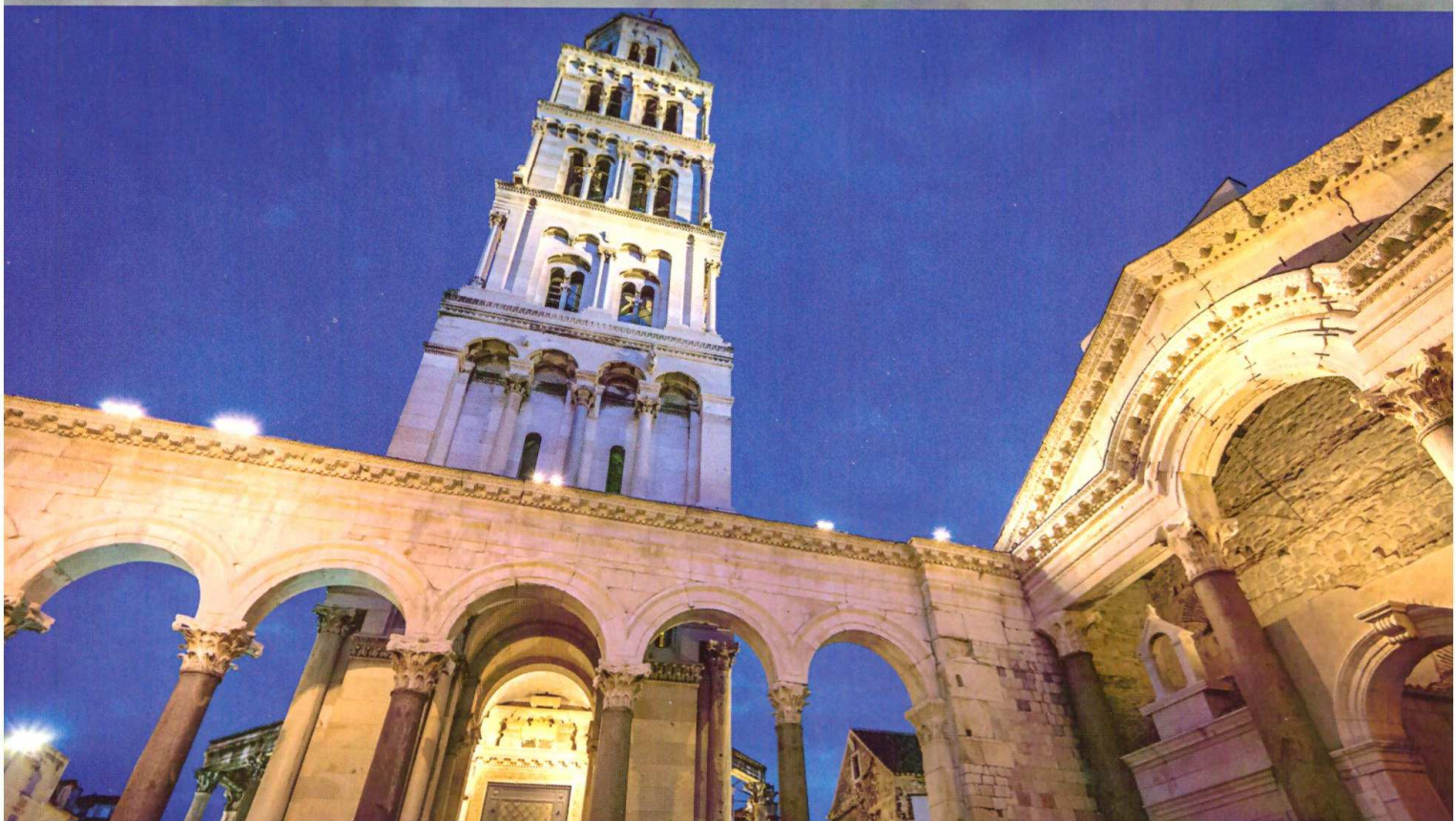
Split • Croatia • September 18 – 22, 2018

9th International Congress of Croatian Society of Mechanics

Book of Abstracts

Editors:

Pavao Marović • Lovre Krstulović-Opara • Mirela Galić



9th ICCSM

9th International Congress of Croatian Society of Mechanics

Organised by

Croatian Society of Mechanics

Under the Auspices of

Central European Association for Computational Mechanics
University of Split

Book of Abstracts

Editors:

Pavao Marović
Lovre Krstulović-Opara
Mirela Galić

CSM
CROATIAN SOCIETY OF MECHANICS
ZAGREB - OSIJEK - RIJEKA - SL. BROD - SPLIT

Split, Croatia, September 18 – 22, 2018

Published by
Croatian Society of Mechanics

Head Office
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb
Ivana Lučića 5, HR-10000 Zagreb, Croatia
http://www.csm.hr/

Printed by:
REDAK d.o.o., Split, Croatia

Issues: 200 copies

ISSN 2584-7716

General chairs

Lovre KRSTULOVIĆ-OPARA, University of Split
Pavao MAROVIĆ, University of Split
Mirela GALIĆ, University of Split

Organising Committee

Mirela GALIĆ, University of Split
Gordan JELENIĆ, University of Rijeka
Pejo KONJATIĆ, University of Osijek
Lovre KRSTULOVIĆ-OPARA, University of Split
Pavao MAROVIĆ, University of Split
Davorin PENAVA, University of Osijek
Ivica SKOZRIT, University of Zagreb
Jurica SORIĆ, University of Zagreb

Scientific Committee

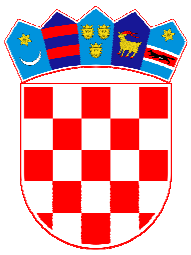
Giulio ALFANO, Brunel University
Ivo ALFIREVIĆ, University of Zagreb
Ferri M.H. ALIABADI, Imperial College, London
Klaus-Jürgen BATHE, Massachusetts Institute of Technology
Zdeněk P. BAŽANT, Northwestern University
Daniela P. Boso, University of Padova
Josip BRNIĆ, University of Rijeka
Francesca COSMI, University of Trieste
Werner DAUM, Federal Institute for Materials and Testing
Samir DOLAREVIĆ, University of Sarajevo
Željko DOMAZET, University of Split
Josef EBERHARDSTEINER, Vienna University of Technology
António J. M. FERREIRA, University of Porto
Thomas FIEDLER, University of Newcastle
Alessandro FREDDI, University of Bologna
Mirela GALIĆ, University of Split
Marc GEERS, Technische Universiteit Eindhoven
Hu HAIYAN, Beijing Institute of Technology
Kazuyuki HOKAMOTO, Kumamoto University
Adnan IBRAHIMBEGOVIĆ, UT Compiegne / Sorbonne Universities
Alojz IVANKOVIĆ, University College Dublin
Stjepan JECIĆ, University of Zagreb
Gordan JELENIĆ, University of Rijeka
Alexander KONYUKHOV, Karlsruhe Institute of Technology
Jože KORELC, University of Ljubljana
Dražan KOZAK, University of Osijek

Ivica KOŽAR,	University of Rijeka
Lovre KRSTULOVIĆ-OPARA,	University of Split
Przemyslaw LITEWKA,	Poznan University of Technology
Laura DE LORENZIS,	Technical University of Braunschweig
Herbert A. MANG,	Vienna University of Technology
Pavao MAROVIĆ,	University of Split
Franjo MATEJIČEK,	University of Osijek
Hermann G. MATTHIES,	Technical University of Braunschweig
Giangiacomo MINAK,	University of Bologna
Ante MUNJIZA,	University of Split
Justin MURIN,	Slovak Technical University
Masatoshi NISHI,	National Institute of Technology
Roger J. OWEN,	Swansea University
Joško OŽBOLT,	University of Stuttgart
Pavel POLACH,	Research and Testing Institute Plzeň
Ekkehard RAMM,	University of Stuttgart
Franz G. RAMMERSTORFER,	Vienna University of Technology
Stefanie REESE,	RWTH Aachen University
Zoran REN,	University of Maribor
Carlo SANSOUR,	University of Nottingham
Ivo SENJANOVIĆ,	University of Zagreb
Jan SLADEK,	Slovak Academy of Sciences
Jurica SORIĆ,	University of Zagreb
Stanislaw STUPKIEWICZ,	Institute of Fundamental Technological Research, Warsaw
Srđan ŠIMUNOVIĆ,	Oak Ridge National Laboratory
Leopold ŠKERGET,	University of Maribor
Boris ŠTOK,	University of Ljubljana
Zdenko TONKOVIĆ,	University of Zagreb
Matej VESENJAK,	University of Maribor
Zdravko VIRAG,	University of Zagreb
Werner WAGNER,	Karlsruhe Institute of Technology
Peter WRIGGERS,	Leibniz University of Hannover
Giorgio ZAVARISE,	University of Salento
Tarek I. ZOHDI,	University of California at Berkeley

Congress secretariat

Tourist agency VIP TRAVEL DMC & PCO®, Jerome d.o.o.
Trg Hrvatske bratske zajednice 8, HR-21000 Split, Croatia

Sponsors:



Ministry of Science and Education of the Republic of Croatia

Tourist Board of Split

Split-Dalmatia County Tourist Board

Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture
University of Split

Faculty of Civil Engineering, Architecture and Geodesy
University of Split

TABLE OF CONTENTS

Invited Lectures

Minisymposia on
Mathematical and Mechanical Aspects
of Modern Discretization Methods
organized by
Jörg Schröder and Peter Wriggers

Contributed lectures

Preface

Dear Reader,

The Book of Abstracts of the 9th Congress of Croatian Society of Mechanics is a printed overview of 96 contributions to the series of international congresses organized by the Croatian Society of Mechanics. The congresses are organized every 3 years with the goal to present highlights in the field of Mechanics. The complete version of the papers is available as an e-document within the Proceedings of the 9th Congress of Croatian Society of Mechanics ISSN 2623-6133.

The main goal of the Congress is to bring together researchers from leading international and regional institutions in the field of Mechanics including Biomechanics, Computational mechanics, Mechanics of materials, Fluid dynamics, Dynamics and vibrations, Experimental mechanics, Fatigue and impact mechanics, Wind engineering, Civil engineering, Mechanical engineering etc. As an event within the conference, the minisymposium "Mathematical and Mechanical Aspects of Modern Discretization Methods" chaired by Prof. Dr.-Ing. habil. Jörg Schröder and Prof. Dr.-Ing habil. Dr. h.c. mult. Dr.-Ing. E.h. Peter Wriggers is taking place. The mini symposium's contributions are contained within this Book of Abstracts.

I would like to use this opportunity to thank prof. Mirela Galić as well as prof. Pavao Marović for taking on the task of organizing and preparing this Book of Abstract. Furthermore I would like to thank the Faculty of Mechanical Engineering and Naval Architecture, University of Split for financially supporting the production of this Book of Abstracts and congress proceedings.

I would like to welcome you to the town of Split, wishing you all a successful conference and lots of memorable moments in this Mediterranean gem. Thank you for participating at the most important event of the Croatian Society of Mechanics and making it what it is.

With regards,

Lovre Krstulović-Opara

President of the
Croatian Society of Mechanics

Invited lectures

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Dynamic Adaptive Recursive Concurrent Multi Scale Modelling in Impact Engineering

Nicola BOMBACE, Francesco DE COLA, Simone FALCO, Mattia MONTANARI, Nik PETRINIC

University of Oxford, Impact Engineering Laboratory, Department of Engineering Science, Parks Road, OX1 3PJ Oxford, England, United Kingdom
E-mails: nik.petrinic@eng.ox.ac.uk, nicola.bombace@eng.ox.ac.uk, mattia.montanari@eng.ox.ac.uk, simone.falco@eng.ox.ac.uk

Abstract

The design against rapidly applied excitation of structures such as those arising from explosions or collisions represents often one of the most critical aspects of all new engineering projects. Currently, all final designs are assessed using elaborate numerical simulations, but the ability to meet the design requirements, in which both the global structural response and detailed stress analysis that respects all material characteristics and manufacturing processes are addressed, still remains a challenge due to massive computational requirements even for geometrically very small products. The research into concurrent multi scale modelling which is capable of simulating the response of the structure at large (global) level simultaneously with accurately representing the behaviour of materials (ingredients) at the smallest relevant (local) level [1] is the backbone of the adopted integrated experimental-modelling approach presented in this paper. In particular, initial results of stress wave propagation phenomena are presented, by focusing on the impulsive excitation and emphasizing the issues related to the communication between the length scales during the concurrent simulations, in order to demonstrate the ability of the algorithms to maintain the energy balance throughout the calculations. A new three-dimensional multi-scale adaptive method for explicit formulation is introduced, that allows a computationally efficient simulation of dynamic problems [2, 3]. The introduction of the different spatial and temporal scales only on as/where needed basis, removes the limitation of those approaches which rely upon a-priori knowledge of the "hot-spots", hence simulating de-facto the whole domain at the lowest scale of interest. The results of simulations show that considerably larger problems could be solved more efficiently by the developed dynamic adaptive recursive concurrent multi scale modelling approach, while guaranteeing that both the global and local responses are at least as accurate as "brute-force" approach would show, if such computing power was available.

References

[1] N. Bombace. Dynamic Adaptive Concurrent Multi-Scale Simulation of Wave Propagation in 3D Media. DPhil Thesis, Oxford, 2018.

[2] M. Silani, H. Talebi, S. Ziaei-Rad, A.M. Hamouda, G. Zi, T. Rabczuk. A Three Dimensional Extended Arlequin Method for Dynamic Fracture. *Comp. Materials Science*, 96: 425-431, 2015.

[3] A. Gravouil, A. Combescure. Multi-time-step Explicit-implicit Method for Non-linear Structural Dynamics. *Int. J. for Numerical Methods in Engineering*, 50(1): 199-225, 2001.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

The Method of Multiscale Virtual Power as a General Tool for Multiscale Modelling: Theory and Applications

Eduardo A. DE SOUZA NETO[*], P.J. BLANCO[+], K.Q. HOANG[*], F FIGUEIREDO[+], Y. CHEN[*], P.J. SANCHEZ[**], S. TORO[**], R.A. FEIJOO[+]

[*]University of Swansea, Zienkiewicz Centre for Computational Engineering, Swansea SA2 8PP, Wales, United Kingdom
E-mails: e.desouzaneto@wansea.ac.uk

[+]National Laboratory for Scientific Computing (LNCC), Petropolis, Brazil
E-mail: {pjblanc, feij}@lncc.br

[**]CIMEC-UNL-CONICET, Santa Fe, Argentina
E-mail: psanchez@intec.unl.edu.ar

Abstract

The Method of Multiscale Virtual Power [1-4] proposed by the authors is discussed. The methodology relies fundamentally on the concepts of: (i) kinematical averaging; (ii) kinematical insertion; (iii) mathematical duality, and (iv) the Principle of Multiscale Virtual Power – a variational statement of an extension of the well-known Hill-Mandel Principle. The methodology has proven to be extremely useful in multiscale modelling based on the concept of RVE in a wide range of situations of interest. It provides a robust framework whereby multiscale models can be developed in a rigorous and systematic manner that minimizes the likelihood of inconsistencies in the resulting theories. Its use in the context of continuum-continuum and discrete-continuum systems is explored and a number of new applications are presented, including the modelling of nanoscale fibrous materials, atomic lattices and material failure.

References

[1] P.J. Blanco, P.J. Sanchez, E.A. de Souza Neto, R.A. Feijoo. Variational Foundations and Generalized Unified Theory of RVE-Based Multiscale Models. *Archives of Computational Methods in Engineering*, 23(2): 191-253, 2016. (http://DOI:10.1007/s11831-014-9137-5)

[2] E.A. de Souza Neto, P.J. Blanco, P.J. Sanchez, R.A. Feijoo. An RVE-based Multiscale Theory of Solids with Micro-scale Inertia and Body Force Effects. *Mechanics of Materials*, 80(A):136-144, 2014.

[3] S. Toro, P.J. Sanchez, P.J. Blanco, E.A. de Souza Neto, R.A. Feijoo. Multiscale Formulation for Material Failure Accounting for Cohesive Cracks at the Macro and Micro Scales. *International Journal of Plasticity*, 76:75-110, 2016.

[4] P.J. Blanco, P.J. Sanchez, E.A. de Souza Neto, R.A. Feijoo. The Method of Multiscale Virtual Power for the Derivation of a Second Order Mechanical Model. *Mechanics of Materials*, 99: 53-67, 2016. (http://DOI:10.1016/j.mechmat.2016.05.003)

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Refined Modelling of Smart Structures: Coupled Thermomechanical-electromagnetic Formulation and FE Computations

Adnan IBRAHIMBEGOVIC[*], Pablo MORENO-NAVARRO[*], Ivan RUKAVINA[*], Alejandro OSPINA[*], Faker BEN BELGACEM[*], Jose-Luis PEREZ-APARICIO[+]

[*]***Université de Technologie Compiègne – Sorbonne Universités, France***
E-mails: adnan.ibrahimbegovic@utc.fr

[+]***Polytechnic University of Valencia, Valencia, Spain***

Abstract

Consistent thermodynamics framework is presented, capable of coupling elastic, thermal and electric fields. The complete set of governing equations is obtained from the conservation principles for electric charge, energy and momentum. The second principle of thermodynamics is taken into account to introduce the irreversible phenomena, such as plastic dissipation or Joule's heating. The constitutive relations are derived from the Helmholtz free-energy potential for each corresponding dual variable in terms of the defined set of state variables. The first solution procedure is entirely based on the finite element method and time-stepping schemes. The fast convergence properties of the finite element computations with the proposed coupled elasticity and plasticity models are ensured [1, 2]. The implementation is carried out in a research version of the computer code FEAP [3]. Several numerical simulations are presented in order to illustrate the proposed model and formulation capabilities for providing an enhanced formulation of an important practical application in terms of Peltier cells. The second solution procedure is also examined with an alternative coupling, where we bring into seamless coupling two existing codes: solid mechanics FEAP [3] and electromagnetics GetDP [4], which requires the mortar elements in order to ensure the seamless communication between different fields [5]. The challenge to ensure the unconditional stability for the operator split computations, is achieved by following in the footsteps of our works coupling FEAP with Open-Foam code for fluids [6].

References

[1] P. Moreno-Navarro, A. Ibrahimbegovic, J.L. Perez-Aparicio. Plasticity Coupled with Thermo-Electric Fields: Thermodynamics Framework and Finite Element Method Computations. *Computer Methods in Applied Mechanics and Engineering*, 10: 543–561, 2017.

[2] P. Moreno-Navarro, A. Ibrahimbegovic, J.L. Perez-Aparicio. Linear Behavior for Fully Coupled Thermo-Electro-Magneto-Mechanic Systems. *Coupled Systems Mechanics*, 2018. (in press)

[3] O.C. Zienkiewicz, R.L. Taylor. *The Finite Element Methods*. vols I, II, III, Elsevier, 2005.

[4] P. Dular, C. Geuzaine. GetDP: A General Environment for the Treatment of Discrete Problems. http://www.geuz.org/getdp/, 2015.

[5] F. Ben Belgacem, A. Buffa, Y. Madey. The Mortar Finite Elements for 3D Maxwell Equations: First Results. *SIAM Journal of Numerical Analysis*, 39: 880-901, 2001.

[6] A. Ibrahimbegovic, R. Niekamp, C. Kassiotis, D. Markovic, H.G. Matthies. Code-coupling Strategy for Efficient Development of Computer Software in Multiscale and Multiphysics Nonlinear Evolution Problems in Computational Mechanics. *Adv. Eng. Software*, 72: 8-17, 2014.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Mechanistic Data-science Self-consistent Clustering Analysis

Wing Kam LIU

Northwestern University, McCormick School of Engineering,
2145 Sheridan Road, Evanston, Illinois 60208, USA
E-mail: w-liu@northwestern.edu

Abstract

An open frontier in mechanical science is the efficient and accurate description of heterogeneous material behavior that strongly depends on complex microstructure. This lecture introduces our latest efforts to expand this frontier: Mechanistic Data-science Self-consistent Clustering Analysis (SCA) for material systems modelling and its concurrent homogenization. SCA concurrent homogenization was developed to avoid the limitations of phenomenological models by directly generating material laws on-the-fly, using an efficient two-stage solution to compute microscale material response from a statistically Representative Volume Element (RVE). The first stage, known as the offline or training stage, uses data science theories such as k-means clustering and self-organizing maps to "compress" the RVE. The second, online or correction, stage solves the Lippmann-Schwinger equation to predict the response of each compressed RVE (CRVE) to applied load using any constitutive relationship desired within the CRVE, thus effectively predicting the material law produced by the overall response of the CRVE. The CRVE may then be considered a material point in the larger concurrent simulation. The SCA theory integrates multiscale mechanics of materials and data science theories to efficiently generate material laws with a drastic reduction of computational cost and resources compared to methods that use the RVE directly. A number of prediction comparisons of nonlinear behavior of metal alloys and polymer matrix composites, using different constitutive laws within the CRVEs during the online stage with direct numerical simulation, have shown that SCA can achieve accurate solutions at an incredible reduction of computational expense. Applications of data science methods and SCA to Additive Manufacturing will also be discussed.

References

[1] Z. Liu, M. Fleming, W.K. Liu. Microstructural Material Database for Self-consistent Clustering Analysis of Elastoplastic Strain Softening Materials. *Computer Methods in Applied Mechanics and Engineering*, 330: 547-577, 2018.

[2] M.A. Bessa, R. Bostanabad, Z. Liu, A. Hu, D. Apley, C. Brinson, W. Chen, W.K. Liu. A framework for data-driven analysis of materials under uncertainty: Countering the curse of dimensionality. *Comp. Methods in Applied Mechanics and Engineering*, 320: 633–667, 2017.

[3] Z. Liu, M.A. Bessa, W.K. Liu. Self-consistent clustering analysis: An efficient multi-scale scheme for inelastic heterogeneous materials. *Computer Methods in Applied Mechanics and Engineering*, 306, 319–341, 2016.

[4] R. Bostanabad, Y. Zhang, X. Li, T. Kearney, L.C. Brinson, L., D.W. Apley, W.K. Liu, W. Chen. Computational Microstructure Characterization and Reconstruction: Review of the State-of-the-art Techniques. *Progress in Materials Science*, 95, 1–41, 2018.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

New Vistas in Hybrid Multiphysics Virtual Experimentation Based Science and Engineering

Ante MUNJIZA, Mirela GALIĆ, Pavao MAROVIĆ, Hrvoje SMOLJANOVIĆ, Ante MIHANOVIĆ

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, HR-21000 Split, Croatia
E-mails: {ante.munjiza, mirela.galic, pavao.marovic}@gradst.hr
{hrvoje.smoljanovic, ante.mihanovic}@gradst.hr

Abstract

In this paper the state of the art aspects of the so called virtual experimentation approach to solving complex problems in science and engineering are considered. These include a novel approach to: (a) tensorial calculus; (b) constitutive equations for both fluids and solids; (c) integral and differential formulations in conjunction with associated methods of finite volumes and finite element; (d) integrated Lagrangian-Eulerian solvers for hybrid problems; (e) transition from continuum to discontinuum and apriori discontinuum assumptions; (f) applications in science and engineering ranging from traditional civil and mechanical engineering to bioscience and medical engineering.

References

[1] A. Munjiza, E. Rougier, E.E. Knight. *Large Strain Finite Element Method: A Practical Course*. Wiley, Chichester, 2015.

[2] D. Xu, Ch. Ji, E. Avital, E. Kaliviotis, A. Munjiza, J. Williams. An Investigation on the Aggregation and Rheodynamics of Human Red Blood Cells Using High Performance Computations. *Scientifica*, 2017: Article ID 6524156 (10 p.), 2017.

[3] D. Xu, E. Kaliviotis, A. Munjiza, E. Avital, Ch. Ji, J. Williams. Large Scale Simulation of Red Blood Cell Aggregation in Shear Flows. *Journal of Biomechanics*, 46(11): 1810-1817, 2013.

[4] G. Hosseini, J.J.R. Williams, E.J. Avital, A. Munjiza, X. Dong, J.S.A. Green. Simulation of the Upper Urinary System. *Critical Reviews in Biomedical Engineering*, 41(3): 259-268, 2013.

[5] A. Munjiza, E.E. Knight, E. Rougier. *Computational Mechanics of Discontinua*. John Wiley & Sons, Chichester, 2012.

[6] A. Munjiza. *The Combined Finite-Discrete Element Method*. John Wiley & Sons, Chichester, 2004.

