate the mechanical behavior of masonry structures are presented. Different micro-modeling computational options are considered and compared with regard to their ability to define the initial state of the structure, realism in simulation, computer efficiency and data availability for their application to model low bond strength masonry structures. It is highlighted that different computational approaches should lead to different results and these will depend on the adequacy of the approach used and the information available. From the results analysis it is also highlighted that a realistic analysis and assessment of existing masonry structures using numerical methods of analysis is not a straight forward task even under full knowledge of current conditions and materials.

The "distinct element method" was proposed by Peter Cundall in 1971 for the analysis of rock slopes by means of rigid block or circular particle models. This method led to the UDEC and 3DEC codes, presently in wide use in rock engineering. Their application to masonry structures started in the 90's, as researchers found that they were also excellent tools to approach the highly nonlinear behavior of masonry, in particular the collapse processes of stone block structures under static or seismic loads. This chapter reviews the essential assumptions of UDEC and 3DEC, relating them to other methods and codes, and stressing the features that make them suitable for masonry analysis. Rigid and deformable blocks, contact mechanics, contact detection, and solution algorithms are examined. Key issues in the modelling of masonry are addressed, including: irregular block models; determination of collapse loads; large displacement analysis; computational efficiency issues in dynamic analysis. Practical examples taken from the published literature illustrate these issues.

"DDA" stands for "Discontinuous Deformation Analysis", suggesting that the displacement field of the analyzed domain shows abrupt changes on the element boundaries in the model. This chapter introduces the theoretical fundaments of DDA: mechanical characteristics of the elements together with the basic degrees of freedom, contact behavior, the equations of motion and their numerical integration with the help of Newmark's beta-method taking into account contact creation, loss and sliding with the help of an open-close iteration technique. Finally, a short overview on practical and scientific applications for masonry structures is given.

The Contact Dynamics method, developed still in the 1980s, was originally applied for granular assemblies because of its efficiency in simulating rapid granular flows or vibration problems of discrete systems. In the oldest models the elements were spherical and perfectly rigid, but later the application of polyhedral and deformable elements also became widespread, allowing for the reliable simulation of problems related to masonry structures. The basic unit of the analysis in Contact Dynamics is the pair of two randomly chosen elements. The essence of the method is to find the contact force vector between the two elements in such a way that during the analysed time step the elements should not overlap each other. At the considered time instant an iterative process sweeps along randomly chosen pairs over and over again, and gradually adjusts the estimated contact forces to get an improving approximation of a state that satisfies the dynamic equations of the system. The method is particularly advantageous for earthquake analysis of masonry structures.

This chapter presents a general overview of the combined Finite-Discrete Element Method (FEM/DEM) which is considered as a state-of-the-art technique for the mechanical analysis of masonry structures. In a FEM/DEM simulation each discrete element representing a stone block is discretized into finite elements in order to describe the deformability of the blocks. This chapter deals with the main steps of the FEM/DEM including contact detection, contact interaction, fracture and fragmentation algorithms, calculation of deformations and the time integration of the equation of motion. The FEM/DEM is advantageously used to simulate transition from continua to discontinua processes which may lead to the collapse of the structure. Some examples for practical applications found in the literature are mentioned.

Circular Particle Models (PM) are a class of discrete elements which has been increasingly used for detailed analysis in rock and concrete structures. There have been few applications to masonry, but the potential of these techniques appears significant, due to their proven ability to simulate fracture processes through random particle assemblies representing quasi-brittle materials at the grain scale. The present chapter presents the fundamentals of this approach and reviews some previous applications of PM models to masonry. The model capabilities are first exemplified by simple models involving a few irregular blocks formed by particles. Irregular stone masonry wall specimens under compression and under in-plane shear loading are then presented. In these models both the units and the mortar are represented by circular particles, and failure processes through the joints or through joints and stones are analyzed. The main issues regarding the use of these models are finally discussed.

This work concerns the numerical modelling of masonry dams using the Discrete Element Method. It begins with a review of the history of masonry dams and their behaviour. A numerical tool based on the Discrete Element Method developed specifically for the structural assessment of masonry dams is then presented. The mechanical calculations performed by the tool are discussed in detail, together with the approach used for the modelling of passive anchors and the modules for seismic analysis and hydromechanical analysis. Structural and hydraulic analyses of a diverse set of existing masonry dams conducted using the tool are then presented. The Discrete Element Method is shown to be capable of reproducing the structural behaviour of masonry dams and identifying their likely failure mechanisms as required for structural safety evaluations.