[7] M. Galić, P. Marović. Validation of the Developed Triaxial Nonlinear Material Model for Concrete. *Engineering Review*, 37(3): 298-313, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Multiscale Modeling Using Finite Elements, Fast Fourier Transforms and Proper Orthogonal Decomposition in Engineering

Stefanie REESE, Julian KOCHMANN, Fabiola CAVALIERE, Shahed REZAEI, Jaan SIMON, Stephan WULFINGHOFF

RWTH Aachen University, Institute of Applied Mechanics, Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany
E-mails: {stefanie.reese, julian.kochmann, fabiola.cavaliere, shahed.rezaei, jaan.simon, stephan.wulfinghoff}@rwth-aachen.de

Abstract

The necessity to provide physically reasonable and mathematically sound descriptions of mechanical behaviour at different scales is without discussion. Nevertheless, for engineering design quick estimations of important quantities such as stresses and strain are needed. At a larger scale, information about the overall behaviour of complex systems has to be supplied. For this reason, we need to develop computational methods which on the one hand enable a detailed material description, on the other hand allow the bridging to coarser scales without losing too much information. In the present contribution, various methods concerning applications in production technology (process signature) and medical technology (tissue-engineered heart valves) are discussed. The scale bridging is achieved by coupling finite element modeling on the macro scale with (1) fast Fourier transforms discretization using the phase field method (see e.g. [1,2]) or (2) proper orthogonal decomposition (see e.g. [3]) on the micro scale. Another possibility is standard up-scaling using differently detailed finite element models [4].

References

[1] J. Kochmann, J.R. Mianroodi, S. Wulfinghoff, S. Reese, B. Svendsen. Two-scale FE–FFT- and Phase-field-based Computational Modeling of Bulk Microstructural Evolution and Macroscopic Material Behavior. *Computer Methods in Applied Mechanics and Engineering*, 305: 89-110, 2016.

[2] J. Spahn, H. Andrae, M. Kabel, R. Müller. A Multiscale Approach for Modeling Progressive Damage of Composite Materials Using Fast Fourier Transforms. *Computer Methods in Applied Mechanics and Engineering*, 268: 871-883, 2014.

[3] A. Radermacher, B.A. Bednarcyk, B. Stier, J. Simon, L. Zhou, S. Reese. Displacement-based Multiscale Modeling of Fiber-reinforced Composites by Means of Proper Oorthogonal Decomposition. *Advanced Modeling and Simulation in Engineering Sciences*, 3(1): 1-23, 2016.

[4] D. Sodhani, S. Reese, R. Moreira, P. Mela, S. Jockenhoevel, S.E. Stapleton. Multi-scale Modelling of Textile Reinforced Artificial Tubular Aortic Heart Valves. *Meccanica*, 57(3): 1-17, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Nonlinear Strain-induced Product Properties of Magneto-Electric Two-phase Composites

Jörg SCHRÖDER, Matthias LABUSCH

University Duisburg-Essen, Institute of Mechanics,
Universitätsstraße 15, 45141 Essen, Germany
E-mails: {j.schroeder, matthias.labusch}@uni-due.de

Abstract

Multiferroic materials combine two or more ferroic characteristics and can exhibit a magneto-electric (ME) coupling. This ME coupling can find applications in sensor technology or in data storage devices, [1]. Most ME single-phase materials show such a coupling far below room temperature. Therefore, the manufacturing of two-phase composites, consisting of a ferroelectric matrix with magnetostrictive inclusions, becomes important. Due to the interaction of both constituents the composite generates a strain-induced ME coupling at room temperature, which is not present in the individual phases. We distinguish between the direct and converse ME effect. The direct effect characterizes magnetically induced polarization, whereas the converse effect denotes an electrically induced change in magnetization. The ME coupling significantly depends on the microscopic morphology and the ferroic properties of the individual constituents. In order to take both aspects into account, a finite element (FE^2) homogenization approach is performed, which combines via a scale bridging the macro- and microscopic level, [2, 3]. Thereby, the ferroic properties of the phases are described by suitable material models. The typical ferroic hysteresis curves are modeled by considering the switching behavior, depending on an energy based switching criterion, of the spontaneous polarizations of barium titanate unit cells [4], whereas the magnetic hysteresis loops are described by a suitable Preisach operator [5] for the magnetization.

References

[1] N.A. Spaldin, M. Fiebig. The Renaissance of Magnetoelectric Multiferroics. *Science*, 309(5733): 391-392, 2005.

[2] J. Schröder, M. Labusch, M.-A. Keip. Algorithmic Two-scale Transition for Magneto-Electro-Mechanically Coupled Problems – FE^2-scheme: Localization and Homogenization. *Computer Methods in Applied Mechanics and Engineering*, 302: 253-280, 2016.

[3] J. Schröder. A Numerical Two-scale Homogenization Scheme: The FE^2-method. In: J. Schröder, K. Hackl, eds., Plasticity and Beyond: Microstructures, Crystal-Plasticity and Phase Transitions, 1-64. Springer, 2013.

[4] S.C. Hwang, C.S. Lynch, R.M. McMeeking. Ferroelectric/Ferroelastic Interaction and a Polarization Switching Model. *Acta Metallurgica et Materialia*, 43(5): 2073-2084, 1995.

[5] M. Kaltenbacher, B. Kaltenbacher, T. Hegewald, R. Lerch. Finite Element Formulation for Ferroelectric Hysteresis of Piezoelectric Materials. *Journal of Intelligent Material Systems and Structures*, 21(8): 773-785, 2010.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Minimal Gradient-enhancement of Crystal Plasticity for Modelling of the Indentation Size Effect

Stanisław STUPKIEWICZ, Maciej J. LEWANDOWSKI, Henryk PETRYK

Institute of Fundamental Technological Research, Polish Academy of Sciences, Pawińskiego 5b, 02-106 Warsaw, Poland
E-mails: {sstupkie, maclewan, hpetryk}@ippt.pan.pl

Abstract

Size effects in metal plasticity are currently the subject of a significant research interest. As a prominent example, the size-dependent behaviour in indentation testing, i.e. the indentation size effect (ISE), is observed experimentally and also modelled theoretically [1, 2]. However, the *predictive* modelling of the ISE still constitutes a challenge, even if a great variety of gradient plasticity and gradient crystal plasticity models exists in the literature. Our recent minimal gradient-enhancement of crystal-plasticity [3, 4] is a step towards predictive modelling of the ISE. In contrast to the frequently used concept of the split of the total dislocation density into the densities of statistically stored dislocations (SSDs) and geometrically necessary dislocations (GNDs), the model employs such split applied in an incremental form only. This apparently minor difference has a significant influence on the structure of the model. In particular, the internal length scale, which is derived in a closed form, is closely related to the mean free path of dislocations, and the resulting gradient-enhanced hardening law is free of any fitting parameters. Three-dimensional simulations of spherical indentation into a Cu single crystal have been performed using the finite-element method, and the predicted ISE shows a good agreement with the experiment [4]. A detailed calibration of the model for a Ni single crystal has also been performed, followed by two-dimensional simulations of wedge indentation and of the related ISE [5].

References

[1] G.M. Pharr, E.G. Herbert, Y. Gao. The Indentation Size Effect: A Critical Examination of Experimental Observations and Mechanistic Interpretations. *Annual Review of Materials Research*, 40: 271-292, 2010.

[2] W.D. Nix, H. Gao. Indentation Size Effects in Crystalline Materials: A Law for Strain Gradient Plasticity. *Journal of the Mechanics and Physics of Solids*, 46(3): 411-425, 1998.

[3] H. Petryk, S. Stupkiewicz. A Minimal Gradient-enhancement of the Classical Continuum Theory of Crystal Plasticity - Part I: The Hardening Law. *Archives of Mechanics*, 68(6): 459-485, 2016.

[4] S. Stupkiewicz, H. Petryk. A Minimal Gradient-enhancement of the Classical Continuum Theory of Crystal Plasticity - Part II: Size Effects. *Archives of Mechanics*, 68(6): 487-513, 2016.

[5] M.J. Lewandowski, S. Stupkiewicz. Modelling of Lattice Rotation and Distortion in Wedge Indentation using a Gradient-enhanced Crystal-plasticity Model, 2018. (submitted)

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Virtual Element Formulations for Engineering Applications

Peter WRIGGERS, Blaž HUDOBIVNIK, Fadi ALDAKHEEL

Leibniz Universität Hannover, Institute for Continuum Mechanics,
Appelstrasse 11, D-30167 Hannover, Germany
E-mail: wriggers@ikm.uni-hannover.de

Abstract

Virtual elements (VEM) were developed during the last decade and applied to various problems in elasticity. Due to the fact that the element shape of virtual elements can be arbitrary including even non convex shapes these elements are more flexible when the geometry of the element is considered. The success of VEM discretizations in the linear range using different polynomial orders leads directly to the question whether these elements can also be applied successfully to nonlinear situations.

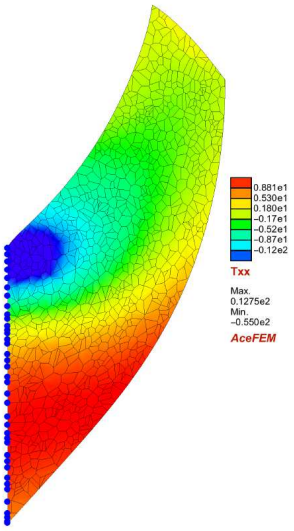


Figure 1. Deformed state and Cauchy stresses τ_{xx}

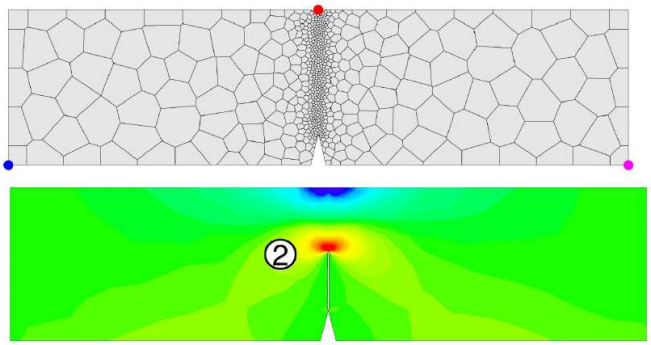


Figure 2. Mesh and crack propagation with VEM

This contribution is concerned with a simple low order virtual element formulation and its extension to different nonlinear problems such as finite elasticity, anisotropic elastic materials, finite plasticity, phase field approaches and contact mechanics. Several possible formulations are discussed and compared by means of examples; see e.g. Figure 1 that shows the deformation state of Cooke's membrane for finite hyperelastic material behaviour using an irregular shaped Voronoi mesh. Figure 2 then shows the crack propagation using a phase field approach based on a VEM simulation with a Voronoi mesh.

9th ICCSM

Minisymposia on Mathematical and Mechanical Aspects of Modern Discretization Methods organized by Jörg Schröder and Peter Wriggers

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Viscous Dissipation Effect for Double Diffusive Mixed Convection Flow past a Vertical Plate in a Porous Medium Filled with Buongiorno Nanofluid

Annis AGHBARI[*], Hamza ALI AGHA[+], Djamel SADAOUI[*]

[*]***University of Bejaia, Faculty of Technology, Laboratory of Mechanics, Materials and Energetic, Bejaia, 06000, Algeria***
E-mail: ***anisaghbari@hotmail.com***

[+]***University of Bejaia, Faculty of Technology, Department of Mechanical Engineering, Bejaia, 06000, Algeria***
E-mail: ***hamzamedea20011@gmail.com***

Abstract

A numerical analysis was performed to study the effects of combined double diffusive and viscous dissipation under non-uniform wall boundary conditions over a semi-infinite vertical plate embedded in a non-Darcy porous medium. Coupled heat and mass transfer of mixed convective boundary layer with viscous nanofluid are considered. The model used for the nanofluid includes the effects of Brownian motion and thermophoresis mechanisms, while the Darcy-Forchheimer model is used for the porous medium. Double-diffusion is governed by the conservation of mass, momentum, energy and concentration of species and nanoparticles equations, by employing Oberbeck-Boussinesq approximation and boundary layer for the nanofluid. Based on the model developed by Nield and Kuznetsov [1], the local thermal equilibrium in the homogeneous porous medium is also supposed. The governing partial differential equations are transformed a non-dimensional form and the resulting non-linear system of partial differential equations are solved using the efficient Keller-box implicit numerical finite difference method. To validate the numerical results, comparison is made with those available and a good agreement is obtained. In order to get a clear insight on the physics of the problem, a parametric study is performed and the obtained numerical results are displayed with the help of graphical illustrations, i.e. some parameters are shown in appropriate figures. How governing parameters of the problem affect the local Nusselt number Nu_x, the local regular Sherwood number Sh_x, and the local nanoparticle Sherwood number Sh'_x are discussed.

References

[1] D.A. Nield, A.V. Kuznetsov. The Cheng–Minkowycz Problem for the Double-diffusive Natural Convective Boundary Layer Flow in a Porous Medium Saturated by a Nanofluid. *International Journal of Heat and Mass Transfer*, 54(1-3): 374–378, 2011.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Free-Edge Delamination in Composite Laminates: Analysis and Prediction by Means of the Scaled Boundary Finite Element Method

Sebastian DÖLLING, Sascha HELL, Wilfried BECKER

[*]TU Darmstadt, Institute of Structural Mechanics, Darmstadt, Germany
E-mails: {doelling, hell, becker}@fsm.tu-darmstadt.de

Abstract

Along the free edges of laminate composite structures due to the layerwise discontinuous stiffness properties of the plies localized theoretically infinite interlaminar stresses may occur, possibly leading to an onset of delamination and as a consequence premature failure of the whole laminate. Due to the singular character of the local stress field and the absence of a pre-existing crack, neither classical stress based failure criteria nor fracture mechanical energy release rate based criteria allow for realistic strength and failure load predictions in the underlying situation. The given problems, however, can be overcome in the framework of finite fracture mechanics (FFM), anticipating an instantaneous formation of a delamination crack of finite length and employing a coupled stress and energy criterion, as proposed by Leguillon [1]. Such an approach has already proven successful for the analysis of interlaminar cracking in angle-ply laminates [2]. In the present work, interlaminar crack initiation at a free edge in symmetric laminates is investigated in the framework of FFM assuming a generalized plane strain state. For the determination of the required singular stress fields the scaled boundary finite element method (SBFEM) is used in order to keep the numerical effort as low as possible. The SBFEM, first introduced by Song and Wolf [3], reduces the dimension of the problem by one by only discretizing the boundary of the given laminate. The variation of the field quantities inside the laminate are represented in a closed-form analytical manner. This method has been implemented and validated by comparative finite element analyses. The method turns out to predict the effective laminate strength in good accordance with experimental data from literature.

References

[1] D. Leguillon. Strength or Toughness? A Criterion for Crack Onset at a Notch. *European Journal of Mechanics – A/Solids*, 21: 61-72, 2002.

[2] E. Martin, D. Leguillon, N. Carrere. A Twofold Strength and Toughness Criterion for the Onset of Free-edge Shear Delamination in Angle-ply Laminates. *International Journal of Solids and Structures*, 47: 1297-1305, 2010.

[3] C. Song, J.P. Wolf. The Scaled Boundary Finite-element Method – Alias Consistent Infinitesimal Finite-element Cell Method – for Elastodynamics. *Computer Methods in Applied Mechanics and Engineering*, 147: 329-355, 1997.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Mixed Isogeometric Collocation for Elastoplasticity

Frederik FAHRENDORF[*], Simone MORGANTI[+], Alessandro REALI[+], Laura DE LORENZIS[*]

[*]*Technical University of Braunschweig, Institute of Applied Mechanics, Pockelsstrasse 3, D-38106 Braunschweig, Germany*
E-mails: {f.fahrendorf, l.delorenzis}@tu-braunschweig.de

[+]*University of Pavia, Department of Civil Engineering and Architecture, via Ferrata 3, I-27100 Pavia, Italy*
E-mail: {simone.morganti, alessandro.reali}@unipv.it

Abstract

Isogeometric analysis (IGA) is a recently developed framework for the discretization of partial differential equations. The concept is based on smooth basis functions, commonly employed in Computer Aided Design. This particular choice of basis functions leads to an exact description of the geometry in the analysis model. Beyond the original motivation, isogeometric analysis delivers a higher accuracy per degree of freedom compared to conventional C^0 finite element methods as well as several additional advantages. However an efficient numerical implementation is still an issue and one field of attention in current research in IGA. The isogeometric collocation method is a promising alternative to standard Galerkin approaches, as it provides a significant reduction of the computational cost for high-order discretizations [1]. In some preliminary work a pure displacement based isogeometric collocation framework has been applied to rate-independent elastoplasticity with isotropic hardening. Due to the necessary linearization of the algorithmic tangent modulus, instabilities occurred occasionally. To circumvent these issues, we present a mixed isogeometric collocation method in this work. In the proposed approach, both stress and displacement fields are approximated as primary variables (see e.g. [2] for an analogous Galerkin formulation). The method is applied to two- and possibly three-dimensional numerical examples of elastoplasticity in combination with multi-patch parameterizations and the results are compared to Galerkin reference solutions.

References

[1] D. Schillinger, J.A. Evans, A. Reali, M.A. Scott, T.J.R. Hughes. Isogeometric Collocation: Cost Comparison with Galerkin Methods and Extension to Adaptive Hierarchical NURBS Discretizations. *Computational Methods in Applied Mechanical Engineering*, 267: 170-232, 2013.

[2] R. Bouclier, T. Elguedj, A. Combescure. Development of a Mixed Displacement-stress Formulation for the Analysis of Elastoplastic Structures under Small Strains: Application to a Locking-free, NURBS-based Solid-shell Element. *Computational Methods in Applied Mechanical Engineering*, 295: 543-561, 2015.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

The Method of Vertical Lines in Finite Elements

Stefan HARTMANN, Matthias GRAFENHORST

Clausthal University of Technology, Adolph-Roemer-Strasse 2A,
D-38678 Clausthal-Zellerfeld, Germany
E-mails: {stefan.hartmann, matthias.grafenhorst}@tu-clausthal.de

Abstract

The application of the method of vertical lines to boundary-value problems for single and multi-field problems considering elastic and inelastic material properties provides a clear procedure: in a first step, the spatial discretization is done (here, we use finite elements), and, in the second step, the time discretization is applied on the resulting system of equations [1]. This resulting system represents linear or non-linear systems, systems of ordinary differential equations, or systems of differential-algebraic equations dependent on the physical problem under consideration. There are several advantages for problems where ordinary-differential equations are chosen to describe the evolution of the physical problem over the time. Apart from classical problems in elastoplasticity, viscoelasticity, and viscoplasticity, this is the case for transient problems in thermomechanics, electromagnetics, fluid-structure interaction, etc. Use can be made of various high-order time integration schemes with automatic step-size selection, where we draw on diagonally-implicit Runge-Kutta methods (DIRK), which have the advantage to incorporate other methods such as the Backward-Euler method or trapezoidal rules as special cases. Even time-adaptive contact problems and staggered schemes in coupled field problems are embedded in the entire procedure. Using the method of vertical lines offers a further advantage, namely a clear concept of material parameter identification using finite elements [2]. In this sense, a very consistent scheme is provided. In this presentation a selection of problems is discussed using DIRK-methods, namely the combination of high-order spatial (p-FEM) and temporal discretization (finite strain viscoelasticity), see [3], thermo-mechanics with acceleration techniques (thermo-viscoplasticity), see [4], and contact problems. A particular focus lies also on problems implied by the method. The experience of the last two decades with DIRK-methods in comparison to other schemes is presented.

References

[1] P. Fritzen, Numerische Behandlung nichtlinearer Probleme der Elastizitäts- und Plastizitäts-theorie. Doctoral thesis, University of Darmstadt, Department of Mathematics, 1997.

[2] S. Hartmann. A Remark on Material Parameter Identification using Finite Elements Based on Constitutive Models of Evolutionary-type, *Computer Assisted Methods in Engineering and Science*, 24(2): 113-126, 2017.

[3] T. Netz, S. Hartmann. A Monolithic Finite Element Approach using High-order Schemes in Time and Space Applied to Finite Strain Thermo-viscoelasticity. *Computers and Mathematics with Applications*, 70(7): 1457-1480, 2015.

[4] S. Rothe, P. Erbts, A. Düster, S. Hartmann. Monolithic and Partitioned Coupling Schemes for Thermo-viscoplasticity. *Computer Methods in Applied Mechanics and Engineering*, 293: 375-410, 2015.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Aspects of Least-squares Finite Elements in the Framework of Hyperelasticity

Maximilian IGELBÜSCHER*, Jörg SCHRÖDER*, Alexander SCHWARZ*

****University of Duisburg-Essen, Institute of Mechanics,***
Universitätsstr. 15, D-45141 Essen, Germany
E-mails: {maximilian.igelbuescher, j.schroeder, alexander.schwarz}@uni-due.de

Abstract

The main aspect of this contribution is an investigation of mixed finite element formulations for the framework of elastic material behaviour at finite strains. Therefore, a mixed least-squares finite element formulation is discussed, where the displacements and the stresses are used as unknown fields. The construction of the least-squares functional is based on the L^2-norm minimization of the residuals of a first-order system of differential equations, see e.g. [1]. In the proposed formulation the residuals are given by the balance of momentum, a constitutive equation and additionally the balance of moment of momentum. The introduction of an additional residual is based on the approximation of the stress field with vector-valued Raviart-Thomas functions (RT_m), see e.g. [2], which yields to a not a priori fulfilment of the stress symmetry condition. As shown in [3], an additional control of the symmetry constraint, by introducing a skewsymmetric term, could lead to more reliable results, especially for low order elements. Furthermore, the displacement field is approximated with Lagrange functions. Additionally, in order to validate and compare the performance and efficiency of the proposed approach, results for standard displacement formulations are presented.

References

[1] Z. Cai, G. Starke. Least-Squares Methods for Linear Elasticity. *SIAM Journal on Numerical Analysis*, 42(2): 826-842, 2004.

[2] P.A. Raviart, J.M. Thomas. A Mixed Finite Element Method for 2-nd Order Elliptic Problems. In: I. Galligani, E. Magenes, eds., Mathematical Aspects of Finite Element Methods, 292-315. Lecture Notes in Mathematics, vol. 606, Springer-Verlag, Berlin, 1977.

[3] A. Schwarz, K. Steeger, J. Schröder. Weighted Overconstrained Least-squares Mixed Finite Elements for Static and Dynamic Problems in Quasi-incompressible Elasticity. *Computational Mechanics*, 54(3): 603-619, 2014.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Multi-spectral Approximations of Stochastic Anisotropic Bone Response

Sharana Kumar SHIVANAND, Bojana ROSIC, Hermann G. MATTHIES

Technical University of Braunschweig, Institute of Scientific Computing, Mühlenpfordstraße 23, Braunschweig D-38106, Germany
E-mails: s.shivanand@tu-bs.de, bojana.rosic@tu-bs.de wire@tu-bs.de

Abstract

Human bone tissue is a typical example of material which exhibits randomness in the mechanical response due to an uncertain heterogeneous micro-structure. In order to develop an appropriate probabilistic macro-scale mathematical description, the essential step is to address the material as well as possible other sources of uncertainties (e.g. excitation's, change in geometry etc.) in the model. By extending already existing deterministic models derived from the Helmholtz free energy, the goal of this talk is to identify and quantify uncertainty in the system response. Due to essentially large number of parameters describing the material model, the process of obtaining the functional representation of the stochastic response is often proven to be computationally expensive. To relieve the computational demand, in this talk will be considered hybrid uncertainty quantification approaches that are based on the multi-element and multi-level approximations coming from the corresponding variational formulations.

9th ICCSM

Contributed lectures

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

On the Low Order Virtual Element Method for Phase-field Modelling of Brittle Fracture

Fadi ALDAKHEEL, Blaž HUDOBIVNIK, Peter WRIGGERS

[*]Leibniz Universität Hannover, Institut für Kontinuumsmechanik,
Appelstraße 11, D-30167 Hannover, Germany
E-mails: {aldakheel, hudobivnik, wriggers}@ikm.uni-hannover.de

Abstract

An efficient low order ***virtual element formulation*** that account for isotropic brittle failure response in two-dimensional case is outlined within this work. Virtual elements were introduced in the last decade and applied to various problems in solid mechanics [1]. The modeling of crack formation can be achieved in a convenient way by continuum ***phase-field*** approach to fracture, which are based on the regularization of sharp crack discontinuities [2, 3]. In this work, we propose a rigorous variational-based framework for the phase-field modeling of brittle fracture in elastic solids. The key goal here is the extension towards the recently developed virtual element formulation due to the flexible choice of the number of element nodes which can be changed easily during the simulation process [4]. Thus, the potential energy is formulated in terms of *suitable polynomial functions*, instead of computing the unknown shape functions for complicated element geometries, e.g. arbitrary convex or concave polygonal elements. The performance of the formulation is underlined by means of some representative examples.

References

[1] P. Wriggers, W. Rust, B.D. Reddy. A Virtual Element Method for Contact. *Computational Mechanics*, 58(6): 1039-1050, 2016. https://doi.org/10.1007/s00466-016-1331-x

[2] F. Aldakheel, P. Wriggers, C. Miehe. A Modified Gurson-type Plasticity Model at Finite Strains: Formulation, Numerical Analysis and Phase-field Coupling. *Computational Mechanics*, 2017. https://doi.org/10.1007/s00466-017-1530-0

[3] F. Aldakheel. Mechanics of Nonlocal Dissipative Solids: Gradient Plasticity and Phase-field Modeling of Ductile Fracture. Ph.D. thesis, Institute of Applied Mechanics (CE), Chair I, University of Stuttgart, 2016. http://dx.doi.org/10.18419/opus-8803

[4] P. Wriggers, B. Hudobivnik. A Low Order Virtual Element Formulation for Finite Elasto-plastic Deformations. *Computer Methods in Applied Mechanics and Engineering*, 327: 459-477, 2017. https://doi.org/10.1016/j.cma.2017.08.053

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Isogeometric Multiscale Modelling with Galerkin and Collocation Methods

Milad AMIN GHAZIANI[*], Josef KIENDL[+], Laura DE LORENZIS[*]

[*]*Technical University of Braunschweig, Institute of Applied Mechanics, Pockelsstrasse 3, D-38106 Braunschweig, Germany*
E-mails: {n.amin-ghaziani, l.delorenzis}@tu-braunschweig.de

[+]*Norwegian University of Science and Technology, Department of Marine Technology, Otto Nielsen veg 10, Trondheim, Norway*
E-mail: josef.kiendl@ntnu.no

Abstract

Computational homogenization in the framework of finite elements (FE2) is well established but is known to be computationally demanding [1]. In this contribution, we apply computational homogenization by means of isogeometric analysis (IGA) and set this method as IGA2. Despite more accuracy given by IGA, its efficient implementation especially in the context of a two-scale boundary value problem (BVP) is an issue. Aiming to optimize the computational efficiency of IGA, isogeometric collocation has been recently introduced [2, 3]. As the first step to solve a two-scale BVP more efficiently, we utilize isogeometric collocation at the global scale and IGA-Galerkin at the local scale. In this approach the number of macroscopic evaluation points is dramatically reduced, thus a substantial gain in efficiency is obtained over the mentioned IGA2 and FE2 techniques. Moreover, employing isogeometric collocation in the local BVP gives an additional gain in the sense of computational efficiency, as a result of decreased number of evaluation points at both scales. The different methods and their combinations across the different scales are investigated and compared in terms of efficiency and robustness.

References

[1] M.G.D. Geers, V.G. Kouznetsova, W.A.M. Brekelmans. Multi-scale Computational Homogenization: Trends and Challenges. *Journal of Computational and Applied Mathematics*, 234(7): 2175-2182, 2010.

[2] F. Auricchio, L. Beirao da Veiga, T.J.R. Hughes, A. Reali, G. Sangalli. Isogeometric Collocation Methods. *Mathematical Models and Methods in Applied Sciences*, 20(11): 2075-2107, 2010.

[3] D. Schillinger, J.A. Evans, A. Reali, M.A. Scott, T.J.R. Hughes. Isogeometric Collocation: Cost Comparison with Galerkin Methods and Extension to Adaptive Hierarchical NURBS Discretizations. *Computer Methods in Applied Mechanics and Engineering*, 267: 170-232, 2013.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Calibration of a 3D Cyclically Loaded RC Frame with URM Infill Wall Micromodel

Filip ANIĆ*, Davorin PENAVA*, Lars ABRAHAMCZYK+, Dmitrii LEGATIUK+, Uwe KÄHLER‡

***Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, 3 Vladimir Prelog Street, HR-31000 Osijek, Croatia**
E-mails: {filip.anic, davorin.penava}@gfos.hr

+Bauhaus-Universität Weimar, Earthquake Damage Analysis Center & Institut für Angewandte Mathematik, Marienstraße 13B, D-99421 Weimar, Germany
E-mail: {lars.abrahamczyk, dmitrii.legatiuk}@uni-weimar.de

‡Universidade de Aveiro, Departamento de Matemática, 3810-193 Aveiro, Portugal
E-mail: ukaehler@ua.pt

Abstract

Structural systems consisting of reinforced concrete (RC) frames infilled with unreinforced masonry (URM) walls is a common practice in seismically active South Europe [1]. During the seismic excitation, frames are dynamically loaded both in out-of-plane (OOP) and in-plane (IP) direction. It was known from late 60's [2] that the infill walls contribute greatly to overall seismic behaviour. However, due to lack of understanding, many provisions such as Eurocode 8 [3] regard infill as a secondary element. This paper is a part of OOP frame – infill interaction study with 3D micro modelling approach. The micromodel was assembled based on experimental specimens and 2D – IP micromodels by [4]. The 3D micromodel resulted in higher response after reaching plasticity. Consequently, calibration of 3D models was needed. Firstly, the bare frame was calibrated, after which infilled frame with and without opening was calibrated. Various numerically depended parameters were considered and showed, more or less, impact on its behaviour. The direction of plastic flow showed the greatest influence on the micromodel response as it regulates material volume during crushing [5]. Negative values of plastic flow showed the best response due to material volume decrease. Calibration included comparison of force–displacement curve and failure mechanisms.

References

[1] E. Booth, D. Key. *Earthquake Design Practice for Buildings*. Thomas Telford, London, 2006.
[2] B. Stafford Smith. Methods for Predicting the Lateral Stiffness and Strength of Multi-storey Infilled Frames. *Building Science*, 2(3): 247-257, 1967.
[3] EN 1998-1:2004: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings, CEN, Brussels, 2004.
[4] D. Penava, V. Sigmund, I. Kožar. Validation of a Simplified Micromodel for Analysis of Infilled RC Frames Exposed to Cyclic Lateral Loads. *Bulletin of Earthquake Engineering*, 14(10): 2779-2804, 2016.
[5] J. Cervenka, V. Cervenka, R. Eligehausen. Fracture-plastic Material Model for Concrete, Application to Analysis of Powder Actuated Anchors. In: Proc. FRAMCOS-3, 1107-1116, Aedificatio Publ., Freiburg, 1998.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

The Defect Depth Characterization Using Pulsed Thermographic Data

Petra BAGAVAC, Lovre KRSTULOVIĆ-OPARA, Željko DOMAZET

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia
E-mails: {petra.bagavac, lovre.krstulovic-opara, zeljko.domazet}@fesb.hr

Abstract

Defects in material can be fully described if their shape and position is determined. In previous works [1, 2] we discussed several methods for shape determination of material defects revealed by means of infrared thermal imaging. Previous research was focused on composites and flood lamps as a heat source. The focus is now on metals and Xenon flash lamps. The main aim of this research is to estimate the depth of detected damage. The infrared camera is used for capturing temperature development on the surface of an aluminium sample in time. Contrary to Lock-in thermography where several acquisitions are needed, in presented approach the depth of defect can be revealed from single acquisition of cooling sequence. As shown in previous work, thermal decay curve of every pixel can be reconstructed as a convolution of sinus functions by applying the Fourier transform. The depth of damage can be estimated as:

$$z = C\sqrt{\frac{\alpha}{\pi f_b}} \ [m] \qquad (1)$$

where α is thermal diffusivity, f_b is blind frequency and constant C specifies material characteristics. The method was applied to the aluminium sample, a flat plate with flat bottom milled holes of different depths representing defects. The determination procedure for coefficient of thermal diffusivity and blind frequency is demonstrated. Measured and estimated values were compared for every depth, including the deviation analysis. Equipment limitations, denoising of thermographic signal and limitations of method are discussed as well.

References

[1] C. Ibarra-Castanedo. Quantitative Subsurface Defect Evaluation by Pulsed Phase Thermography: Depth Retrieval with the Phase. Ph.D. Thesis, Laval University, Quebec, 2005.

[2] P. Bagavac, L. Krstulović-Opara, Ž. Domazet. Pulse Phase Thermography: Impact Damage Retrieval. In: F. Cosmi, ed., The 34th Danubia Adria Symposium on Advances in Experimental Mechanics, Trieste, 2017.

[3] P. Bagavac, L. Krstulović-Opara, Ž. Domazet. Lock-in Thermography in Detection of Osmotic Damage. In: A. Aulova, A. Rogelj Ritonja, I. Emri, eds., The 33rd Danubia Adria Symposium on Advances in Experimental Mechanics, 54-55, SSEM, Ljubljana, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Classification of Bivariate Distribution Based on EM Algorithm

Ante BARBIR, Dario BAN, Stipe PERIŠIĆ

[*]University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia
E-mails: {abarbir, darioban, sperisic}@fesb.hr

Abstract

In present, there are many possibilities to collect large amount of data readings during measurement of specific physical quantities on various systems. This large number of readings is time-consuming for determining in which class some data could be assigned. To reduce this classification time, system which classifies reading parameters using estimation-maximization algorithm can be introduced, and afterwards using radial basis functions, get measuring results. EM algorithm is used on two generated bivariate distributions to make classification, and RBF interpolation has been made to estimate third dimension of data. Third dimension can represent various measurement results including incomplete data readings, which can be restored using RBF interpolation due RBF reconstruction property. Two sets of Gaussian distribution were used in this paper, classified, and interpolated using radial basis functions for the multivariate interpolation with Euclidean L_2 norm.

References

[1] J.A. Bilmes. A Gentle Tutorial of the EM Algorithm and its Application to Parameter Estimation for Gaussian Mixture and Hidden Markov Models. Technical Report TR-97-021, International Computer Science Institute, Berkeley, 1998.

[2] I.T. Nabney. *NETLAB – Algorithms for Pattern Recognition.* Springer-Verlag, London, 2001.

[3] D. Shepard. A Two-dimensional Interpolation Function for Irregularly-spaced Data. In: R.B. Blue, A.M. Rosenberg, eds., Proceedings of the 23rd ACM National Conference, 517-524. ACM, New York, 1968.

[4] D. Ban, B. Blagojević, J. Barle. Ship Geometry Description using Global 2D RBF Interpolation. *Shipbuilding*, 61(3): 233-242, 2010.

[5] D. Ban, S. Perišić. Surface Approximation using RBFs with L1 Norm in Polynomial Form. In: Proceedings of the International Multidisciplinary Conference on Computer and Energy Science. SpliTech, Split, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Nonlocal Thermoelasticity of Nanobeams – A Stress Driven Integral Formulation

Raffaele BARRETTA[*], Marko ČANAĐIJA[+], Francesco MAROTTI DE SCIARRA[*]

[*]University of Naples Federico II, Department of Structures for Engineering and Architecture, Via Claudio 21, I-80121 Naples, Italy
E-mails: {rabarret, marotti}@unina.it

[+]University of Rijeka, Faculty of Engineering, Department of Engineering Mechanics, Vukovarska 58, HR-51000 Rijeka, Croatia
E-mail: marko.canadija@riteh.hr

Abstract

The paper deals with the thermoelasticity of nanobeams. It is known that at the smaller scales (microscale, nanoscale) forces that are irrelevant at the macroscale should be accounted for [1]. In particular, the stress in a point is not dependent only on the strain in the point in question, but rather the whole neighbourhood affects the stress state. Traditionally, gradient based methods were employed in these kinds of problems, but with a limited success. As an alternative, the strain based integral approach was proposed, yet again with specific problems. Recently, a stress-based integral approach was proposed [2]. The latter method does not suffer from mentioned problems as its predecessors [3]. In the present paper, the formulation is extended to thermoelastic constitutive behaviour [4]. The performance of the formulation is demonstrated on an example.

References

[1] R. Barretta, M. Brčić, M. Čanađija, R. Luciano, F. Marotti de Sciarra. Application of Gradient Elasticity to Armchair Carbon Nanotubes: Size Effects and Constitutive Parameters Assessment. *European Journal of Mechanics - A/Solids*, 65: 1-13, 2017.

[2] G. Romano, R. Barretta. Nonlocal Elasticity in Nanobeams: The Stress-driven Integral Model. *International Journal of Engineering Science*, 115: 14–27, 2017.

[3] R. Barretta, M. Čanađija, L. Feo, R. Luciano, F. Marotti de Sciarra, R. Penna. Exact Solutions of Inflected Functionally Graded Nano-beams in Integral Elasticity. *Composites Part B: Engineering*, 142: 273–286, 2018.

[4] R. Barretta, M. Čanađija, R. Luciano, F. Marotti de Sciarra. Stress-Driven Modeling of Nonlocal Thermoelastic Behavior of Nanobeams. *International Journal of Engineering Science*, 126: 53-67, 2018.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Isogeometric Based Shape Optimization of Plate with Hole under Constant In-plane Tension

Anđela BARTULOVIĆ, Željan LOZINA

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia
E-mail: abartulo@fesb.hr, lozina@fesb.hr

Abstract

Shape optimization usually implies some type of analysis as a background process for defining optimization objectives and/or constraints. In most of structural optimization approaches, the finite element method (FEM) has been employed for structural response analysis [1]. This approach has one major drawback - geometric modelling and numerical analysis are based on different mathematical descriptions, i.e. geometry is defined using spline technology and FEM analysis based on Lagrangian and Hermitian polynomials only approximates given geometry. To overcome this design-analysis gap, T.J.R. Hughes and co-workers introduced the concept of isogeometric analysis (IGA) [2]. In IGA, spline basis used to describe geometry are used as a basis functions in numerical analysis as well, i.e. there is no geometry approximation, and analysis is performed on exact geometry. This method is especially attractive when comes to shape optimization – the shape can be defined via relatively small number of control points which arise as a natural choice for optimization design variables, i.e. there is no need for additional parameterization between design variables and analysis model. In the present work, shape optimization of plate with hole under constant in-plane tension is carried-out. Shape of the hole is defined with 4 control points. The optimization is conducted for 4, 6 and 8 degrees of freedom i.e. with 4, 6 and 8 design variables - coordinates and weights of control points defining hole, respectively. The goal is to find an optimal hole shape which minimizes maximum stress, for a given amount of material (constant volume) using genetic algorithms. For the sake of comparison, optimization is also conducted using gradient method. When comparing to plate with circular hole, it is shown that maximum stress can be significantly reduced (several times) with different shape, i.e. when optimization is performed.

References

[1] Y.-D. Seo, H.-J. Kim, S.-K. Youn. Shape Optimization and Its Extension to Topological Design Based on Isogeometric Analysis. *International Journal of Solids and Structuctures*, 47(11-12): 1618-1640, 2010.

[2] J.A. Cottrell, T.J.R. Hughes, Y. Bazilevs. *Isogeometric Analysis: Toward Integration of CAD and FEA*. Wiley, New York, 2009.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Using Topology Optimization to Design a Novel Auxetic Structure

Matej BOROVINŠEK, Nejc NOVAK, Matej VESENJAK, Zoran REN

University of Maribor, Faculty of Mechanical Engineering, Smetanova ulica 17, SI-2000 Maribor, Slovenia

E-mails: {matej.borovinsek, n.novak, matej.vesenjak, zoran.ren}@um.si

Abstract

Auxetic structures exhibit a negative Poisson's ratio when loaded. When compressed in one direction they shrink perpendicular to the applied load [1]. They have a high energy absorption and high fracture resistance. That makes them suitable for a number of applications in defence and civil protection sectors as body armour, shock absorbing material and packaging material. Some well-known and researched auxetic structures are re-entrant hexagons, chiral structures and rotating units. However, the new shapes of auxetic structures are required to fulfil different design goals for their intended use, such as particular dynamic behavior, fatigue resistance, manufacturability etc. The auxetic structure behavior under external load can be considered as the behavior of a compliant mechanism that transfers an input force and displacement to an output force and displacement through elastic body deformation [2]. The compliant mechanism design is governed by two opposing objective functions, namely the flexibility and stiffness. In this study the topological optimization based on the finite element method was used to determine the optimal shape of such a compliant mechanism. The optimization was performed on a single representative unit cell, which is a building block of the auxetic structure. The optimized representative unit cells were then assembled into an auxetic structure using different transformation functions to achieve desired design goal.

References

[1] N. Novak, M. Vesenjak, Z. Ren. Auxetic Cellular Materials - A Review. *Strojniški Vestnik – Journal of Mechanical Engineering*, 62(9): 485-493, 2016.

[2] L.L. Howell. *Compliant Mechanisms*. John Wiley & Sons, New York, 2001.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

A Porous Media Approach for Biologically Inspired Scaffolds

Daniela BOSO

University of Padua, Department of Civil, Environmental and Architectural Engineering, Via Marzolo 9, I-35131, Italy
E-mail: daniela.boso@unipd.it

Abstract

Scientific advances in biomaterials, stem cells, growth and differentiation factors, and biomimetic environments have created unique opportunities to fabricate tissues in the laboratory from combinations of engineered extracellular matrices (scaffolds), cells, and biologically active molecules. Within a scaffold, complex biological phenomena take place: cell seeding, cell migration and proliferation, cell differentiation, consumption of nutrients, to name a few. In this work, we combine a mathematical model and laboratory experiments to study the evolution of bone formation in a bio-inspired scaffold used for spinal fusion. We investigate the influence of the physiological parameters and the mechanical stimulus on the differentiation of mesenchymal stem cells into trabecular bone and, at a later stage, of trabecular bone cells into cortical bone. The mathematical model is based on porous media mechanics. We consider the scaffold as composed by two main constituents: a solid phase that is made by cells and extracellular matrix (ECM), and a liquid phase given by the interstitial fluid. The two phases include different species. In particular, in the solid phase we have the mesenchymal stem cells (MSC), the trabecular bone (TB) and the cortical bone (CB). To investigate the effects of the external loading on tissue differentiation, three different analyses are performed. In the first one, no external loads are considered, to assess the capacity of the model to match in vivo results. In the second one, a pressure is linearly increased over a time of 200 minutes, starting at 10000 minutes (about 1 week) and then is kept almost constant until the end of the simulation. In the third case the scaffold is loaded at four weeks, to study the effects of a delayed mechanical stimulus on the phenomenon. We report the cell differentiation curves for the three cases mentioned above, supplemented with the evolution of quantities of interest, such as the effective stresses and interstitial fluid pressures. We analyze the dependence of the bone development on the mechanical environment, with a particular focus on the capability of hydrostatic effective pressure to limit the velocity of tissue differentiation during time.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Numerical and Experimental Investigation of Anisotropic Material Behaviour in Crimping Process

Ante BUBALO[*], Zdenko TONKOVIĆ[+], Lovre KRSTULOVIĆ-OPARA[++], Martin SURJAK[+], Janoš KODVANJ[+], Dalibor ZORICA[*]

[*]*Yazaki Europe Limited, Slavonska 26/6, HR-10000 Zagreb, Croatia*
E-mails: ante.bubalo@yazaki-europe.com, dalibor.zorica@yazaki-europe.com

[+]*University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia*
E-mails: zdenko.tonkovic@fsb.hr, martin.surjak@fsb.hr, janos.kodvanj@fsb.hr

[++]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia*
E-mail: lovre.krstulovic-opara@fesb.hr

Abstract

The wire crimping process is solderless procedure of making an electrical connection between wire strands and terminal. This process is widely used in automotive industry. In order to predict the final shape of a crimped terminal and to reduce costs of production, the numerical simulations are unavoidable. The modelling of such problems using the finite element method is a challenging and complicated task. The nonlinear dynamic models include complex constitutive equations, nonlinear kinematics, friction and large contact pressures, which lead to element overclosure and non-physical behaviour of the model [1]. Copper and copper alloys, with large ductility and strength, are typically used as terminal material. Due to metal rolling process of copper and its alloys, severe anisotropy of mechanical properties may occur. There are only limited experimental data available on the influence of anisotropy and strain rate on the mechanical behaviour of these materials. This paper presents an experimental and numerical study of anisotropic elasto-plastic behaviour of two different copper materials Cu-ETP and CuFe2P. Tensile and compression tests at 0º, 45º and 90º to the rolling direction, and under different strain rates are carried out to determine the Lankford coefficients and hardening coefficients in each direction. Loading process has been acquired by infrared thermography and digital image correlation techniques [2]. Numerical simulations of the process are carried out by using ABAQUS Standard and ABAQUS/Explicit. Computed results are compared with experimental data.

References

[1] K. Mocellin, M. Petitprez. Experimental and Numerical Analysis of Electrical Contact Crimping to Predict Mechanical Strength. *Procedia Engineering*, 81: 2018-2023, 2014.

[2] L. Krstulović-Opara M. Surjak, M. Vesenjak, Z. Tonković, J. Kodvanj, Ž. Domazet. Comparison of Infrared and 3D Digital Image Correlation Techniques Applied for Mechanical Testing of Materials. *Infrared Physics & Technology*, 73: 166-174, 2015.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Experimental Study of Environmental Loads on a Monopole-supported Offshore Wind Turbine

Andrija BULJAC[*], Hrvoje KOZMAR[*], Wenxian YANG[+], Ahsan KAREEM[#]

[*]University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {abuljac, hkozmar}@fsb.hr

[+]Newcastle University, School of Engineering, Newcastle, England, United Kingdom
E-mail: wenxian.yang@ncl.ac.uk

[#]University of Notre Dame, Department of Civil and Environmental Engineering and Earth Sciences, Notre Dame, Indiana, United States of America
E-mail: kareem@nd.edu

Abstract

Offshore wind turbines are commonly challenged by inconsistent loads of wind, wave and tidal current [1]. It is hence necessary to carefully analyze the effects of environmental loads on these structures to increase their lifetime. In this study, both individual and coupled effects of wind, wave and sea current on integral loading of a bottom-fixed monopole supported offshore wind turbine were studied. The small-scale laboratory experiments were carried out in the Wind-Wave-Current (WWC) Tank at Newcastle University, UK. This facility generally allows the simulation of wind, sea current and waves with controllable amplitude and frequency. The small-scale model of Siemens Sapiens FFA W3 offshore wind turbine was mounted in the test section center via a six-component high-frequency force balance measurement system. The blade tip-speed ratio was controlled through adjusting the rotational speed of the rotor. The dynamic integral loads were measured at different tip-speed ratios and under a variety of offshore conditions. The measured loads were processed using spectral analysis method and the resultant frequency characteristics were used for analyzing the dynamic performance of the wind turbine. The results indicate that the sea current and waves have a significant influence on the integral loads, while the waves contribute more to the dynamic response of the wind turbine.

Acknowledgements: The authors acknowledge the Croatian Science Foundation support under the project *Wind and Sea Loading on Energetic Structures* (*WESLO*) (HRZZ-IP-2016-06-2017). Special thanks are extended to the WWC technical staff for their help in performing the experiments and to Mr. Peter Bowes for his kindness with respect to coordinating the WWC tests.

References

[1] A. Henderson, M. Collu, M. Masciola. Overview of Floating Offshore Wind Technologies. In: J. Cruz, M. Atcheson, eds., Floating Offshore Wind Energy, 87-132. Springer, New York, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

On the Torsional Response of Framed-Masonry Building under Earthquake Action

Dalibor BURILO[*], Davorin PENAVA[*], Ivica GULJAŠ[*], Lucas LAUGHERY[+], Santiago PUJOL[-]

[*]*Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, 3 Vladimir Prelog Street, HR-31000 Osijek, Croatia*
E-mails: {dburilo, dpenava, iguljas}@gfos.hr

[+]*Nagoya Institute of Technology, Department of Architecture & Design, Gokiso, Showa, Nagoya, Aichi, 466-8555, Japan*
E-mail: llaugher@purdue.edu

[-]*Purdue University, Department of Civil Engineering, 550 Stadium Mall Drive, West Lafayette, Indiana, United States of America*
E-mail: spujol@purdue.edu

Abstract

Earthquakes have shown that buildings that are regular in plan and elevation have more favorable behavior than irregular buildings. This is in part because torsional effects in irregular buildings can amplify demands. But sources of irregularity are not always the result of structural design decisions, [1]. Masonry walls are often used in reinforced concrete buildings for architectural purposes, but their presence and the locations of openings in them can introduce stiffness irregularities that affect structural response. The aim of this paper is to show, through dynamic earthquake-simulation tests, the torsional response of a three-story reinforced concrete frame-masonry building. Two series of tests were considered: in the first series, the structure had unreinforced clay block masonry walls; in the second, the masonry walls in the first and the second stories were replaced by solid brick walls and vertical reinforced confining elements were added around openings, [2, 3]. In both series, the structure was subjected to sequences of ten ground motions of increasing intensity from 0.05 up to 1.2 g along a single axis. In addition to in-plane drift, out-of-plane drift at the roof also was observed, suggesting rotational response. Conclusions are given in the form of torsional stiffness variation with respect to ground motion intensity i.e. structural damage increase.

References

[1] P. Negro, A. Colombo. Irregularities Induced by Nonstructural Masonry Panels in Framed Buildings. *Engineering Struct*ures, 19(7): 576–85, 1997.

[2] V. Sigmund. FRAmed-MAsonry Composites for Modelling and Standardization [Internet]. 2015 [cited 2015 Jan 13]. Available from: http://framed-masonry.com/

[3] G. Necevska-Cvetanovska, V. Sendova, R. Apostolska. FRAme - MAsonry Composites for Modelling and Standardization (Framed-Masonry). Report IZIIS 2015 - 31, Skopje, 2015.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Prediction of the Behavior of Experimentally Tested Structure Using the N2 Method

Adriana CEROVEČKI[*], Ivan KRAUS[*], Balázs KÖVESDI[+], Ivica GULJAŠ[*]

[*] ***Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, 3 Vladimir Prelog Street, HR-31000 Osijek, Croatia***
E-mails: {acerovecki, ikraus, iguljas}@gfos.hr

[+] ***Budapest University of Technology and Economics, Budapest, Hungary***
E-mail: kovesdi.balazs@epito.bme.hu

Abstract

The very beginnings of the N2 method started in late 1980's [1] and since then method has been developing by many researchers e.g. [1, 2]. The N2 method is a nonlinear static method implemented in European norms [3] and it is considered as a useful tool in seismic design of buildings. The method is considered to be simpler compared to other complexed approaches proposed in the norms, e.g. nonlinear dynamic analysis, while the results remain accurate and similar to other methods. In this paper, the N2 method is compared to experimental results of Blind Test Challenge model conducted in Portugal in 2012. Within the challenge, a 3D reinforced concrete frame model was experimentally tested using bi-directional shaking table [4]. The structure has undergone four different simulated earthquake motions, different in magnitude but similar in frequency content. Records comprising displacement time history data were available to the authors and used in the current research program. To make the data analysis easier the signals were filtered and smoothed. After filtering and smoothing brief study regarding the fundamental period of oscillations was conducted and the numerically, experimentally and analytically obtained values are compared. Finally, the N2 method was applied to the concrete 3D frame model. Using the method target displacement was determined and compared to displacements recorded in the test.

References

[1] P. Fajfar, M. Fischinger. N2 – A Method for Non-linear Seismic Analysis of Regular Buildings. In: Proceedings of the 9th World Conference on Earthquake Engineering, 111-116, Tokyo-Kyoto, 1988.

[2] P. Krolo, M. Čaušević, M. Bulić. The Extended N2 Method in Seismic Design of Steel Frames Considering Semi-rigid Joints. In: Proceedings of the 2nd European Conference on Earthquake Engineering and Seismology, 2418-2427, EAEE, Istanbul, 2014.

[3] EN 1998-1: 2004: *Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings*, CEN, Brussels, 2004.

[4] 15WCEE Blind Test Challenge - Design Report, 2012.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Aerodynamic Mitigation and Wind Energy Generation using Roof Mounted Turbines

Arindam G. CHOWDHURY [*], Andres TREMENTE [*], Ioannis ZISIS[*], Mohhammadtaghi MORAVEJ[*], Bodhisatta HAJRA[+]

[*]Florida International University (FIU), 10555 W. Flagler Street, Engineering Center, Miami, FL 33174, United States of America
E-mails: {chowdhur, tremante, izisis, mmora229}@fiu.edu

[+]Former Research Scientist, Florida International University (FIU), 10555 W. Flagler Street, Miami, FL 33174, United States of America
E-mail: hajra.bodhisatta@gmail.com

Abstract

Roofing is the most vulnerable part of a low rise building as it is often damaged in high winds that produce high suctions or uplift forces on the edges and corners [1]. This study investigates the application of a smart mitigation strategy, in the form of an Aerodynamic Mitigation and Power Production System (AMPS) (United States Patent Application Publication, Pub. No.: US 2015/0345472 A1). This dual-function system can simultaneously reduce wind induced uplift on roofs and produce wind energy. The system consists of horizontal axis wind turbines attached to the roof edges. Different configurations of this system were tested on a flat roof of a low rise building model at the Florida International University's Wall of Wind (WOW) -- an NSF designated Natural Hazards Engineering Research Infrastructure (NHERI) Experimental Facility (EF) [2]. Significant reduction in mean and peak pressure coefficients were obtained when the wind turbines were placed closer to the roof edge as compared to the bare roof deck (no mitigation) case. Preliminary estimates show that the system can generate power of around 190-195 Watt per linear meter starting at 225 rpm of rotational speed. The electricity generated by AMPS fitted on the roof perimeter of a moderate size single family home, can be stored in battery systems, which during a blackout-level storm could power various equipment. It is to be noted that the 2017 hurricanes in the U.S. caused severe power outage and community disruption. AMPS would not only produce power under strong winds but also generate supplementary power even from the ubiquitous 5 to 7 mph winds that occur day and night across most parts of the U.S. This retrofitting technology is multifunctional (or smart) as it can make individual buildings more self-sufficient while also reducing risk of roof damage from major storms.

References

[1] E. Gavanski, B. Kordi, G.A. Kopp, P.J. Vickery. Wind loads on roof sheathing of houses. *Journal of Wind Engineering and Industrial Aerodynamics*, 114: 106–121, 2013.

[2] A. Gan Chowdhury, I. Zisis, P. Irwin, G. Bitsuamlak, J.-P. Pinelli, B. Hajra, M. Moravej. Large-Scale Experimentation Using the 12-Fan Wall of Wind to Assess and Mitigate Hurricane Wind and Rain Impacts on Buildings and Infrastructure Systems. *Journal of Structural Engineering*, 143(7), 04017053-1-16, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Numerical Simulation of Annular Flow Boiling in a Vertical Pipe Using Two-Fluid Model

Alen CUKROV[*], Yohei SATO[+], Ivanka BORAS[*], Bojan NIČENO[+]

[*]*University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia*
E-mails: {alen.cukrov, ivanka.boras}@fsb.hr

[+]*Laboratory of Thermal Hydraulics, Paul Scherrer Institute (PSI), CH-5232 Villigen, Switzerland*
E-mails: {yohei.sato, bojan.niceno}@psi.ch

Abstract

The goal of this paper is to develop a numerical model for computation of annular flow boiling in a vertical pipe under 70 bar pressure and 10 K inlet subcooling. The model is based on two-fluid formulation in conjunction with an extended formulation of Rensselaer Polytechnic Institute model for boiling flows. Here, the successful modelling of the annular flow boiling is achieved by use of closure correlations for interfacial transfer proposed in [1]. This refers to constitutive relations for vapour-bubble diameter and interfacial lift force, both being computed as flow regime dependent. A uniform wall heat flux is applied at the pipe wall, while the inlet mass fluxes were varied. The model validation is done by comparison of vapour volume fraction at specific points near the pipe outlet with the data extracted from measurements conducted in [2]. The obtained results agree well with the experimental data, thus indicating the reliability of the developed model in computation of such multiphase flow phenomena.

References

[1] S.-J. Yoon, G. Agostinelli, E. Baglietto. Assessment of Multiphase CFD with Zero Closure Model for Boiling Water Reactor Fuel Assemblies. In: S.G. Wang, N.E. Todreas, G.X. Li, F.B. Cheung, J.H. Kim, B.W. Yang, eds., Proceedings of the 17th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-17). Xi'an, 2017.

[2] C. Adamsson. Measurements of Film Flow Rate in Heated Tubes with Various Axial Power Distributions. PhD Thesis, KTH Stockholm, 2006.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Dynamics of Mass-in-Mass Units in Elastic Metamaterial

Livija CVETICANIN, Miljana PRICA

University of Novi Sad, Faculty of Technical Sciences, 21000 Novi Sad, Trg D. Obradovića 6, Serbia
E-mails: {cveticanin, miljana}@uns.ac.rs

Abstract

In order to improve vibrational isolation in machinery, vehicles, buildings and other applications, some novel materials that stop the vibration propagation at certain frequencies have been developed. The elastic metamaterials represent a new generation of vibration absorbing materials that work efficiently over a broad frequency range and, in particular, at low frequencies. A key concept for the generation of these band gaps is an inhomogeneous structure. Different design strategies for elastic metamaterials have been reported in the literature, [1], but concept of the composite with mass-in-mass subunits that create a set of resonances is of special interest for engineering. The material structure is analogous to traditional honey comb panels - it consists of periodic unit cells. Each unit cell has a locally resonant structure, which exhibits exceptional phenomena at resonance: either a negative effective bulk modulus or a negative effective mass density, [2]. If properly designed, both characteristics can be achieved and the propagation of vibration will be prohibited. The negative mass behaviour is generated by resonant structures within the material that oscillate 180^o out of phase with the excitation force. The aim of this presentation is to give the overview on the dynamics of the mass-in-mass unit which is the basic element of elastic metamaterial. Nonlinear properties and multi-periodical excitation are considered. Analytic procedure for solving strong nonlinear two-degree-of-freedom oscillator is developed, [3]. The computed results are compared with numerical ones. They are in good agreement. Our intention is to utilize these results in praxis and to increase the vibration absorption by widening the frequency band-gaps.

References

[1] L. Cveticanin, Gy. Mester. Theory of Acoustic Metamaterials: An Overview. *Acta Polytechnica Hungarica*, 13(7): 43-62, 2016.

[2] H.H. Huang, C.T. Sun, G.I. Huang. On the Negative Effective Mass Density in Acoustic Metamaterials. *International Journal of Engineering Science*, 47: 610-617, 2009.

[3] L. Cveticanin, M. Zukovic. Negative Effective Mass in Acoustic Metamaterial with Nonlinear Mass-in-Mass Subsystems. *Communications in Nonlinear Science and Numerical Simulation*, 51: 89-104, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Comparison of Full and Simple Approach under Non-associated Flow Rule for an Evolutionary Anisotropic Model

Vedrana CVITANIĆ, Maja KOVAČIĆ

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia
E-mails: vcvit@fesb.hr, majkovac@fesb.hr

Abstract

In elasto-plastic constitutive formulations based on the non-associated flow rule the evolution equation for the equivalent plastic strain as hardening parameter can be established by two approaches [1-3]. By the full approach, the evolution equation is derived using the principle of plastic work equivalence. Consequently, the equivalent plastic strain increment is proportional to the ratio of plastic potential and yield function with the plastic multiplier as proportionality factor. By the simple approach, the difference between plastic potential and yield function in this evolution equation is neglected and the equivalent plastic strain corresponds to the plastic multiplier. In this paper, the full approach and the simple approach are applied for an evolutionary anisotropic plasticity model intended for sheet metals that is based on the non-associated flow rule and the orthotropic Hill1948 stress function as yield function/plastic potential. In the considered model, anisotropy parameters of the yield function are adjusted to yield stress ratios and anisotropy parameters of the plastic potential function are adjusted to Lankford coefficients. Since the evolution of material plastic anisotropy with ongoing deformation process is assumed, anisotropy parameters of the yield function/plastic potential are considered as continuous functions of the equivalent plastic strain. Algorithmic formulations, based on the implicit return mapping, of the full and simple approach for the considered evolutionary anisotropy model are reviewed. Considering experimental data for DC06 steel sheet sample, analyzed algorithmic formulations are compared in predicting some simple deformation processes. The difference in the predicted equivalent plastic strain and related contours of the yield function/plastic potential are considered. The applicability of the simple approach, as more computationally efficient, is estimated for the considered material.

References

[1] V. Cvitanić, F. Vlak, Ž. Lozina. A Finite Element Formulation Based on Non-associated Plasticity for Sheet Metal Forming. *International Journal of Plasticity*, 24: 646-687, 2008.

[2] V. Cvitanić, M. Kovačić. Algorithmic Formulations of Evolutionary Anisotropic Plasticity Models based on Non-Associated Flow Rule. *Latin American Journal of Solids and Structures*, 14(10): 1853-1871, 2017.

[3] Q. Hu, X. Li, J. Chen. On the Calculation of Plastic Strain by Simple Method under Non-associated Flow Rule. *European Journal of Mechanics A/Solids*, 67: 45-57, 2018.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Performance of Standard and Mixed Finite Elements for Kirchhoff and Mindlin Plates

Jasmin ČALUK[*], Senad MEDIĆ[+], Samir DOLAREVIĆ[+]

[*]***Pont Ltd, Borak 2, 71000 Sarajevo, Bosnia and Herzegovina***
E-mails: jasmin.caluk91@gmail.com

[+]***University of Sarajevo, Faculty of Civil Engineering,***
Patriotske lige 30, 71000 Sarajevo, Bosnia and Herzegovina
E-mail: {senad.medic, samir.dolarevic}@gf.unsa.ba

Abstract

Overview of finite elements for analysis of Kirchhoff and Mindlin plates is presented in this paper. The final elements for Kirchhoff plates have a demanding formulation regarding the continuity of vertical displacement and rotation as the governing differential equation is of the fourth order. If some of the continuity requirements are not met, the elements are called non-conforming and may have problems with convergence if the mesh is refined [1]. The alternative formulation pertains to Mindlin theory, which encompasses shear deformation. Relevant differential equations are of the second order, so the continuity requirement is weaker. Standard displacement based and mixed finite elements [2] for Kirchhoff and Mindlin plates are derived and implemented in MATLAB and critically tested using practical examples and patch tests. The obtained results are compared with solutions obtained in commercially available software.

References

[1] M.A. Bhatti. *Advanced Topics in Finite Element Analysis of Structures: With Mathematica and Matlab Computations.* John Wiley and Sons, New Jersey, 2006.

[2] A. Ibrahimbegović. *Nonlinear Solid Mechanics: Theoretical Formulations and Finite Element Solution Methods. (Nelinearna mehanika deformabilnih tijela).* Faculty of Civil Engineering, Sarajevo, 2010. (in Bosnian)

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Rocking Stability: Numerical and Experimental Investigations on Prismatic Blocks

Nina ČEH, Gordan JELENIĆ, Nenad BIĆANIĆ†

University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia
E-mails: {nina.ceh, gordan.jelenic}@uniri.hr

Abstract

Rocking of prismatic rigid blocks is analysed and a numerical procedure based on precise contact detection is developed and tested. First, a parametric study of free rocking of blocks of different slenderness and size is conducted experimentally. Energy loss in relation to existing restitution models (Housner's classical model [1] and the improved model by Kalliontzis et al. [2]) is investigated in detail. Based on the numerically and experimentally obtained results, the use of the improved model is strongly encouraged, and a procedure to estimate the unknown parameter in the improved formula is suggested. Secondly, full time response due to a single sine- or cosine-wave acceleration excitation is obtained numerically, where the improved restitution model [2] with the suggested estimated parameter is used. Finally, a chosen set of numerical cases is validated experimentally using a specifically designed set of experiments involving shaking tables and optical measurement equipment.

References

[1] G.W. Housner. The Behavior of Inverted Pendulum Structures during Earthquakes. *Bulletin of Seismological Society of America*, 53(2): 403-417, 1963.

[4] D. Kalliontzis, S. Sritharan, A.E. Schultz. Improved Coefficient of Restitution Estimation for Free Rocking Members. *Journal of Structural Engineering*, 142(12): paper no. 06016002 (7 p.), 2016.

† Deceased

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

A New Finite Element for Higher Order Continuum Theory

Joško FRANČESKI, Ivica SKOZRIT, Tomislav LESIČAR, Jurica SORIĆ

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {josko.franceski, ivica skozrit, tomislav.lesicar, jurica.soric}@fsb.hr

Abstract

Heterogeneous microstructure is present in all engineering materials, and an accurate description of microstructural behaviour is necessary in order to correctly predict behaviour of macrostructure. Classical continuum mechanics uses local approach and is unable to describe the effect of the microstructural size. Using higher – order continuum theory, which includes microstructural parameter in its formulation, enables to properly model microstructure of a given material. This contribution deals with a new finite element which can be used for modelling heterogeneous materials using higher order theories. The proposed element is two–dimensional, four node triangle, with displacements and first derivations of displacements as degrees of freedom in corner nodes, and displacements as degrees of freedom in node positioned at triangle centroid in order to satisfy full interpolation polynomial of third degree. The finite element is developed using displacement based method [1] in Cartesian coordinate system and yields linear deformations and constant second-order deformations, and satisfies semi C^1 continuity. Such element is feasible for implementation of both classical continuum theory as well as higher – order theories. In this contribution, Aifantis theory of gradient elasticity [2], which is a simplification of more general gradient theory developed by Mindlin [3], is implemented in the finite element formulation. The research proposed continues work performed by Lesičar et al. [4], where the C^1 finite element in triangular coordinate system has been developed. The benchmark and patch test results, as well as the comparison between previously developed and new element, are reported in numerical examples.

References

[1] J. Sorić. *Metoda konačnih elemenata (Finite Element Method).* Golden Marketing – Tehnička knjiga, Zagreb, 2004. (in Croatian)

[2] E.C. Aifantis. Strain Gradient Interpretation of Size Effects. *International Journal of Fracture*, 95(1-4): 299-314, 1999.

[3] R.D. Mindlin. Micro-structure in Linear Elasticity. *Archive for Rational Mechanics and Analysis*, 16(1): 51-78, 1964.

[4] T. Lesičar, Z. Tonković, J. Sorić. C^1 Continuity Finite Element Formulation in Second-Order Computational Homogenization Scheme. *Journal of Multiscale Modelling*, 4(4): 11-19, 2012.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Numerical Studies of Motion of an Inertially Driven Robot

Pawel FRITZKOWSKI, Roman STAROSTA

[*]Poznan University of Technology, Institute of Applied Mechanics,
ul. Jana Pawła II 24, 60-965 Poznan, Poland
E-mails: {pawel.fritzkowski, roman.starosta}@put.poznan.pl

Abstract

Mobile robots without any external movers (like legs, wheels, tracks etc.) have drawn attention of many researchers in recent years. Within this category, the so called vibration-driven or inertially driven robot is a very interesting conception [1-4]. In what follows, one-dimensional motion of a system on a rough horizontal plane excited by internal periodic oscillations is studied. Two internal masses are considered: one of them moves horizontally, the other vertically (Fig. 1). Equation of motion for the system is derived and presented in a non-dimensional form. Three-phase and four-phase internal motions are taken into account, where the relative accelerations are piecewise-constant. The effects of the parameters of such excitation are analyzed. Moreover, various friction models are employed in numerical simulations.

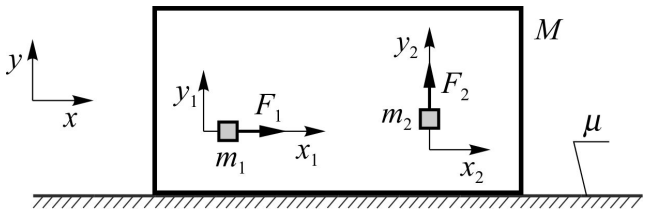


Figure 1. The carrying body with movable internal masses

The main aim of the studies is to select optimal values of the model parameters with respect the average velocity of the robot. Efficiency of the proposed conception, i.e. the velocity and displacement of the system per one period of the internal excitation, is compared with other ideas provided in literature. In particular, harmonic oscillations of the internal masses are treated as the basic variant.

References

[1] N.N. Bolotnik, I.M. Zeidis, K. Zimmermann, S.F. Yatsun. Dynamics of Controlled Motion of Vibration-driven Systems. *J. of Computer and Systems Sciences Int.*, 45(5): 831-840, 2006.

[2] F.L. Chernous'ko. On the Motion of a Body Containing a Movable Internal Mass. *Doklady Physics*, 50(11): 593-597, 2005.

[3] F.L. Chernous'ko. Analysis and Optimization of the Motion of a Body Controlled by Means of a Movable Internal Mass. *J. of Applied Mathematics and Mechanics*, 70(6): 819-842, 2006.

[4] N.A. Sobolev, K.S. Sorokin. Experimental Investigation of a Model of a Vibration-driven Robot with Rotating Masses. *J. of Computer and Systems Sciences Int.*, 46(5): 826-835, 2007.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Analytical Approach to a Two-Module Vibro-Impact System

Pawel FRITZKOWSKI[*], Roman STAROSTA[*], Jan AWREJCEWICZ[+]

[*]Poznań University of Technology, Institute of Applied Mechanics,
ul. Jana Pawła II 24, 60-965 Poznań, Poland
E-mails: {pawel.fritzkowski, roman.starosta}@put.poznan.pl

[+]Technical University of Łódź, Department of Automatics and Biomechanics,
ul. Stefanowskiego 1/15, 90-924 Łódź, Poland
E-mail: jan.awrejcewicz@p.lodz.pl

Abstract

Among strongly nonlinear problems, the vibro-impact systems are of considerable practical importance. Unfortunately, applicability of most approximate analytical methods for nonlinear systems is usually limited to weak nonlinearities. However, over recent years, some techniques for the vibro-impact systems have been developed by imposing certain conditions on their motion [1-3]. In what follows, the approach based on the multiple time scales method combined with a saw-tooth function is used [2, 3]. A two-module vibro-impact system is considered (Fig. 1). The primary coupled oscillators are linear, while the impacting particles that can move freely in the straight cavities are the sources of nonlinearity. It is assumed that mass of the particles is relatively small; the impacts are characterized by the restitution coefficient. The system is subjected to an external harmonic excitation.

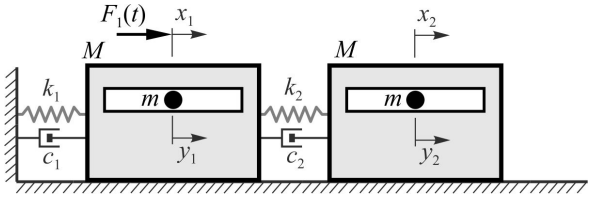


Figure 1. The two-module vibro-impact system

Equations of motion for the system are derived and presented in a non-dimensional form. The relation describing the slow invariant manifold is found. The final approximate solutions in the resonant case have a semi-analytical character. The interplay between the model parameters is analyzed.

References

[1] V.N. Pilipchuk. Impact Modes in Discrete Vibrating Systems with Rigid Barriers. *International Journal of Non-Linear Mechanics*, 36(6): 999-1012, 2001.
[2] O.V. Gendelman. Analytic Treatment of a System with a Vibro-impact Nonlinear Energy Sink. *Journal of Sound and Vibration*, 331(21): 4599-4608, 2012.
[3] T. Li, S. Seguy, A. Berlioz. Dynamics of Cubic and Vibro-Impact Nonlinear Energy Sink: Analytical, Numerical, and Experimental Analysis. *Journal of Vibration and Acoustics*, 138(3): 031010-031010-9, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Mechanical Properties of Wrought and Selective Laser Melted Ti-6Al-7Nb Alloy

Ivan GELO[*], Dražan KOZAK[*], Nenad GUBELJAK[+], Darko DAMJANOVIĆ[*], Tomaž VUHERER[+]

[*]***Josip Juraj Strossmayer University of Osijek, Mechanical Engineering Faculty in Slavonski Brod, Trg Ivane Brlić Mažuranić 2, HR-35000 Slavonski Brod, Croatia***
E-mails: {ivan.gelo, drazan.kozak, darko.damjanovic}@sfsb.hr

[+]***University of Maribor, Faculty of Mechanical Engineering, Smetanova ul. 17, SI-2000 Maribor, Slovenia***
E-mails: {nenad.gubeljak, tomaz.vuherer}@um.si

Abstract

The development of metal powder application in additive manufacturing opens new possibilities and makes new design approaches possible. Nevertheless, when used for purposes other than rapid prototyping, the mechanical properties of additively manufactured parts have to meet the desired values to be able to serve as an alternative to conventional production technologies. Therefore, the experimental testing of mechanical properties has been conducted on additively manufactured test pieces. The test pieces have been produced by selective laser melting as one of the most commonly used procedures in powder metallurgy. The powder is made by gas atomization of biocompatible alloy Ti-6Al-7Nb used mainly for hip implants. In order to gain better perspective to the values obtained, the testing has been conducted on test pieces made from wrought bar as well, so the comparative analysis of mechanical properties can be performed.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Testing the Influence of Creep on Fire-exposed Aluminium Columns

Marko GORETA, Neno TORIĆ, Vladimir DIVIĆ, Ivica BOKO, Jelena LOVRIĆ VRANKOVIĆ

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice Hrvatske 15, HR-21000 Split, Croatia
E-mails: marko.goreta@gradst.hr, neno.toric@gradst.hr, vladimir.divic@gradst.hr, ivica.boko@gradst.hr, jelena.lovric@gradst.hr

Abstract

The paper presents new research conducted on aluminium alloy EN6082AW T6 at high temperature. One of the major reasons for conducting this experimental study is the fact that the influence of creep strain on load capacity of aluminium structures and elements is relatively unknown in scientific literature [1]. The research concerns high-temperature transient tests on column specimens with the length of approximately 2.59 m. The objective of the research is to study the development of high-temperature creep that occurs during transient heating of the column. Transient heating regime that is covered in the tests is within 10°C/min, which represents heating rates that usually occur in fire-protected columns. The results of the transient tests point out that the columns are sensitive to variable heating rates due to different amount of creep that occurs per test. The tests are performed at University of Split. The heating arrangement used in this study is based on novel heating scheme which utilizes induction heating. An induction machine is used to create a magnetic field that induces heating of ferromagnetic materials within its reach. This field is generated around induction cables which are mounted on the steel jacket that surrounds the tested specimen (Figure 1). The steel jacket heats the aluminium specimen by means of radiation heat transfer which in this case represents a uniform heating source due to the round shape of the steel jacket.

Figure 1. Column test-setup

References

[1] N. Torić, J. Brnić, I. Boko, M. Brčić, I.W. Burgess, I. Uzelac. Experimental Analysis of the Behaviour of Aluminium Alloy EN6082AW T6 at High Temperature. *Metals*, 7(4): Paper No. 126 (15 p.), 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Fup Basis Functions: Theory, Applications and Challenges

Blaž GOTOVAC, Hrvoje GOTOVAC, Vedrana KOZULIĆ, Luka MALENICA, Nives BRAJČIĆ-KURBAŠA, Grgo KAMBER

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, HR-21000 Split, Croatia
E-mails: {blaz.gotovac, hrvoje.gotovac, vedrana.kozulic, luka.malenica, nbrajcic, grgo.kamber}@gradst.hr

Abstract

Over last 35 years Croatian scientific team from University of Split led by Professor Blaž Gotovac [1] have investigated and developed theory and applications of Fup basis functions. They belong to the class of atomic basis functions introduced in [2] and can be regarded as infinitely derivable splines sharing many important properties: localization through the compact support, good approximation properties linked with exact presentation of algebraic and exponential polynomials, partition of unity, desired level of continuity, representation of probability density function, etc. Fup basis functions enable efficient numerical and stochastic modeling as well as application in many fields of computational mechanics [3]. They can be applied in elliptic, parabolic and hyperbolic problems through the strong formulation (collocation) or weak formulation (Galerkin and finite volume). Application to elliptic problems, such as in structural mechanics, is very efficient in comparison to conventional finite elements due to enhanced continuity, higher order and superior approximation properties of Fup basis functions. Application to non-stationary parabolic advection dominated problems requires an efficient adaptive procedures or exponential Fup functions which are well suited for description of sharp fronts. Particular difficulty presents description of irregular geometry because Fup basis functions in higher dimensions are obtained by tensor product. Problem can be solved by isogeometric analysis through geometric transformations in parametric or by meshfree approach in physical space. Both approaches do not use the classical finite element meshing as the most time consuming procedure. Stochastic modeling is revised through an application of Monte-Carlo and maximum entropy method. In this paper our previous and recent work is revised and linked with future challenges which include application to open multi-physics and hyperbolic problems and development of efficient parallel 3-D solvers.

References

[1] B. Gotovac, V. Kozulić. On a Selection of Basis Functions in Numerical Analyses of Engineering Problems, *Int. Journal for Engineering Modelling*, 12(1-4): 25-41, 1999.

[2] V.L. Rvachev, V.A. Rvachev. A Certain Finite Function, *Dopovidi Akad. Nauk Ukrain. RSR Ser. A*, 8: 705–707, 1971. (in Ukrainian)

[3] H. Gotovac. *A Multi-resolution Approach for Modeling Flow and Solute Transport in Heterogeneous Porous Media*. PhD Thesis, KTH Stockholm, 2009.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Reliability Analysis of Reinforced–Concrete Frame by Finite Element Method (FEM)

Marin GRUBIŠIĆ

Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, Department for Technical Mechanics, 3 Vladimir Prelog Street, HR–31000 Osijek, Croatia
E–mail: marin.grubisic@gfos.hr

Abstract

The reliability analysis in this study was carried out on the basis of a nonlinear numerical model, where static and dynamic loads can be analysed. This approach has the advantage of reducing the uncertainties that are otherwise present in the analytical definition of the limit state equation, the form of which is considerably complicated by considering the nonlinearity and static indeterminacy of the model. The aim of this paper is to assess the reliability of the horizontal bearing capacity of the nonlinear model by the static pushover analysis. First Order Second Moment (*FOSM*), First– and Second Order Reliability Method (*FORM*, *SORM*), as well as the *Monte Carlo* simulation, were performed by the finite element method (*FEM*), to assess the probability of failure, P_f. The numerical macro model represents a one–bay one–storey reinforced–concrete frame, originally constructed in scale 1:2.5, which is calibrated on the basis of previously performed static in–plane reversed–cyclic experiments. Parameters of constituent materials and basic random variables were defined, while the other variables are embedded in terms of load– and geometry–related uncertainties of the model, all based on experimental validation. For the most realistic description of the behaviour of structures in earthquake engineering by nonlinear dynamic time–history analysis (*NLTHA*), the greatest source of uncertainty stems from the strong ground motion record parameters, while the uncertainties associated with the material characteristics and geometry are significantly lower but not negligible. The results of the *FORM* analysis are comparable to the *Monte Carlo* simulations, and the optimum combination of material parameters for reaching the target displacement defined by the limit state equation is obtained. This approach to reliability analysis provides practically unlimited capabilities in the field of earthquake engineering and the overall implementation of uncertainty within a single numerical model, which is necessary for assessing the risk of collapse or estimating losses within the framework of the *PEER PBEE* methodology.

References

[1] F. McKenna, G.L. Fenves, M.H. Scott, S. Mazzoni, B. Jeremić. *OpenSees – Open System for Earthquake Engineering Simulation*. Pacific Earthquake Engineering Research Center, PEER, University of California, Berkeley, 2000. http://opensees.berkeley.edu

[2] T. Haukaas, A.D. Kiureghian. *Finite Element Reliability and Sensitivity Methods for Performance-Based Earthquake Engineering*. PEER Report 2003/14, PEER Center, College of Engineering, University of California, Berkeley, 2004.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

High-velocity Impact of UniPore Copper Using Powder Gun

Kazuyuki HOKAMOTO[*], Masatoshi NISHI[+], Shigeru TANAKA[*], Takashi HORI[*]

[*]*Kumamoto University, Institute of Pulsed Power Science, Kumamoto 860-8555, Japan*
E-mails: {fhokamoto, tanaka}@mech.kumamoto-u.ac.jp

[+]*National Institute of Technology, Kumamoto College, Yatsushiro 866-8501, Japan*
E-mail: nishima@kumamoto-nct.ac.jp

Abstract

UniPore copper, having many holes in one direction, was fabricated using explosive welding technique [1, 2], and the cubic copper sample (17.3 mm each length) was impacted by a projectile around 600 m/s using powder gun vertical to the direction of the holes. The deformation process was visualized using high-speed camera and compared with numerical simulation using Autodyn3d code. The deformation process was successfully recorded and the deformed shape was corresponds with the numerical results as found in Figure 1. Also, it was suggested by the numerical result that high pressure was achieved when the pores are closing.

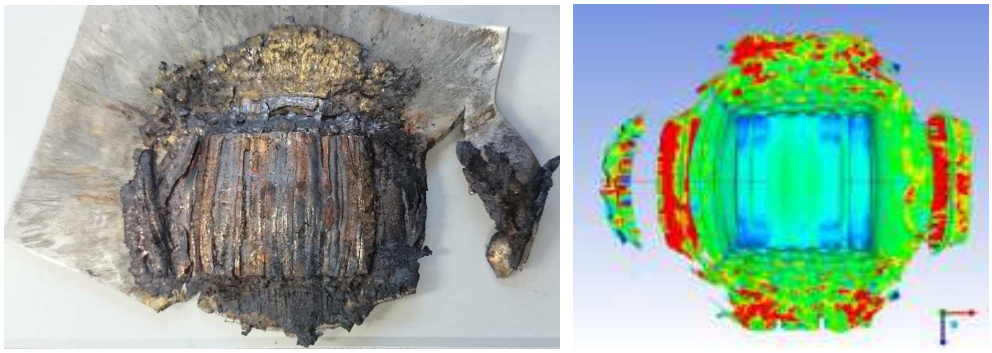


Figure 1. Final deformation shape compared with numerical simulation

References

[1] K. Hokamoto, M. Vesenjak, Z. Ren. Fabrication of Cylindrical Uni-directional Porous Metal with Explosive Compaction. *Materials Letters*, 137: 323-327, 2014.

[2] M. Vesenjak, K. Hokamoto, M. Sakamoto, T. Nishi, L. Krstulović-Opara, Z. Ren. Mechanical and Microstructural Analysis of Unidirectional Porous (UniPore) Copper. *Materials & Design*, 90: 867-880, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Fluctuating and Peak Internal Pressures in Buildings – Some Recent Results

John HOLMES[*], John GINGER[+]

[*]*JDH Consulting, Mentone, Victoria, Australia*
E-mail: john.holmes@jdhconsult.com

[+]*James Cook University, Townsville, Queensland, Australia*
E-mail: john.ginger@jcu.edu.au

Abstract

Numerous surveys of damage after strong wind events have shown internal pressures to be a major contributor of net wind loads on building surfaces, particularly on the roofs of low-rise buildings, when a large opening occurs in a windward wall produced by the failure of a door or window. The occurrence of Helmholtz-type resonance in building models with a single windward opening in wind-tunnel tests, was identified by the first author nearly forty years ago [1], and it is clear that buildings with large internal volume can have Helmholtz resonant frequencies that are under 1 Hertz, and in the range of potential excitation frequencies by atmospheric turbulence. Whether flow losses through the opening, background porosity and/or building flexibility are sufficient to generate enough damping so that amplification of internal pressure fluctuations in *real* full-scale buildings is never large, is a question still to be answered. The paper will describe some proposed non-dimensional relationships [2] for the ratio of root-mean-square internal pressure fluctuations to root-mean-square external pressures near the opening. A key non-dimensional parameter is S^* [2], defined in Eq. (1):

$$S^* = \Phi_1 . \Phi_2^{\,2} \qquad (1)$$

where Φ_1 is $(A^{3/2}/V_o)$, A being the opening area and V_o the internal volume, and Φ_2 is the ratio of the speed of sound to a mean wind speed in the approach flow, [1]. For $S^* < 1$, most experimental data indicates a ratio of root-mean-square internal to external pressures less than 1.0. However, for $S^* > 1$, amplification due to Helmholtz resonance has been observed in wind-tunnel models [2], and may occur in full-scale buildings. Recent results from James Cook University, including full-scale measurements on a shipping container and a small industrial building, will be presented in the final paper. Possible effects of turbulence intensity and scale in the approach flow will be discussed.

References

[1] J.D. Holmes. Mean and Fluctuating Internal Pressures Induced by Wind. In: J.E. Cermak, ed., Proceedings of the Fifth International Conference on Wind Engineering, 435-450, Pergamon Press, Oxford, 1979.

[2] J.D. Holmes, J.D. Ginger. Internal Pressures – The Dominant Windward Opening Case – A Review. *Journal of Wind Engineering and Industrial Aerodynamics*, 100: 70-76, 2012.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Finite Element Growth Model of Abdominal Aortic Aneurysm

Nino HORVAT, Lana VIRAG, Igor KARŠAJ

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {nino.horvat, lana.virag, igor.karsaj}@fsb.hr

Abstract

Computational models of the abdominal aortic aneurysm (AAA) growth are important because they can broaden our understanding of disease formation and development, analyze the influence of risk factors, test different hypotheses about AAA growth, and eventually, they could predict the rupture risk. In this work, a 3D finite element growth and remodelling (G&R) model of AAA is presented. The model is based on a numerical model from [1] and it is implemented into finite element analysis program FEAP via subroutines for the user-defined material model. In order to enforce incompressibility, the Augmented Lagrange method was used. Using this model we can simulate formation and growth of clinically observed aneurysm types, e.g. a fusiform and saccular aneurysm. We start from the cylindrical geometry of a healthy aorta, and by employing spatio-temporal elastin degradation functions we induce the formation of different aneurysms. 3D hexahedral elements enable modelling and tracking changes in the axial, circumferential and radial direction of an aneurysm. By changing model parameters for production and degradation of constituents in aortic wall (elastin, collagen, and smooth muscle cells), we can achieve different types of aneurysm growth (e.g. continuous growth, stabilization, rupture, and discontinuous growth). Additionally, we can confirm clinically observed geometrical features of an aneurysm that likely lead to rupture, e.g. length of the aneurysmal sac, height of the neck or the proximal neck to the maximum diameter.

Acknowledgments: This work was supported by a grant from the Croatian Science Foundation '*BioChemoMechanical Modeling of Aneurysmal Growth*' (project IP-2014-09-7382, leader I. Karšaj) and project '*Training of New Doctoral Students*' (DOK-2015-10-3164).

References

[1] I. Karšaj, J. Sorić, J.D. Humphrey. A 3-D Framework for Arterial Growth and Remodeling in Response to Altered Hemodynamics. *International Journal of Engineering Science*, 48:1357–1372, 2011.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Gradient-Thermo-Plasticity Using an Efficient Virtual Element Method (VEM)

Blaž HUDOBIVNIK, Fadi ALDAKHEEL, Peter WRIGGERS

[*]Leibniz Universität Hannover, Institut für Kontinuumsmechanik,
Appelstraße 11, D-30167 Hannover, Germany
E-mails: {hudobivnik, aldakheel, wriggers}@ikm.uni-hannover.de

Abstract

The coupled thermo-mechanical strain gradient plasticity theory, based on an efficient low order ***virtual element formulation*** is outlined within this work. To this end, we introduce a micromorphic approach to gradient thermo-plasticity model at finite strains. The key point is the introduction of dual local-global field variables via a penalty method, where only the global fields are restricted by boundary conditions. Hence, the problem of restricting the gradient variable to the plastic domain is relaxed, which makes the formulation very attractive for implementation, see [1, 2]. In the presented contribution, the *recently developed* virtual element method (VEM**)** will be used, because of the flexible choice of nodes number in an element which can be changed easily during the simulation process, as addressed in [3,4]. Thus, the potential energy is formulated in terms of *suitable polynomial functions*, instead of computing the unknown shape functions for complicated element geometries, e.g. arbitrary convex or concave polygonal elements. The modeling capabilities and algorithmic performance of the proposed formulation is demonstrated by a number of numerical examples.

References

[1] F. Aldakheel, Ch. Miehe. Coupled Thermomechanical Response of Gradient Plasticity. *International Journal of Plasticity*, 91: 1-24, 2017. https://doi.org/10.1016/j.ijplas.2017.02.007

[2] F. Aldakheel. Micromorphic Approach for Gradient-extended Thermo-elastic-plastic Solids in the Logarithmic Strain Space. *Continuum Mechanics and Thermodynamics*, 29(6): 1207-1217, 2017. https://doi.org/10.1007/s00161-017-0571-0

[3] P. Wriggers, W. Rust, B.D. Reddy. A Virtual Element Method for Contact. *Computational Mechanics*, 58(6): 1039-1050, 2016. https://doi.org/10.1007/s00466-016-1331-x

[4] P. Wriggers, B. Hudobivnik. A Low Order Virtual Element Formulation for Finite Elasto-plastic Deformations. *Computer Methods in Applied Mechanics and Engineering*, 327: 459-477, 2017. https://doi.org/10.1016/j.cma.2017.08.053

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Consideration about H-type Rotor with the Magnus Effect

Mateusz JAKUBOWSKI, Roman STAROSTA, Paweł FRITZKOWSKI

Poznan University of Technology, Institute of Applied Mechanics,
ul. Jana Pawła II 24, 60-965 Poznań, Poland
E-mails: mateusz.ja.jakubowski@doctorate.put.poznan.pl
{roman.starosta, pawel.fritzkowski}@put.poznan.pl

Abstract

One of the most important disadvantages in the case of vertical axis wind turbines (VAWT) is a change of the pitch angle during rotor rotation [1]. H-type rotor is a lift-type rotor whose straight airfoil blades produce a shaft torque by means of a lift force. The lift force depends strictly on the pitch angle which changes non-linearly from zero value to the highest value [2, 3]. Between these levels the pitch angle reaches a certain value which means the maximal available value of the lift force is not achievable for current aerodynamic conditions. In this work the authors consider an H-type rotor which uses the Magnus effect to generate lift force. In this case straight blades are replaced by Magnus rotors. Rotating cylinder is an airfoil which produces lift force independently on the pitch angle [4]. Thus, this solution seems to be proper for presented issue. It has to be noted that value of the lift force may be high however, large drag force could occur [5]. The rotor contained rotating cylinders might achieve satisfactory efficiency but it is necessary to take into account the energy cost of the Magnus rotor rotation. The aim is to find such an aerodynamic condition and geometry of the rotor to increase turbine efficiency. In this work the authors propose mathematical formulation of the problem and some preliminary results.

References

[1] A.P. Schaffarczyk. *Introduction to Wind Turbine Aerodynamics*. Springer-Verlag, Berlin, 2014.

[2] M. Jakubowski, R. Starosta, P. Fritzkowski. Kinematics of a Vertical Axis Wind Turbine with a Variable Pitch Angle. In: J. Podgorski, E.-B. Borowa, J. Latalski, Proc. of the 22nd Int. Conf. on Computer Methods in Mechanics (CMM2017), AIP Conference Proceedings 1922, Lublin, 2018.

[3] R.E. Sheldahl, P.C. Klimas. *Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections through 180-Degree Angle of Attack for Use in Aerodynamic Analysis of Vertical Axis Wind Turbines*. National Technical Information Service, Springfield, 1981.

[4] J. Seifert. A Review of the Magnus Effect in Aeronautics. *Progress in Aerospace Sciences*, 55: 17-45, 2012.

[5] A. Thom. Effect of Discs on the Air Forces on a Rotating Cylinder. *Aeronautical Research Committee Reports and Memoranda*, No. 1623, 1934.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Modelling of Finite Gradient Elasticity Using Optimal Transportation Method

Boris JALUŠIĆ[*], Christian WEIßENFELS[+], Jurica SORIĆ[*], Peter WRIGGERS[+]

[*]*University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia*
E-mails: {boris.jalusic, jurica.soric}@fsb.hr

[+]*Leibniz Universität Hannover, Institut für Kontinuumsmechanik, Appelstraße 11, D-30167 Hannover, Germany*
E-mail: {weissenfels, wriggers}@ikm.uni-hannover.de

Abstract

In this contribution, the meshfree Optimal Transportation Method (OTM) [1] is applied for modelling of gradient hyperelasticity using higher-order theory based on only one microstructural parameter [2]. The OTM method is utilized for the purpose of structural behaviour modelling undergoing large deformation. Therefore, the method is based on the weak-form of gradient continuum for finite strain and applied for the modelling of homogeneous and heterogeneous structures. In the considered weak-form approach the fourth-order dynamic equilibrium equations are solved at each material point directly without using any uncoupling procedures. The independent displacement variables are approximated using interpolating Maximum-Entropy functions [3]. This enables the satisfaction of the boundary conditions in a simple and straightforward manner without the need for the calculation of additional parameters. The analysis of accuracy and numerical performance of the applied approach is demonstrated by a couple of benchmark examples and the obtained results are compared to the ones available in the literature. Furthermore, the considered method is utilized for simulation of material microstructure and description of size effects in the heterogeneous material.

Acknowledgements: This work has been supported in part by Croatian Science Foundation under the project *Multiscale Numerical Modelling of Material Deformation Responses from Macro- to Nanolevel* (HRZZ-IP-2013-11-2516). The investigations are also a part of the project supported by Alexander von Humboldt Foundation.

References

[1] B. Li, F. Habbal, M. Ortiz. Optimal Transportation Meshfree Approximation Schemes for Fluid and Plastic Flows. *International Journal for Numerical Methods in Engineering*, 83(12): 1541-1579, 2010.

[2] P. Fischer, J. Mergheim, P. Steinmann. On the C^1 Continuous Discretization of Non-linear Gradient Elasticity: A Comparison of NEM and FEM Based on Bernstein-Bezier Patches. *International Journal for Numerical Methods in Engineering*, 82(10): 1282-1307, 2010.

[3] M. Arroyo, M. Ortiz. Local Maximum-Entropy Approximation Schemes: A Seamless Bridge between Finite Elements and Meshfree Methods. *International Journal for Numerical Methods in Engineering*, 65(13): 2167-2202, 2006.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Adaptive Isogeometric Analysis Based on Truncated Hierarchical Basis Functions

Grgo KAMBER, Hrvoje GOTOVAC, Vedrana KOZULIĆ, Luka MALENICA, Blaž GOTOVAC

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, HR-21000 Split, Croatia
E-mails: {grgo.kamber, hrvoje.gotovac, vedrana.kozulic, luka.malenica, blaz.gotovac}@gradst.hr

Abstract

Isogeometric analysis (IGA) represents a recently developed technology in computational mechanics that offers the possibility of integrating methods for numerical analysis and Computer Aided Design (CAD) of engineering problems into a single, unified process [1]. Important part of isogeometric analysis is local refinement enabling construction of different adaptive procedures [1, 3]. In this paper we present adaptation using truncation mechanism to form a partition of unity and to decrease the overlapping of basis functions for better numerical conditioning. Through classical adaptive h-refinement (decreasing of compact support of basis functions in higher resolution levels) we are presenting Truncated Hierarchical B-spline [2] (THBS) basis functions. Using more efficient higher order concept, adaptive k-refinement (h+p strategy which at the same time decreases compact support and increases order of basis functions in higher levels) is presented through Truncated Hierarchical Fup (THF) basis functions. Both adaptive procedures use finite volume weak formulation. Using THBS and THF we will show efficient modelling of advection-dispersion processes controlling numerical error and onset of non-physical oscillations and numerical dispersion. Furthermore, different stabilization techniques and effects of “upstream” position of finite volumes will be discussed as additional factors which could improve these adaptation procedures.

References

[1] J.A. Cottrell, T.J.R. Hughes, Y. Bazilevs. *Isogeometric Analysis: Toward Integration of CAD and FEA*. Wiley, New York, 2009.

[2] X. Wei, Y. Zhang, T.J.R. Hughes, M.A. Scott. Truncated Hierarchical Catmull-Clark Subdivision with Local Refinement. *Computer Methods in Applied Mechanics and Engineering*, 291: 1-20, 2015.

[3] H. Gotovac, R. Andričević, B. Gotovac. Multi-resolution Adaptive Modelling of Groundwater Flow and Transport Problems. *Advances in Water Resources*, 30(5): 1105–1126, 2007.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Potential Use of Recycled Aggregate in Structural Concrete Elements

Nikolina KARAKAŠ, Kristina STRUKAR, Tanja KALMAN ŠIPOŠ, Ivana MILIČEVIĆ

[+]***Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, 3 Vladimir Prelog Street, HR-31000 Osijek, Croatia***
E-mail: {nikolina.karakas, kstrukar, tkalman, ivana.milicevic}@gfos.hr

Abstract

From the standpoint of sustainability, increase of the consumption of renewable resources is a key factor to preserve the natural resources. Concrete is the most usable material for structural elements, and the major contributors to concrete volume are natural aggregates. A significant amount of natural resources can be saved if recycled aggregates from construction and demolition waste (concrete, bricks, tiles, ceramics, wood, glass, tires, bituminous mixtures, plastic) can be used in concrete industry. Their use in structural concrete production has been explored in literature [1-3], principally at the lab-scale level, often reporting good results when the replacement ratio of natural aggregates is limited and high quality recycled aggregates are used. However, the international codes, guidelines and recommendations vary greatly from country to country, with respect to the maximum allowable quantity and quality allowed in structural concrete mixtures [4]. This paper presents an overview of the previous researches carried out on the use of recycled aggregates as partially or fully natural aggregate replacement in concrete mixtures and in concrete elements. The effects of recycled aggregate on compressive strength, modulus of elasticity and ductility of materials, flexural strength and shear strength of structural concrete elements were reviewed.

References

[1] J. Xiao, *Recycled Aggregate Concrete Structures*. Springer-Verlag, Berlin Heidelberg, 2018.

[2] I. Kesegić, I. Netinger, D. Bjegović. Recycled Clay Brick as an Aggregate for Concrete: Overview. *Technical Gazette - Tehnički vjesnik*, 15(3): 35-40, 2008.

[3] A.M. Rashad. A Comprehensive Overview about Recycling Rubber as Fine Aggregate Replacement in Traditional Cementitious Materials. *International Journal of Sustainable Built Environment*, 5: 46-82, 2016.

[4] C. Pellegrino, F. Faleschini. Recycled Aggregates for Concrete Production: State-of-the-Art. In: *Sustainability Improvements in the Concrete Industry. Green Energy and Technology*. Springer, Cham, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

A Novel Model Order Reduction Method for FFT-based Solvers Using a Sparse Sampling Technique

Julian KOCHMANN[*], Kiran MANJUNATHA[*], Stephan WULFINGHOFF[*], Bob SVENDSEN[,#], Stefanie REESE[*]**

[*]RWTH Aachen University, Institute of Applied Mechanics, Mies-van-der-Rohe Strasse 1, D-52074 Aachen, Germany
[**]RWTH Aachen University, Chair of Material Mechanics, Schinkelstrasse 2, D-52062 Aachen, Germany
[#]Max-Planck Institut für Eisenforschung GmbH, Microstructure Physics and Alloy Design, Max-Planck-Strasse 1, D-40237 Düsseldorf, Germany
E-mails: {julian.kochmann, kiran.manjunatha, stephan.wulfinghoff, stefanie.reese}@rwth-aache.de svendsen@mpie.de

Abstract

Predicting the overall constitutive response of heterogeneous materials in dependence on the underlying microstructure has been and continues to be a challenging task. Recently, FE-FFT-based methods [1, 2, 3] have been developed to tackle this problem. However, high-fidelity two-scale simulations of heterogeneous materials are still correlated to an excessive computational effort. This fact motivates the development of model order reduction techniques (MOR) for FFT-solvers which has barely been addressed in the literature, yet. The purpose of this work is the development of a single and flexible MOR technique for FFT-based solvers [4]. The underlying concept is a compressed sensing technique which allows a significant reduction of frequencies based on which the Lippmann-Schwinger equation is solved. Highly-resolved local fields can easily be generated in a post-processing step using reconstruction algorithms. The numerical results on linear and non-linear composites show that the proposed technique leads to a significant reduction of overall CPU times and a negligibly small error in terms of local and overall constitutive quantities. Furthermore, it is worth mentioning that the proposed approach is not restricted to any kinematic or constitutive assumptions.

References

[1] J. Spahn, H. Andrae, M. Kabel, R. Muller. A Multiscale Approach for Modeling Progressive Damage of Composite Materials Using Fast Fourier Transforms. *Computer Methods in Applied Mechanics and Engineering*, 268: 871-883, 2014.

[2] J. Kochmann, J.R. Mianroodi, S. Wulfinghoff, S. Reese, B. Svendsen. Two-scale FE–FFT-and Phase-field-based Computational Modeling of Bulk Microstructural Evolution and Macroscopic Material Behavior. *Computer Methods in Applied Mechanics and Engineering*, 305: 89-110, 2016.

[3] J. Kochmann, S. Wulfinghoff, L. Ehle, J. Mayer, B. Svendsen, S. Reese. Efficient and Accurate Two-scale FE-FFT-based Prediction of the Effective Material Behavior of Elasto-viscoplastic Polycrystals. *Computational Mechanics*, 2017. https://doi.org/10.1007/s00466-017-1476-2

[4] J. Kochmann, K. Manjunatha, S. Wulfinghoff, B. Svendsen, S. Reese. A Simple and Flexible Model Order Reduction Technique for FFT-based Homogenization Problems Using a Sparse Sampling Technique. *Submitted for publication.*

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Early-age Evolution of Compressive Strength of Cement Pastes, Mortars, and Concretes: A Validated Engineering Mechanics Model

Markus KÖNIGSBERGER[*], Michal HLOBIL[+], Brice DELSAUTE[*], Stephanie STAQUET[*], Christian HELLMICH[#], Bernhard PICHLER[#]

[*]***ULB – Université libre de Bruxelles, BATir Department, CP194/04, 50 avenue F.D. Roosevelt, Brussels B-1050, Belgium***
E-mails: mkonigsb@ulb.ac.be, brice.delsaute@gmail.com, sstaquet@ulb.ac.be

[+]***Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, Prosecká 76, Prague 9, 190 00, Czech Republic***
E-mail: michalhlobil@seznam.cz

[#]***TU Wien – Vienna University of Technology, Institute for Mechanics of Materials and Structures, Karlsplatz 13/202, Vienna A-1040, Austria***
E-mails: Christian.Hellmich@tuwien.ac.at, Bernhard.Pichler@tuwien.ac.at

Abstract

Since the pioneering developments of Féret (1892) and Abrams (1919), cement and concrete research has aimed at relating the composition and maturity of cementitious material to their uniaxial compressive strength. These research activities were mainly related to the development of empirical fitting functions. Herein, a more fundamental approach based on continuum micromechanics is presented [1]. The macroscopic loading applied onto a specimen of concrete or mortar, is first translated into stress peaks related to cement paste volumes located in the interfacial transition zones (ITZ) around the aggregates. These stress states are further translated into stress peaks related to microscopic hydrate needles, based on second-order stress averages. These effective stresses of the hydrate needles enter a Drucker-Prager failure criterion with material constants quantified based on nanoindentation tests into low-density calcium-silicate-hydrates. Predictions of the engineering mechanics model agree well with macroscopic strength measurements referring to the material scales of cement pastes, mortars, and concretes.

References

[1] M. Königsberger, M. Hlobil, B. Delsaute, S. Staquet, Ch. Hellmich, B. Pichler. Hydrate Failure in ITZ Governs Concrete Strength: A Micro-to-macro Validated Engineering Mechanics Model. *Cement and Concrete Research*, 103: 77-94, 2018.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

An Additional Explanation of the Incisura Origin in the Aortic Pressure Waveform

Ivan KORADE, Zdravko VIRAG, Severino KRIZMANIĆ

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {ivan.korade, zdravko.virag, severino.krizmanic}@fsb.hr

Abstract

The arterial pressure waveform consists of systolic and diastolic phase. Systolic phase includes blood ejection from the left ventricle into the aorta, which lasts form the aortic valve opening to the valve closing, when the diastolic phase starts. During diastolic phase the aorta is emptying due to blood flow from the aorta to the peripheral vascular beds [1]. These two phases are separated by an incisura in the pressure profile, which includes a sudden pressure drop at the end of systolic phase and a sudden pressure growth at the beginning of diastolic phase. A common believe today is that the cause of incisura is water hammer, due to the aortic valve closing. Apart from this interpretation, here we hypothesized that the wall viscosity also contributes to appearance of the incisura. Based on 1D numerical simulation of blood flow in the arterial tree [2], we showed that the increase of the wall viscosity makes the incisura deeper (see Fig. 1).

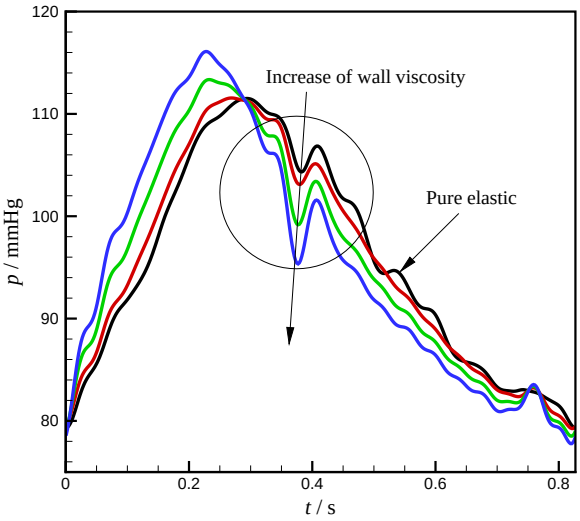


Figure 1. Aortic root pressure waveform for different wall viscosity

References

[1] A.C. Guyton, J.E. Hall. *Textbook of Medical Physiology*. 11th ed., Elsevier Saunders, Philadelphia, 2006.

[2] I. Korade. *Modeling of Blood Flow in an Arterial Tree with Viscoelastic Wall*. PhD Thesis, University of Zagreb, Zagreb, 2017. (in Croatian)

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Fast Second Order Sensitivity Analysis of Large-scale Elasto-plastic Models

Jože KORELC, Teja MELINK

University of Ljubljana, Faculty of Civil and Geodetic Engineering,
Jamova 2, SI-1000 Ljubljana, Slovenia
E-mails: {joze.korelc, teja.melink}@fgg.uni-lj.si

Abstract

The aim of the sensitivity analysis is to calculate derivatives of an arbitrary response functional with respect to chosen parameters. While the first order sensitivity analysis is already established tools for the improvement of numerical algorithms, (e.g. optimization) is the second order sensitivity analysis still rarely used. This is mainly due to the high numerical cost especially in the case of time dependent problems. Finite difference approximation of the second order sensitivities is in the case of time dependent problems also ill posed and consequently analytical sensitivities have to be derived. The paper presents a new implementation of fast analytical second order sensitivity analysis of general time dependent problems with the large strain elasto-plastic problems as a target example. The efficiency of the new implementation is presented on an example of stochastic analysis of elasto-plastic problems.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Finite Elements for Differentiation

Ivica KOŽAR[*], Danila LOZZI-KOŽAR[+]

[*]*University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia*
E-mails: ivica.kozar@gradri.uniri.hr

[+]*Croatian Waters, Đure Šporera 3, HR-51000 Rijeka, Croatia*
E-mail: danila.lozzikozar@voda.hr

Abstract

At first, there seems to be a contradiction in the title of the paper; finite elements are based on integral (weak) formulation and differentiation is connected with strong form of the problem. However, it is common to perform differentiation over the field of results obtained with some finite element procedure. Examples include determination of stresses from the field of displacements (e.g., see [1]) or calculation of heat flux from the known temperature field [2]. Moreover, the determination of derivatives can be part of the original problem as when the field equation (e.g., displacements) and flux equation (e.g., stress) are weakly coupled. Only in the case of Dirichlet boundary conditions is this weak coupling resolved, allowing equations to be solved consecutively. In the case of Neumann boundary conditions, the derivative equation should be treated as a constraint of the field equation. In inverse problems with determination of non-constant parameters this coupling is always present. Moreover, due to stability requirements, high accuracy that is required in inverse problems could not be achieved without additional reformulation of the problem (e.g., see [3]). In this work, the derivative equation is formulated in the weak form, as an adjoint problem. That enables the both equations, the field and the derivative equation, to be formulated in their weak forms. Moreover, this approach allows the same finite element discretization to be applied to both equations. Application of the same discretization and calculation procedure to both field and derivative quantities greatly increases accuracy of the result. Weak formulation of the differentiation procedure is resented in the following equation:

$$\int \mathbf{N}(x)\left[\mathbf{q}(x)-\mathbf{k}(x)\frac{d\mathbf{N}(x)}{dx}\mathbf{T}(x)\right]dx=0 \qquad (2)$$

References

[1] J.E. Akin. *Finite Element Analysis with Error Estimators*. Elsevier Butterworth-Heinmann, Oxford, 2005.

[2] I. Kožar, D. Lozzi-Kožar. Flux Determination using Finite Elements: Global vs. Local Calculation. *Tehnički vjesnik – Technical Gazette*, 24(1): 247-252, 2017.

[3] G.I. Marchuk. *Adjoint Equations and Analysis of Complex Systems*. Springer – Science + Business Media, Dordrecht, 1995.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Wind Flow Simulation under Thermally-Stratified Atmospheric Boundary Layer

Sergey KUZNETSOV[*], Stanislav POSPÍŠIL[*], Hrvoje KOZMAR[+], Arsenii TRUSH[*], Michael MACHÁČEK[*], Petr MICHÁLEK[*]

[*]***Institute of Theoretical and Applied Mechanics, Prosecká 76, 190 00 Prague, Czech Republic***
E-mails: kuznetsov@itam.cas.cz, pospisil@itam.cas.cz, trush@itam.cas.cz

[+]***University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia***
E-mail: hkozmar@fsb.hr

Abstract

Detailed characteristics of thermal effects in wind-tunnel simulations of the Atmospheric Boundary Layer (ABL) flow developing above hill terrain are discussed in the paper. There are two main reasons for simulating ABL in a wind tunnel. One reason is to help the understanding of airflows in the atmosphere [1]. The other is to help solve engineering and environmental problems, such as, predicting the wind forces on structures, predicting the way in which the structures affect the wind, and studying diffusion from various sources of air pollution. The principle designs are focused on features such as dealing with strongly stratified, low turbulent flows and it is also focused to have enough dimensions of the test section for topographic model experiments. This paper presents Convective boundary layer of the ABL flow develops as the ground is warmed up by the solar radiation and the thermally induced turbulence. Particle Image Velocimetry (PIV) experiments were carried out in order to distinct contributions of thermally- and mechanically induced atmospheric turbulence for a number of characteristic topographies and urban areas. Stratification effects between the windward and leeward hillsides were investigated for different upwind velocity and ABL flows. Buoyancy effects on turbulent boundary layers in a wide range of stability conditions defined using the Richardson number (*Ri*) were focused. Convective Boundary Layer (CBL) of the ABL flow develops as the ground is warmed up by the solar radiation and the thermally induced turbulence were simulated. These effects were modelled in the Vincenc Strouhal Climatic Wind Tunnel in Telč creating the “heat” islands in the scaled model [2].

Acknowledgement: The authors acknowledge the Croatian Science Foundation support under the project *Wind and Sea Loading on Energetic Structures* (*WESLO*) (HRZZ-IP-2016-06-2017).

References

[1] S. Kuznetsov, M. Ribičić, S. Pospíšil, M. Plut, A. Trush, H. Kozmar. Flow and Turbulence Control in a Boundary Layer Wind Tunnel Using Passive Hardware Devices. *Experimental Techniques*, 41(6): 643-661, 2017.

[2] S. Pospíšil, S. Kuznetsov, H. Kozmar, V. Michalcová. Wind-tunnel Simulation of Thermally Unstable Atmospheric Flow in Complex Terrain. *Procedia Engineering*, 190: 575-580, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

A Homogenization Approach in Multiscale Modelling of Ductile Damage in Heterogeneous Materials

Tomislav LESIČAR, Jurica SORIĆ, Zdenko TONKOVIĆ

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {tomislav.lesicar, jurica.soric, zdenko.tonkovic}@fsb.hr

Abstract

Standard homogenization techniques performing averaging over the whole representative volume element (RVE) are not well suited for the analysis of its softening response. The problem is relying in the phenomenological behaviour during softening, when a narrow localization zone is governing all the relevant microstructural mechanisms, while the rest of material remains unloaded. This also reveals important issue of the RVE representativeness. It has been shown that increase in the RVE size leads to increased brittle response at the macroscale. The problems mentioned are successfully overwhelmed for the softening of brittle materials, e.g. [1, 2]. In this contribution, a new multiscale model is proposed for the modelling of ductile damage in heterogeneous materials. At the microstructural level, the nonlocal implicit ductile damage model derived in [3] is employed, where discretization is performed by means of the mixed quadrilateral finite elements. At the macrolevel, the 4-node plane strain quadrilateral finite elements, employing damage variable, are used. Two separate RVE analyses should be performed at the microlevel. First analysis is carried out on the undamaged material, where the homogenized stress and constitutive operator are obtained using the conventional first-order homogenization. In another RVE analysis, which includes softening, the homogenized damage variable is computed. Afterwards, all homogenized variables are mapped to the macrolevel. All algorithms derived are implemented into the FE software ABAQUS. The proposed computational model is verified on the usual examples.

Acknowledgement: This work has been fully supported by Croatian Science Foundation under the project *Multiscale Numerical Modelling of Material Deformation Responses from Macro- to Nanolevel* (HRZZ-IP-2013-11-2516).

References

[1] V.P. Nguyen, O. Lloberas-Valls, M. Stroeven, L.J. Sluys. Computational Homogenization for Multiscale Crack Modeling. Implementational and Computational Aspects. *International Journal for Numerical Methods in Engineering*, 89(2): 192-226, 2012.

[2] V.P. Nguyen, M. Stroeven, L.J. Sluys. An Enhanced Continuous–discontinuous Multiscale Method for Modeling Mode-I Cohesive Failure in Random Heterogeneous Quasi-brittle Materials. *Engineering Fracture Mechanics*, 79: 78-102, 2012.

[3] R.A.B. Engelen, M.G.D. Geers, F.P.T. Baaijens. Nonlocal Implicit Gradient-enhanced Elasto-plasticity for the Modelling of Softening Behaviour. *International Journal of Plasticity*, 19(4): 403-433, 2003.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Temperature Dependence of Dynamic Properties of Structures with Dampers Described by the Fractional Derivative Rheological Models

Roman LEWANDOWSKI

Poznan University of Technology, Faculty of Civil and Environmental Engineering, ul. Piotrowo 5, 61-138 Poznan, Poland
E-mail: roman.lewandowski@put.poznan.pl

Abstract

Viscoelastic (VE) dampers are often used to mitigate vibrations of structures and systems, [1]. Properties of viscoelastic materials from which dampers are built depend on the frequency of excitation and temperature, [1]. The effect of the frequency of excitation is taken into account in modelling dampers, choosing the appropriate rheological model. The thermal mechanical model for VE dampers is also presented in [2]. The fractional derivative model and the WLF relationship was used to take into account the dependence of damper parameters on temperature rising. The influence of temperature on the dynamic characteristics of structures with VE dampers is very rarely investigated, [3]. The process of self-heating in dampers is considered in [2]. In this paper, the method for determination of the dynamic characteristics of structures with VE dampers is presented. The method enables analyses which take into account the influence of temperature on the dynamic characteristics of systems with VE dampers. It is assumed that ambient temperature or temperature inside the damper is constant for an appropriately-long span of time. The frequency-temperature correspondence principle, valid for thermorheologically simple materials, is used. This approach reduces the considered problem to the nonlinear eigenvalue problem. Solutions to the nonlinear eigenvalue problem enable the calculation of dynamic characteristics of structure. The convergence of the continuation method and the incremental procedure used are very fast. The method was tested for two structures with VE dampers. The first example evaluates the correctness of the method while the second one illustrates the influence of temperature on the dynamic characteristics of typical structures with dampers. The method presented is general; it can be used for structures with VE dampers modelled using the fractional rheological models.

Acknowledgement: The author acknowledges financial support received from the Poznan University of Technology (Grant No. 01/11/DSPB/002) in connection with this work.

References

[1] A.D. Nashif, D.I.G. Jones. *Vibration, Damping*. Wiley, New York, 1985.

[2] J.W. Guo, Y. Daniel, M. Montgomery, C. Christopoulos. Thermal-mechanical Model for Predicting the Wind and Seismic Response of Viscoelastic Dampers. *Journal of Engineering Mechanics*, 142(10), 2016. https://doi.org/10.1061/(ASCE)EM.1943-7889.0001121

[3] H. Park, C. Min. Temperature Effect on Vibration Characteristics of Viscoelastic Laminated Beam. *The International Society of Offshore and Polar Engineers*, 20(2): 118–124, 2010.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Modelling of Adhesively Bonded Structures

Maria LIßNER[*], Hao CUI[+], Mattia MONTANARI[*], Enrique ALABORT[*], Antonio PELLEGRINO[*], Borja ERICE[*], Nik PETRINIC[*]

[*]University of Oxford, Department of Engineering Science, Parks Road, OX1 3PJ Oxford, England, United Kingdom
E-mails: {maria.lissner}@eng.ox.ac.uk

[+]Cranfield University, School of Aerospace, Transport and Manufacturing, College Road, MK43 0AL Cranfield, England, United Kingdom

Abstract

The desire to create lightweight structures with uncompromised mechanical properties leads to the combination of different materials, such as composites and lightweight alloys. These hybrid structures are increasingly employed in various key components among the aerospace and automotive industry [1]. The adhesive joint technology overcomes limitations which traditional joining techniques (i.e. screws, rivets) have in combination with composites – through the creation of a hole, stress concentrations are induced which negatively influence the structural stability. Therefore, adhesive joints are widely used for manufacturing of structures in combination with composites [2]. Traditional characterization experiments for composite or metal joints, such as the double cantilever beam (DCB) [3], the end notched flexure test (ENF) [4] or the mixed-mode bending test (MMB) [5] are well established and corresponding numerical modelling methods have been successfully developed. However, the mechanical behaviour of adhesive joints is not fully understood when subjected to rapidly applied and dynamic loads. Therefore, this work is dedicated to a comprehensive study of the rate-dependent behaviour of adhesive joint structures. First, the development of a material model based on the experimental findings in [6] is carried out. Second, the newly developed material model is validated against larger scale experiments. Finally, an application of a composite-metal adhesive joint is presented.

References

[1] A.J. Kinloch, M.S.G. Little, J.F. Watts. The Role of the Interface in the Environmental Failure of Adhesive Joints. *Acta Materialia*, 48(18-19): 4543-4553, 2000.
[2] J.D. Russel. 3.3 The Impact of Large Integrated and Bonded Composite Structures on Future Military Transport Aircraft. *Comprehensive Composite Materials II*, 3: 91-130, 2018.
[3] I.A. Ashcroft, D.J. Hughes, S.J. Shaw. Mode I Fracture of Epoxy Bonded Composite Joints: 1. Quasi-static Loading. *Int. Journal of Adhesion and Adhesives*, 21(2): 87-89, 2001.
[4] Q.D. Yang, M.D. Thouless, S.M. Ward. Elastic-plastic Mode-II Fracture of Adhesive Joints. *Int. Journal of Solids and Structures*, 38(18): 3251-3262, 2001.
[5] J.R. Reeder, R. Crews Jr. Mixed-Mode Bending Method for Delamination Testing. *AIAA Journal*, 28(7): 1270-1276, 1990.
[6] M. Lißner, E. Alabort, H. Cui, A. Pellegrino, N. Petrinic. On the Rate Dependent Behaviour of Epoxy Adhesive Joints: Experimental Characterization and Modelling of Mode I Failure. *Composite Structures*, 189: 286-303, 2018.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Comparison of Viscoelastic Material Models in Non-linear Vibrations of Plates

Przemysław LITEWKA*, Roman LEWANDOWSKI+

Poznan University of Technology, Institute of Structural Engineering,
ul. Piotrowo 5, 60-965 Poznań, Poland
E-mails:* przemyslaw.litewka@gmail.com +roman.lewandowski@put.poznan.pl

Abstract

Plates are ones of the most frequently used structural elements in engineering. They form parts of larger structures and can be subjected to a multitude of external influences, among which the dynamic excitation may play a very important role. In such cases vibrations will result, that in many cases have to be reduced to meet the more and more strict engineering requirements. The methods to reduce the undesired vibrations include an application of materials which exhibit viscoelastic properties. These materials may form the bulk of a plate or be applied as damping layers. In both situations taking into account the viscoelastic character of the material in the formulation of the dynamic problem is of great importance. Viscoelastic properties can be modelled in many ways, classical simple models as Kelvin-Voigt [1], as well as more complex models as Zener [2, 3], LTU or Burgers [4] can be used. There are also works carried out on the fractional models where time derivatives in the physical law have a non-integer order [5]. In this presentation the results of numerical analyses with a comparison of three classical models: Kelvin-Voigt, Zener and LTU will be reported. Kinematics of the plate are based on Reissner-Mindlin and von Kármán assumptions. The problem is expressed in the frequency domain for a harmonic excitation. The amplitude equation is derived using the harmonic balance method applied for each of the physical viscoelastic models. Space discretization of the plate is done using the finite element method and the discretized amplitude equation is solved by the continuation method to yield response curves in resonance zones. Parameters of the analyzed viscoelastic models used in the comparison are assumed by a simple averaging of storage and loss moduli.

References

[1] M. Amabili. Nonlinear Vibrations of Viscoelastic Rectangular Plates. *Journal of Sound and Vibration*, 362: 142-156, 2016.

[2] M. Amabili. Nonlinear Damping in Large-amplitude Vibrations: Modelling and Experiments. *Nonlinear Dynamics*, 2017. https://doi.org/10.1007/s11071-017-3889-z

[3] P. Litewka, R. Lewandowski. Nonlinear Harmonically Excited Vibrations of Plates with Zener Material. *Nonlinear Dynamics*, 89(1): 691-712, 2017.

[4] S. Ren, G. Zhao, S. Zhang. Elastic-Viscoelastic Composite Structures Analysis with an Improved Burgers Model. *Journal of Vibration and Acoustics*, 140(3): 031006 (10 p), 2018.

[5] P. Litewka, R. Lewandowski. Steady-state Non-linear Vibrations of Plates Using Zener Material with Fractional Derivative. *Computational Mechanics*, 60(2): 333-354, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Experimental Investigation of Glued Laminated Timber Beams Failures

Jelena LOVRIĆ VRANKOVIĆ, Ivica BOKO, Neno TORIĆ, Vladimir DIVIĆ, Marko GORETA

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice Hrvatske 15, HR-21000 Split, Croatia
E-mails: ***{jelena.lovric, ivica.boko, neno.toric, vladimir.divic, marko.goreta}@gradst.hr***

Abstract

The paper presents experimental tests and finite element analysis of several glulam beams made of different wood species. The glulam beams are tested by means of 3-point bending tests on short samples (Figure 1). Experimental tests include measurements of applied forces, strains and displacements. The displacements and strains are obtained using a novel photogrammetric approach [1]. In this work we present details of the test specimens, test set-up, procedures and results of the bending tests. The current research aims to determine the behaviour of glulam wood and to obtain elastic properties for each specimen. Particular attention is given to the accurate analysis of the type and mechanisms of failure [2]. The results of the bending tests have shown that delamination of the glulam beams causes a decrease in their stiffness and leads to bending failure of the individual lamella. Finally, comparison is made between photogrammetric and linear variable differential transducer deflection measurements. The mechanical properties obtained from the experiments are validated with the results from FEM analysis.

Figure 1. Experimental test of glulam beam

References

[1] W.A. Van Beerschoten, D.M. Carradine, A. Carr. Development of Constitutive Model for Laminated Veneer Lumber Using Digital Image Correlation Technique. *Wood Science and Technology*, 48(4): 755-772, 2014.

[2] J. Gomes Ferreira, H. Cruz, R. Silva. Failure Behaviour and Repair of Delaminated Glulam Beams. *Construction and Building Materials*, 154: 384-398, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

The Nonlinear Cable Structures Dynamics IGA Approach

Željan LOZINA, Damir SEDLAR, Anđela BARTULOVIĆ

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia
E-mails: ***{zeljan.lozina, damir.sedlar, andjela.bartulovic}@fesb.hr***

Abstract

The cable structures undergoing large displacement and rotations are nonlinear in stiffness and the space discretization leads to the matrix equation of the form:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{K}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{Q} \tag{3}$$

where mass matrix **M** is constant and damping matrix **C** can be eider constant or displacement dependent. In this paper IGA approach to the space discretization is implemented and compared with finite element models. The single patch and multi patch are compared for a different number of control knots and polynomial order. B-spline versus NURBS efficiency is discussed. The tangential matrix eigen-analysis has been performed in order to check the model against the known linearized analytical solutions. A number of the time integration schemes are combined in order to develop reliable transient dynamics solution strategy. The composite time integration scheme [1, 2] and the generalized-α schemes [3, 4] are applied to the nonlinear benchmark problems monitoring overshoots, higher frequency dissipation controllability, period elongations and amplitude decays. The adopted algorithm is applied to the space cable structures and transient problems are solved.

References

[1] K.J. Bathe, M.M.I. Baig. On a Composite Implicit Integration Procedure for Nonlinear Dynamics, *Computers and Structures*, 83(31-32): 2513-2524, 2005.

[2] K.J. Bathe, G. Noh. Insight into an Implicit Time Integration Scheme for Structural Dynamics, *Computers and Structures*, 98-99: 1-6, 2012.

[3] C. Kadapa, W.G. Dettmer, D. Perić. On the Advantages of Using the First-order Generalised-alpha Scheme for Structural Dynamic Problems, *Computers and Structures*, 193: 226-238, 2017.

[4] J. Chung, G.M. Hulbert. A Time Integration Algorithm for Structural Dynamics with Improved Numerical Dissipation: The Generalized-α Method, *Journal of Applied Mechanics*, 60(2): 371-375, 1993.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Structure of a Detonation Wave in a Binary Mixture with the Multi-temperature Approach

Damir MADJAREVIĆ[*], Srboljub SIMIĆ[+], Ana Jacinta SOARES[++]

[*]*University of Novi Sad, Faculty of Technical Sciences, Department of Mechanics, Novi Sad, Serbia*
E-mail: damirm@uns.ac.rs

[+]*University of Novi Sad, Faculty of Sciences, Department of Mathematics and Informatics, Novi Sad, Serbia*
E-mail: ssimic@uns.ac.rs

[++]*Universidade do Minho, Centro de Matemática, Braga, Portugal*
E-mail: ajsoares@math.uminho.pt

Abstract

The aim of this paper to propose a variant of the Zel'dovich-von Neumann-Döring (ZND) detonation model within the framework of multi-temperature extended thermodynamics of mixtures [1] and to investigate the detonation wave structure problem. The main intention of this approach is to bridge the gap between macroscopic and mesoscopic level of description. The detonation wave structure is analyzed in a binary mixture undergoing a reversible chemical reaction between reactants and products, represented by $A_r \rightleftharpoons A_p$. It is assumed that the flow satisfies basic assumptions proper of the ZND detonation model [2], namely the flow is one dimensional and the shock is represented by a jump discontinuity, but the assumption of local thermodynamic equilibrium is disregarded. This allows to deeply investigate the coupling between the detonation structure and its chemical kinetics. The thermodynamic non-equilibrium effects are taken into account in the mathematical description, using the model of multi-temperature mixture developed within extended thermodynamics [3], which has been proved to be consistent with a kinetic theory approach. The reaction rate is enriched with terms that take into account the temperatures of the constituents. Numerical computations prove the existence of non-monotonous profiles in the reaction zone which are sensitive to changes in the activation energy and reaction heat.

Acknowledgments: This work was supported (D.M. & S.S.) by the Ministry of Education, Science and Technological Development, Republic of Serbia, Project No. ON174016 and partially supported by the University of Novi Sad, Faculty of Technical Sciences, Project 2018-054, and (A.J.S.) by the Portuguese Funds FCT, Portugal Project UID/MAT/00013/2013.

References

[1] I. Müller, T. Ruggeri. *Rational Extended Thermodynamics*. Springer-Verlag, New York, 1998.

[2] J.H.S. Lee. *The Detonation Phenomenon*. Cambridge University Press, Cambridge, 2008.

[3] T. Ruggeri. Multi-temperature Mixture of Fluids. *Theoretical and Applied Mechanics*, 36(3): 207-238, 2009.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Groundwater Flow Modelling in the Karst Aquifers: Coupling Laminar Matrix Flow and Turbulent Conduit Flow - Verification on Physical Model

Luka MALENICA, Hrvoje GOTOVAC, Grgo KAMBER

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, HR-21000 Split, Croatia
E-mails: {luka.malenica, hrvoje.gotovac, grgo.kamber}@gradst.hr

Abstract

Karst aquifers are characterized by the existence of the highly permeable conduit network embedded in less permeable rock matrix which makes them different from other aquifers [1]. This duality in the permeability (as well as the existence of many other specific karst features) makes karst aquifers particular difficult to model [2]. In this work we present novel numerical model for flow in karst aquifers. Slow laminar seepage flow in the karst matrix is described by the mixed form of 3D Richard's equation. Used equation considers flow in both saturated and unsaturated zone which is quite important (but usually omitted) to account for realistic hydrodynamic behaviour of the karst aquifers. Flow in the conduits is usually turbulent and can be free surface flow (like in open channels) or pressurized (especially during rainy periods). Both flow conditions in the karst conduits are captured by diffusive wave approximation of 1D shallow water equations. Iterative coupling of two flow domains is established through flux relation governed by pressure difference of two domains. Novel numerical approach based on Fup basis functions [3] is used for spatial discretization of the governing equations. Due to similarity with the Isogeometric Analysis [4] concept (IGA), we label it as Control Volume Isogeometric Analysis method (CV-IGA). Particular difficulty with complex 3D karst flow models lies in its verification due to lack of input data such as parameters of aquifer as well as position, shape and dimensions of conduit network [1, 2]. Therefore, this work shows possibility to verify karst flow models under the laboratory controlled conditions on the 3D physical model.

References

[1] M. Bakalowicz. Karst Groundwater: A Challenge for New Resources. *Hydrogeology Journal*, 13(1): 148–160, 2005.

[2] R. De Rooij. *Towards Improved Numerical Modeling of Karst Aquifers: Coupling Turbulent Conduit Flow and Laminar Matrix Flow under Variably Saturated Conditions*. PhD Thesis, University of Neuchatel, 2008.

[3] H. Gotovac, R. Andričević, B. Gotovac. Multi-resolution Adaptive Modelling of Groundwater Flow and Transport Problems. *Advances in Water Resources*, 30(5): 1105–1126, 2007.

[4] J.A. Cottrell, T.J.R. Hughes, Y. Bazilevs. *Isogeometric Analysis: Toward Integration of CAD and FEA*. Wiley, New York, 2009.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Experimental and Numerical Investigations of RC Beams Strengthened with CFRP Strips

Pavao MAROVIĆ, Mirela GALIĆ, Alen ZEMUNIK, Mirjana LUBINA

University of Split, Faculty of Civil Engineering, Architecture and Geodesy,
Matice hrvatske 15, HR-21000 Split, Croatia
E-mails: {pavao.marovic, mirela.galic}@gradst.hr

Abstract

Many engineering structures have been built or are still being built out of reinforced concrete. When required, the strengthening of such structures due to the need for additional reinforcement or retrofitting damaged parts the use of fiber reinforced polymers (FRP) has become very efficient. This paper describes performed initial experimental and numerical investigations of reinforced concrete (RC) beams strengthened with carbon fiber reinforced polymers (CFRP), [1-2]. Two sets of RC beams have been tested. The first set consist of two identical RC beams (L×b×h = 1000 × 100 × 200 mm) made of concrete C30/37, reinforced with 2ϕ6 in the upper zone and 2ϕ10 in the lower zone, with stirrups. The second beam was strengthened with CFRP strip throughout the whole bottom, [1]. The second set consist of three identical RC beams (L×b×h = 1000 × 100 × 200 mm) made of concrete C25/30, reinforced with 2ϕ10 in both zones, upper and lower, with stirrups. The second beam was strengthened with CFRP strip throughout the whole bottom while the third beam was strengthened only in the mid 500 mm, [2]. All tests have been performed with the same equipment in the Laboratory for Testing Materials of the Civil Engineering Institute in Split. Tested RC beams after failure can be seen in Figure 1. To verify obtained test results, numerical calculations have been carried out with programme SCIA Engineer, [3].

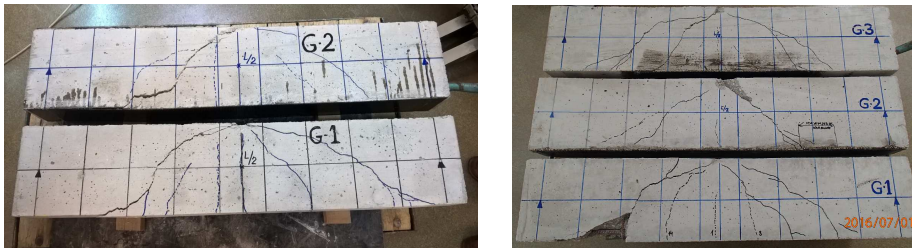


Figure 1. Tested RC beams after failure: first set (left), [1]; second set (right), [1]

References

[1] A. Zemunik. *Numerical and experimental analysis of reinforced concrete beams strengthened with carbon fiber strips.* Diploma Thesis, University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Split, 2016.

[2] M. Lubina. *Numerical and experimental analysis of reinforced concrete beams with carbon reinforcement.* Diploma Thesis, University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Split, 2016.

[3] SCIA Engineer 2014, Nemetschek Scia nv, 2013.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

CFD Prediction of High Head Francis Turbine Performance

Nikola MIJALIĆ[*], Zoran MILAS[+], Mate MIŠKOVIĆ[*]

[*] ***HEP - Hydro Department - Hydro Power Plant Dubrovnik,***
Ante Starčevića 7, HR-20000 Dubrovnik, Croatia
E-mails: {Nikola.Mijalic, Mato.Miskovic}@hep.hr

[+]***University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia***
E-mail: zoran.milas@fesb.hr

Abstract

Flow in the high head Francis turbine, installed in the HPP Dubrovnik, is simulated in the paper. The geometry of the turbine components, including the spiral casing, stay vanes, guide vanes, runner and draft tube, is modelled with CAD software using 2D drawings. ANSYS Fluent Software is used for the numerical simulations of the entire turbine flow with the frozen rotor and sliding mesh interface between the stationary and rotating domain. The realizable k-ε turbulence model with scalable wall functions is applied. While simulating the turbine flow a wicket gate opening was varied for given turbine discharges in order to get net head close to the operating conditions. The computational fluid dynamics (CFD) predicted performance of the full-scale turbine is compared with the experimental data from the model tests and the operating data of installed turbine. The CFD results for the turbine power and efficiency fall close to the experimental ones at design flow and off-design conditions as well. The potential increase in draft tube efficiency is analyzed via CFD for the several arrangements of piers inside the existing draft tube at different turbine loads.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Additive Manufacturing of Fatigue Damage Tolerant Structures

Giangiacomo MINAK, Tommaso Maria BRUGO

Alma Mater Studiorum – Università di Bologna, via Fontanelle 40, Forli, Italy
E-mails: Giangiacomo.minak@unibo.it, tommasomaria.brugo@unibo.it

Abstract

This research activity has the aim to take advantage of the capabilities of the additive manufacturing techniques to develop fatigue damage tolerant structures. The main characteristic that these structures should have is the so called "Impossible Design" i.e. they should be impossible to manufacture with any other technique. In the paper, the focus is put on the well-known four-point rotating bending fatigue tests [1] where the usual dog-bone specimen is substituted by a hollow tapered tube, see e.g. [2]. The objective is to design specimens with the same weight of a hollow tube, but with a geometrically embedded hierarchical structure so that a fracture typically originating from the specimen surface could be stopped or slowed down in its propagation by means of an extrinsic mechanism. In Figure 1 an example of the structure of a section of the specimen can be seen. The structure was loaded in plane bending and the Mises stresses calculated by FEM are shown. Numerical crack propagation tests were done as well.

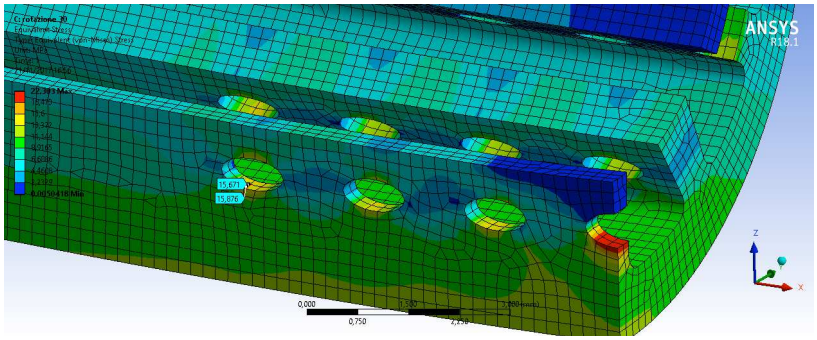


Figure 1. Specimen structure, FEM analysis

Acknowledgements: This research activity is carried out in the framework of the Horizon 2020 – Marie Curie Sklodowska Actions, RISE 2016 Project nº734455 A_Madam: Advanced Design for Optimal Dynamic Properties of Additive Manufacturing Products. Mr Davide Sintoni made most of the FEM simulations and his work is gratefully acknowledged by the authors.

References

[1] ISO 1143:2010: *Metallic materials – Rotating bar bending fatigue testing*, 2010.

[2] N. Gates, A. Fatemi. Fatigue Crack Growth Behavior in the Presence of Notches and Multiaxial Nominal Stress States. *Engineering Fracture Mechanics*, 165: 24-38, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Assessment of Advanced Numerical Methods for Studying Impacts of Ice on Hybrid Structures

Mattia MONTANARI, Maria LIßNER, Antonio PELLEGRINO, Nik PETRINIC

University of Oxford, Department of Engineering Science, Parks Road, OX1 3PJ Oxford, England, United Kingdom
E-mail: mattia.montanari@eng.ox.ac.uk

Abstract

Engineers are offered an increasing number of numerical methods for simulating highly non-linear problems; in this work we assess some of the predominant methods applied in impact engineering and aim to provide useful recommendations. Impact phenomena present a major computational challenge for the traditional finite element method (FEM) [1]. The non-linearities induced by localised large-deformations and crack propagation underpin the use of updated Lagrangian formulations and even Arbitrary Lagrangian-Eulerian (ALE). Due to the importance of inertial forces, it is also necessary to capture the fragmentation mechanisms throughout the whole simulation. This is often achieved by mesh-free methods, such as the smoothed-particle hydrodynamics (SPH) method [2]. Whenever advanced constitutive models are employed to simulate plasticity and fracture, it is appropriate to capture the stress-wave front more accurately by means of high-order FEM elements [4] or NURBS-based isogeometric analysis (IGA) [3]. The results presented in this work discuss the application of all methods cited above for studying high-speed impacts of ice on hybrid structures. The structures considered in this work are obtained by bonding lightweight composite materials and titanium alloys [5]. The conclusions focus on practical aspects of modelling, such as: stress-wave propagation, volumetric locking, time-step size, and scalability on high-performance computers (HPC).

References

[1] P. Wriggers. *Computational Contact Mechanics.* Springer, Berlin, Heidelberg, 2006.

[2] G.R. Liu, M.B. Liu. *Smoothed Particle Hydrodynamics: A Meshfree Particle Method.* World Scientific, Singapore, 2003.

[3] J.A. Cottrell, T.J.R. Hughes, Y. Bazilevs. *Isogeometric Analysis: Toward Integration of CAD and FEA.* John Wiley & Sons, West Sussex, 2009.

[4] P. Šolin, K. Segeth, I. Doležel. *Higher-Order Finite Element Methods*. Chapman and Hall/CRC Press, Boca Raton, 2003.

[5] M. Lißner, E. Alabort, H. Cui, A. Pellegrino, N. Petrinic. On the Rate Dependent Behaviour of Epoxy Adhesive Joints: Experimental Characterization and Modelling of Mode I Failure. *Composite Structures*, 189: 286-303, 2018.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Inverse Determination of Ductile Damage Parameters

Branko NEČEMER[*], Janez KRAMBERGER[*], Matej VESENJAK[*], Lovre KRSTULOVIĆ-OPARA[+], Zoran REN[*], Srečko GLODEŽ[*]

[*]*University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia*
E-mails: {branko.necemer, janez.kramberger, matej.vesenjak, zoran.ren, srecko.glodez}@um.si

[+]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia*
E-mail: Lovre.Krstulovic-Opara@fesb.hr

Abstract

This study presents an inverse procedure for determination of the constitutive material parameters, including the ductile damage parameters, of tensile specimens [1]. A finite element method in the framework of program package Abaqus has been used for the computational simulation, while the open code Optimax has been used for the optimization procedure. The latter was carried out by comparing the reaction force of the computational model and the experiment. The main achievement of the presented study is a useful computational methodology for an exact determination of ductile damage parameters, which can be used for the further numerical simulations of damage propagation in different cellular structures under quasi-static loading.

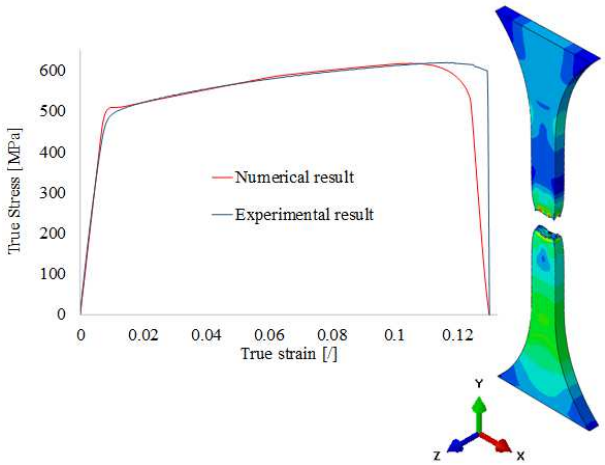


Figure 1. Comparison of experimental and numerical tensile response

References

[1] J. Ružička, M. Španiel, A. Prantl, J. Džugan, J. Kuželka, M. Moravec. Identification of Ductile Damage Parameters in the Abaqus. *Bulletin of Applied Mechanics*, 8(32): 89–92, 2012.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Mechanical Failure of Overhead Power Line Conductors

Mijo NIKOLIĆ[*], Adnan IBRAHIMBEGOVIĆ[+]

[*]*University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, HR-21000 Split, Croatia*
E-mail: mijo.nikolic@gradst.hr

[+]*Université de Technologie de Compiègne, Laboratoire Roberval de Mécanique, Centre de Recherches Royallieu, 60200 Compiègne, France*
E-mail: adnan.ibrahimbegovic@utc.fr

Abstract

We seek to quantify the fretting mechanisms which lead to failure of overhead power line conductors. One can strongly benefit here from usage of powerful numerical tools and nonlinear finite element method. The problem of such kind requires an approach based on multi-physics and multi-scale models. Namely, each conductor is composed of single strands wrapped together which interact with each other leading to complex anisotropic behaviors. Damage mostly occurs at the positions of clamps where clamping devices hold the conductor [1]. Multi-scale methodology is proposed, where conductor is observed at macro, meso and micro scale. In this work we present the macro-scale model where conductor is represented with geometrically nonlinear cable element [2], while part of the cable which is positioned inside the clamping devices is modeled as Timoshenko beam finite element with embedded strong discontinuities [3] capable to provide failure mechanism of the clamped part of the conductor.

References

[1] C.R.F. Azevedo, A.M.D. Henriques, A.R. Pulino Filho, J.L.A. Ferreira, J.A. Araujo. Fretting Fatigue in Overhead Conductors: Rig Design and Failure Analysis of a Grosbeak Aluminium Cable Steel Reinforced Conductor. *Engineering Failure Analysis*, 16(1): 136-151, 2009.

[2] A. Ibrahimbegovic. A Consistent Finite-element Formulation of Non-linear Elastic Cables. *Communications in Applied Numerical Methods*, 8(8): 547-556, 1992.

[3] M. Nikolić, A. Ibrahimbegović, P. Miščević. Brittle and Ductile Failure of Rocks: Embedded Discontinuity Approach for Representing Mode I and Mode II Failure Mechanisms. *International Journal for Numerical Methods in Engineering*, 102(8): 1507-1526, 2015.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Integrated Approach in Analysis of Historical Ancient Monuments

Željana NIKOLIĆ[*], Lidija KRSTEVSKA[+], Pavao MAROVIĆ[*], Hrvoje SMOLJANOVIĆ[*], Nikolina ŽIVALJIĆ[*]

[*]University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, HR-21000 Split, Croatia
E-mails: {zeljana.nikolic, pavao.marovic, hrvoje.smoljanovic, nikolina.zivaljic}@gradst.hr

[+]Institute of Earthquake Engineering and Engineering Seismology (IZIIS), University of Ss. Cyril and Methodius, Todor Aleksandrov 165, MK-1000 Skopje, Republic of Macedonia
E-mail: lidija@pluto.iziis.ukim.edu.mk

Abstract

Comprehensive analysis of seismic resistance of historical ancient monuments is an important aspect in rehabilitation of such structures. Most of them are made of stone blocks with dry joints and sometimes strengthened with metal connectors. Due to discontinuous nature and composition of the materials with significantly different properties, computational analyses of those structures are based on advanced numerical models with discrete or finite discrete element approach, and also knowledge of numerous material and structural parameters. A comprehensive approach to the analysis of such structures should integrate model updating, calibration and validation, as well as experimental investigations which may include testing of the material properties, complex non-linear static and dynamic tests and hopefully, shaking table testing of the structural model. This paper presents integration of the mentioned numerical and experimental investigations in analysis of the seismic resistance of Protiron monument, placed in the Diocletian Palace in Split, Croatia. The applied numerical model based on finite-discrete element method includes sliding of the blocks, fracture and fragmentation, cyclic behaviour, yielding and pulling out of the clamps and the bolts from the stone blocks [1]. Force-displacement relationship for clamps and bolts, obtained by static tests on several specimens, are used to calibrate the model of the metal connectors. Finally, shaking table testing of Protiron model was performed [2] in order to validate applied numerical model in dynamic regime and to provide an insight into the seismic resistance with detailed behaviour of the monument model.

References

[1] H. Smoljanović, Ž. Nikolić, N. Živaljić. A Finite-Discrete Element Model for Dry Stone Masonry Structures Strengthened with Steel Clamps and Bolts, *Engineering Structures*, 90: 117-129, 2015.

[2] Ž. Nikolić, L. Krstevska, P. Marović, H. Smoljanović. Shaking Table Test of Scaled Model of Protiron Dry Stone Masonry Structure. *Procedia Engineering*, 199: 3386–3391, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

2D Lattice Model with Beams as Lattice Elements

Matija NOVAK[*], Eduard MARENIĆ[+], Tomislav JARAK[*]

[*]*University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia*
E-mails: {matija.novak,tomislav.jarak}@fsb.hr

[+]*Université Fédérale Toulouse Midi-Pyrénées, Institut Clément Ader, CNRS UMR 5312, INSA/UPS/Mines Albi/ISAE, France*
E-mail: marenic@insa-toulouse.fr

Abstract

In numerical modelling of failure in brittle materials many numerical models incorporating continuum theories have been developed. In such numerical models, the implementation of complicated procedures to circumvent difficulties in describing phenomena depending on lower material length scales (e.g. microscale), like capturing the finite size of fracture process zone, modelling multiple cracks, fragmenting, etc., are needed. Therefore, lattice models represent an interesting and valuable alternative to the continuum models. The lattice models are discrete numerical models where a solid is represented as an assembly of simple 1D finite elements representing cohesion forces between rigid particles inside the material [1]. With respect to the lattice topology, regular and irregular lattices can be distinguished. The regular lattice is a lattice with structured grid with equal hexagonal or square unit cells, while in the irregular lattices, grids are unstructured. While irregular lattices cannot represent the uniform straining of a solid exactly, they are better suited for capturing the direction of crack propagation correctly and to describe the material heterogeneity at lower scales. In the structured lattices, in general it is easier to compute the parameters of the lattice elements, because all elements have the same properties [2]. In this contribution, the application of lattice models with Timoshenko beams for the application of linear-elastic solids will be investigated. Discretization of the domain will be based on Voronoi tessellation, with the edges of Delaunay triangles as lattice elements [2]. Both structured and unstructured lattices will be considered. Appropriate techniques for defining beam parameters will be implemented and their influence on the model performance will be investigated. The efficiency of the proposed strategies will be demonstrated by suitable numerical examples. The possible research directions for developing lattice models for modelling of piezo-electric materials will be proposed.

References

[1] M. Ostoja-Starzewski. Lattice Models in Micromechanics. *Applied Mechanics Reviews*, 55(1): 35-59, 2002.

[2] M. Nikolić, E. Karavelić, A. Ibrahimbegovic, P. Miščević. Lattice Element Models and Their Peculiarities. *Archives of Computational Methods in Engineering*, 2017. https://doi.org/10.1007/s11831-017-9210-y

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Compressive Properties of Auxetic Cellular Structures Build from Inverted Tetrapods

Nejc NOVAK[*], Matej VESENJAK[*], Lovre KRSTULOVIĆ-OPARA[+], Zoran REN[*]

[*]*University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia*
E-mails: {n.novak, matej.vesenjak, zoran.ren}@um.si

[+]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia*
E-mail: Lovre.Krstulovic-Opara@fesb.hr

Abstract

Auxetic cellular materials are modern metamaterials with negative Poisson's ratio [1]. They get wider when stretched and thinner when compressed. Such behaviour proves to be advantageous in many different applications [2], [3]. The designed auxetic cellular structures build from inverted tetrapods were fabricated at the Joint Institute of Advanced Materials and Processes (ZMP), University of Erlangen-Nürnberg, Germany. Complete characterisation of their mechanical properties was achieved with combination of experimental uniaxial compression testing, infrared thermography and computational simulations. Compression testing was realised in two perpendicular directions at two different strain rates (quasi-static and dynamic). IR thermography was additionally used for observing the deformation patterns. The lattice type computational model of the auxetic structure was analysed with the LS-DYNA explicit finite element code with good correlation to experimental observations (Figure 1).

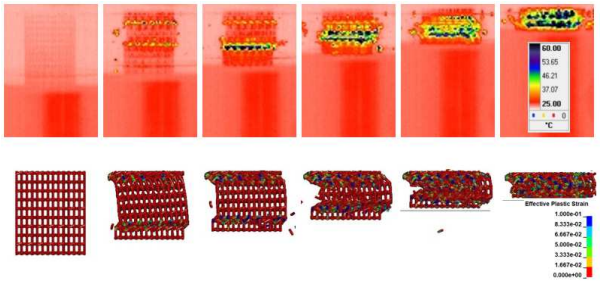


Figure 1: Comparison of IR thermography and computational results

References

[1] K.E. Evans, M.A. Nkansah, I.J. Hutchinson, S.C. Rogers. Molecular Network Design. *Nature*, 353: 124, 1991.

[2] N. Novak, M. Vesenjak, Z. Ren. Auxetic Cellular Materials - A Review. *Strojniški vestnik – Journal of Mechanical Engineering*, 62(9): 485-493, 2016.

[3] N. Novak, M. Vesenjak, Z. Ren. Computational Simulation and Optimization of Functionally Graded Auxetic Structures Made From Inverted Tetrapods. *Physica Status Solidi B*, 254(12): paper no. 1600753, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Magnetic Nonlinear Negative Stiffness in Coupled Oscillators

Akintoye Olumide OYELADE

University of Lagos, Faculty of Engineering, Department of Civil and Environmental Engineering, Nigeria
E-mails: aoyelade@unilag.edu.ng

Abstract

This paper introduces alternative means of eliciting nonlinear stiffness in nonlinear energy sink (NES). The NES possesses essentially nonlinear stiffness nonlinearity of the third degree which has been used to absorb steady state vibration energy from the linear oscillator over a relatively broad frequency range. A number of tentative methods have been proposed in the literature to elicit the cubic nonlinearity in the subsystem by using inclined springs, [1] and leaf/string spring [2]. However, the practical realization of having 1D movement of the inclined springs/leaf without shifting and rotation will be extremely challenging. In the present work, we assembled repelling magnets to realize nonlinear negative springs (NNS) in a chain of oscillators. The restoring magnetic force is approximated using cubic polynomial expansion to pure cubic stiffness. Bearing in mind the critical value of negative stiffness for static stability, dynamics investigations were done on the oscillators for different values of NNS. Furthermore response of one of the oscillators is examined under prescribed displacement harmonically, and resonance phenomenon which is integral part of linear system did not emerge in the system with NNS. There is general agreement with our experiment and theory. The proposed models can also be used as a nonlinear snap-through magnetic spring.

References

[1] K. Remick, D.D. Quinn, D.M, McFarland, L.A, Bergman, A.F. Vakakis. High-frequency Vibration Energy Harvesting from Impulsive Excitation Utilizing Intentional Dynamic Instability Caused by Strong Nonlinearity. *Journal of Sound and Vibration*, 370: 259-279, 2016.

[2] X. Jiang, D.M. McFarland, L.A, Bergman, A.F. Vakakis. Steady State Passive Nonlinear Energy Pumping in Coupled Oscillators: Theoretical and Experimental Results. *Nonlinear Dynamics*, 33(1): 87-102, 2003.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Stresses and Displacements of Short Orthotropic Thin-walled Columns under Eccentric Axial Force

Radoslav PAVAZZA[*], Frane VLAK[*], Marko VUKASOVIĆ[*], Dražen KUSTURA[+]

[*]***University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia***
E-mails: {rpavazza, fvlak, mvukasov}@fesb.hr

[+]***University of Split, Faculty of Science, Ruđera Boškovića 33, HR-21000 Split, Croatia***
E-mail: Drazen.Kustura@pmfst.hr

Abstract

A simple closed analytic solution for the stresses and displacements of short orthotropic thin-walled columns of open bi-symmetrical cross-sections under the eccentric axial tip force is presented in this paper. The expression for stresses and displacements are derived on the basis of the theory of bending [1] and the theory of torsion [2, 3] of thin-walled beams of open section with influence of shear. The normal stresses are given (i) by the compression component, (ii) by the bending components in the principal planes and (iii) by the torsion component with respect to the cross-section principal pole and the principal warping coordinate. The deflections are given by the classical banding and torsion components [4] and by the additional bending and torsion components due to shear [1-3]. The comparisons with the finite element solutions by using shell element are provided.

References

[1] R. Pavazza, A. Matoković. Bending of Thin-walled Beams of Open Sections with Influence of Shear, Part I: Theory. *Thin-Walled Structures*, 116: 357-368, 2017.

[2] R. Pavazza. Torsion of Thin-walled Beams of Open Cross-section with Influence of Shear. *International Journal of Mechanical Sciences*, 47(7): 1099-1122, 2005.

[3] R. Pavazza. *Introduction to the Analysis of Thin-walled Beams*. Kigen, Zagreb, 2007. (in Croatian)

[4] V.Z. Vlasov. *Thin-walled Elastic Beams*. Israel Program for Scientific Translation Ltd, Jerusalem, 1961.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Temperature and Strain Rate Dependent Mechanical Response of METCO 601 Aluminium-Polyester Abradable Seal Coating

Antonio PELEGRINO[*], Kalin DRAGNEVSKI[*], Giuseppe ZUMPANO[+], Nik PETRINIC[*]

[*]***University of Oxford, Department of Engineering Science, Oxford OX1 3PJ, England, United Kingdom***
E-mail: {antonio.pellegrino, kalin.dragnevski, nik.petrinic}@euler.edu

[+]***Rolls-Royce plc, PO Box 31, Derby DE24 8BJ, England, United Kingdom***

Abstract

Coatings are used in all engineering design scenarios when the desired surface properties are different from the desired structural material properties. In aerospace propulsion coatings are employed in various sections of jet engines subjected to different temperature, pressure and loading conditions. Their primary applications include fretting wear protection, thermal barrier, corrosion, oxidation and wear resistance enhancement. Abradable coatings are utilized as sacrificial materials in low pressure compressor casings, and in intermediate and high pressure compressors and seals. The adoption of abradable coatings allows for the clearance between compressor blades and casing to be minimized, increasing the overall efficiency of the engine. During operation the concurrent effects of centrifugal forces generated by the rotational speed, thermal expansion, shaft misalignments, and slight ovalization of the casing and tight geometrical tolerances can lead to the contact between blades and casing. The application of abradable coatings to the containment avoids this contact to occur between metals, with detrimental consequences on the operational life of the engine. Quasi-static and dynamic experiments at different temperatures are conducted to characterize the mechanical response of a thermally sprayed abradable seal coating. The material is composed of an aluminium continuum matrix and fairly well dispersed polyester particles. Stress versus strain histories are measured in uniaxial tension and compression at strain rates ranging from 10^{-3} to 10^{2} s−1, via non-standard experimental techniques; the material displays sensitivity to the strain rate and to the imposed temperature. The mechanical behaviour is brittle in tension while it exhibits higher strains to failure in compression. A pronounced tension/compression asymmetry is displayed both at quasi static and high rates of strain.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

On the Masonry Infill Wall and Reinforced Concrete Frame Interaction during Earthquakes

Davorin PENAVA[*], Filip ANIĆ[*], Vasilis SARHOSIS[+], Lars ABRAHAMCZYK[-], Silva LOZANČIĆ[*]

[*]*Josip Juraj Strossmayer University of Osijek, Faculty of Civil Engineering Osijek, 3 Vladimir Prelog Street, HR-31000 Osijek, Croatia*
E-mails: {dpenava, fanic, lozancic}@gfos.hr

[+]*Newcastle University, School of Engineering, Newcastle upon Tyne, NE1 7RU, United Kingdom, E-mail: vasilis.sarhosis@ncl.ac.uk*

[-]*Bauhaus-Universität Weimar, Earthquake Damage Analysis Centre (EDAC), Marinestrasse 13B, D-99421 Weimar, Germany*
E-mail: lars.abrahamczyk@uni-weimar.de

Abstract

Experience from past earthquakes has revealed damages in masonry infilled reinforced concrete frames. Also, infilled frames containing window and door openings are more prone to damages during earthquake events and thus their vulnerability needs to be quantified. Previous research demonstrated that masonry infill walls located in the upper floors of multi-story reinforced concrete buildings are most vulnerable to out-of-plane collapse. However, new evidence indicates that ground floor walls are also endangered to out-of- plane collapse due to movements of the frame, [1]. The aim of this paper is to use advanced three-dimensional computational analysis tools and investigate the structural behaviour of reinforced concrete framed-masonry walls containing window and door openings, centrically and eccentrically positioned. The computational model was calibrated using full scale experimental tests on framed-walls, [2, 3]. A series of computational analysis developed to simulate the mechanical behaviour of framed-masonry walls subjected to monotonic and cyclic in the out-of-plane direction up to a drift ratio equal to 2.5 % (frame collapse). Conclusions are given with respect to the out-of-plane failure mechanism of the wall, influence of opening type, size and position, and out-of-plane resistance of the frame-masonry composite.

References

[1] D. Penava, V. Sigmund. Out-of-plane behaviour of framed-masonry walls with opening as a result of shaking table tests. Proc. 16th World Conf. on Earthquake Engineering, Chilean Association of Seismology and Earthquake Engineering, 1-8, 2017.

[2] V. Sigmund, D. Penava. Influence of openings, with and without confinement, on cyclic response of infilled RC frames - An experimental study. *J Earthq Eng*, 18(1):113-46, 2014.

[3] F. Anić, D. Penava, V. Sarhosis. Development of a three-dimensional computational model for the in-plane and out-of-plane analysis of masonry-infilled reinforced concrete frames. In: M. Papadrakakis, M. Fragiadakis, eds., 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, 1-15, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Numerical Model of the Pulsed Laser Deposition Process Based on Kinematic Monte Carlo Approach

Konrad PERZYNSKI, Dawid ZYCH, Lukasz MADEJ

AGH University of Science and Technology, 30-059 Krakow, Poland
E-mails: kperzyns@agh.edu.pl, dzych@agh.edu.pl, lmadej@agh.edu.pl

Abstract

To fulfill specific requirements of manufacturing industry, materials scientists are trying to design new types of materials or increase performance of already available ones. One of the concepts is to develop hybrid materials, obtained as a combination of different components e.g. substrate cladded with thin layer of different material. The Pulsed Laser Deposition (PLD) [1] method is frequently used to obtain such complex materials. The main idea of the PLD is based on a high-power laser beam that is focused periodically onto the target material provoking instantaneous evaporation and ionization of the surface atoms. Products of such ionization are driven away from the target plate at high speed into the precisely controlled vacuum. Finally, particles strike with high velocity into the surface of the substrate material, start to nucleate and grow. The PLD approach is widely used in e.g. biomedical industry to obtain multilayer biocompatible materials for e.g.: implants, artificial heart chambers, heart valves etc. [2]. Experimental procedures used for preparation and investigation of nanostructured multilayers are highly expensive because of sophisticated equipment that has to be used at this length scale. Because of this high costs, the idea is to support the research by an efficient numerical approaches based on discrete modelling methods. The Kinetic Monte Carlo (KMC) method was selected in the presented research as an adequate and feasible technique for numerical simulation of the PLD process. The KMC method is based on a dynamic time step, which is coupled with probabilistic approach to describe investigated events in the system [3]. Details of developed algorithms replicating particle desorption, absorption and surface diffusion during PLD are presented in the work. Obtained results generated with presented PLD model and subsequent numerical simulations will be helpful during the designing of deposition processes of different nanolayered structures.

Acknowledgement: This study was funded by the National Science Centre under the 2015/17/D/ST8/01278 project and supported by PLGrid Infrastructure.

References

[1] H. Fujioka. *Handbook of Crystal Growth*. Elsevier, 2015.

[2] J. Sarna, R. Kustosz, R. Major, J. Lackner, B. Major. Polish Artificial Heart - Material, Technology, Diagnostics. *Bulletin of the Polish Academy of Sciences*, 58: 329-336, 2010.

[3] Y. Ichino, Y. Yoshida, S. Miura. Three-dimensional Monte Carlo Simulation of Nanorod Self-organization in $REBa_2Cu_3O_y$ Thin Films Grown by Vapor Phase Epitaxy. *Japanese Journal of Applied Physics*, 56: 015601, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Cross-roll Straightening of Bars – Fast Analysis and Optimization

Jindrich PETRUSKA, Tomas NAVRAT, Marek BENESOVSKY

Brno University of Technology, Technicka 2, 61669 Brno, Czech Republic
E-mails: {petruska, navrat}@fme.vutbr.cz, Marek.Benesovsky@vutbr.cz

Abstract

Straightening of long products has always been a challenging problem for computational analysis and prediction of both the straightening process and the straightening machine loading, its fatigue life and wear of the straightening rollers. Many approaches to solve this problem were tested and applied – from analytical formulas based on theoretical continuum mechanics and empirical knowledge, [1], up to FEM-based solutions, [2]. With finite elements, many over-simplifications of the computational models can be dropped off and fully 3D nonlinear behavior of the straightened product can be simulated, including the interaction of axial movement with rotation along its longitudinal axis in the case of cross-roll straightening, [3]. Nevertheless, this approach is very time consuming and even with the latest computational power still inappropriate for a fast industrial optimization or real-time process control purposes. New FE approach to solve this problem was developed by the authors in [4], which is based on the combination of Eulerian flow of material through a mesh of axially fixed beam elements, and Lagrangian description of their transversal deflection parameters. Application to cross-roll straightening is described in [5]. Practical experience with the new approach proves its efficiency and suitability to solution of fast optimization tasks. The main problem is to evaluate the optimal intermeshing of straightening rollers to obtain the best results for different input parameters like bar diameter, its material composition, initial curvature and residual stress distribution. The meaning of "best results" can be rather broad – the product should not only be straight enough, but show also minimal residual stress and minimal loading and wear of the straightening rollers. A treatise on this multi-objective straightening optimization problem is the main theme of the presented paper.

References

[1] H. Tokunaga. On the Roller Straightener. *Bulletin of the Japan Society of Mechanical Engineers*, 4(15): 605-611, 1961.

[2] M. Nastran, K. Kuzman. Stabilisation of Mechanical Properties of the Wire by Roller Straightening. *Journal of Materials Processing Technology*, 125-126: 711-719, 2002.

[3] A. Mutrux, B. Berisha, B. Hochholdinger, P. Hora. Numerical Modelling of Cross Roll Straightening. In: LS-DYNA Anwenderforum, Bamberg, 33–40, 2008.

[4] J. Petruška, T. Návrat, F. Šebek. A New Model for Fast Analysis of Leveling Process. *Advanced Materials Research*, 586: 389-393, 2012.

[5] J. Petruška, T. Návrat, F. Šebek. Novel Approach to Computational Simulation of Cross Roll Straightening of Bars. *Journal of Materials Processing Technology*, 233: 53-67, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Modelling of Material Deformation Responses using Atomistic Scale Submodel

Robert PEZER[*], Ivan TRAPIĆ[+], Jurica SORIĆ[+]

[*] ***University of Zagreb, Faculty of Metallurgy,***
Aleja narodnih heroja 3, HR-44103 Sisak, Croatia
E-mail: rpezer@simet.hr

[+]***University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture,***
Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {jurica.soric, ivan.trapic}@fsb.hr

Abstract

Classical continuum mechanics approach face substantial difficulties to properly account for stress and strain states around microstructural material discontinuities like dislocations, grain boundaries and porosities. One way to improve the material model is development of the atomistic *ab inito* submodel for atomic motion that underlies metal strength under the temperature and stress loading. In our approach continuum model drives the atomistic submodel by providing boundary displacement for molecular dynamics simulation [1]. As a proof of concept we firstly present simple truss elements with atomistic submodel of 1D chain of atoms interacting through Lennard-Jones interatomic potential. 2D extension of the model is further developed by connecting analytically solvable problems with atomistic submodel employing realistic interatomic potentials that simulate the vicinity of the sharp notches with high stress concentrations. Our approach using atomistic submodel allows significant reduction of vast amount of data and provides effective atomistic to mesoscopic scale unification [2]. We have developed effective algorithm capable of dynamic adaptation in FEM to atomistic submodel information exchange. Our ultimate goal is to utilize the best from both worlds, speed of finite elements methods calculations and catching of relevant atomistic material features by judiciously using molecular dynamics, where continuum approximation fails.

Acknowledgement: This work has been supported by Croatian Science Foundation under the project *Multiscale Numerical Modeling of Material Deformation Responses from Macro- to Nanolevel* (HRZZ-IP-2013-11-2516).

References

[1] P. Čanžar, Z. Tonković, J. Kodvanj. Microstructure Influence on Fatigue Behaviour of Nodular Cast Iron. *Materials Science and Engineering: A*, 556: 88–99, 2012.

[2] N.Ch. Admal, E.B. Tadmor. The Non-uniqueness of the Atomistic Stress Tensor and its Relationship to the Generalized Beltrami Representation. *Journal of the Mechanics and Physics of Solids*, 93: 72-92, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Approaches to the Fibre Modelling in a Simple Laboratory Mechanical System

Pavel POLACH[*], Radek BULÍN[+], Michal HAJŽMAN[*]

[*]***Research and Testing Institute Plzen, Tylova 1581/46, 301 00 Plzen, Czech Republic***
E-mails: {polach, hajzman}@vzuplzen.cz

[+]***University of West Bohemia, Univerzitní 8, 306 14 Plzen, Czech Republic***
E-mail: rbulin@ntis.zcu.cz

Abstract

Cables and fibres can play an important role in the design of many machines. One of the applications is the replacing of the chosen rigid elements of a manipulator or a mechanism with cables. The main advantage of this design is the achievement of a lower moving inertia, which leads to a higher mechanism speed, a large range of motion and the possibility of antibacklash property. Drawbacks can be related to the fact that cables should only be in tension in the course of a motion. In this paper there are presented some possible approaches suitable for the modelling of the cable and fibre dynamics in the framework of various mechanical systems (e.g. [1]): force representation of a cable, a point-mass model and the absolute nodal coordinate formulation (ANCF). The simplest way how to incorporate cables in the equations of motion of a mechanism is the force representation of a cable. This way of the cable modelling is probably most frequently used in the cable-driven robot dynamics and control. A more accurate approach is based on the representation of the cable by the point-mass model. The advantage of this approach consists in a precise physical interpretation of the problem and in a short computational time. A very promising approach usable for the cable modelling is ANCF (e.g. [2]), which is based on the finite element discretization of a cable. Experimental measurements focused on the investigation of the fibre behaviour were performed on an assembled weight-fibre-pulley-drive mechanical system (e.g. [3]). Results of experimental measurement and computational results obtained using force and ANCF models of the fibre are given in this paper.

References

[1] U. Lugrís, J. Escalona, D. Dopico, J. Cuadrado. Efficient and Accurate Simulation of the Rope-sheave Interaction in Weight-lifting Machines. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*, 225: 331-343, 2011.

[2] R. Bulín, M. Hajžman, P. Polach. Nonlinear Dynamics of a Cable-pulley System Using the Absolute Nodal Coordinate Formulation. *Mechanics Research Communications*, 82: 21-28, 2017.

[3] P. Polach, M. Byrtus, Z. Šika, M. Hajžman. Fibre Spring-damper Computational Models in a Laboratory Mechanical System and Validation with Experimental Measurement. *An Interdisciplinary Journal of Discontinuity, Nonlinearity, and Complexity*, 6(4): 513-523, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Creep and Relaxation of Prismatic Bar in State of Bending

Dragan PUSTAIĆ

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mail: dragan.pustaic@fsb.hr

Abstract

The viscoelastic behavior of prismatic bar in state of bending is investigated in this paper. When describing the *creep* phenomenon of such bar it is assumed that the bar is in the state of the *steady-state creep* conditions, i.e. at such state of creeping at which the stresses do not change with time. The dependence of *creep strain* ε_c on *stress* and *time* at a given *temperature* can be written as a product of two functions, of which the first function is a function of stress and temperature, and the second one is a function of time and temperature, [1-3]. The mentioned methodology of calculating is often used in the theory of viscoelasticity for determining the stress distribution in the different structural components, [2-3]. In order to find out how much the stress distribution in a bar is accurate and reliable, the same problem was solved by one variation method, i.e. by applying the *principle of minimum of complementary potential energy*, [1]. The compatibility of the obtained results was even more than expected, excellently. A second phenomenon which was considered in this paper was *relaxation* phenomenon of bending moment in a cross section of prismatic bar. At the initial moment (t = 0), the bending moment acting on the bar amounts to $M_y(0)$. If a *curvature* of the bar $\left(\kappa(0)=\kappa_c(t)=\text{const.}\right)$ is kept *constant over time*, the decrease of the bending moment $M_y(t)$ over time is investigated, [3]. The analytical methods and one approximate numerical method were used in the analysis of creep and relaxation of prismatic bar. Some results, especially relaxation of bending moment, and their graphic interpretations were obtained by means of software package *Wolfram Mathematica 7.0*.

References

[1] N.N. Malinin. *Applied Theory of Plasticity and Viscoelasticity*, Mashinostroenie, Moscow, 1975. (in Russian)

[2] D. Pustaić. Steady-State Creep Analysis of Thick-Walled Pressure Vessels and Piping. In: Z. Virag, H. Kozmar, I. Smojver, eds., Proceedings of the 7th International Congress of Croatian Society of Mechanics – 7th ICCSM, Book of Abstracts, 197-198 & CD-ROM Proc. (8 p.), Croatian Society of Mechanics, Zagreb, 2012.

[3] D. Pustaić, M. Pustaić. Torsion of a Circular Cross Section Shaft in the Steady-State Creep Conditions. In: I. Kožar, N. Bićanić, G. Jelenić, M. Čanađija, eds., Proceedings of the 8th International Congress of Croatian Society of Mechanics – 8th ICCSM, Book of Abstracts, p. 83 & CD-ROM Proc. (11 p.), Croatian Society of Mechanics, Zagreb, 2015.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Mathematical Modeling of Cohesive Zone in the Ductile Metallic Materials

Dragan PUSTAIĆ[*], Martina LOVRENIĆ - JUGOVIĆ[+]

[*]*University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia*
E-mail: dragan.pustaic@fsb.hr

[+]*University of Zagreb, Faculty of Metallurgy, Aleja narodnih heroja 3, HR-44103 Sisak, Croatia*
E-mail: mlovrenic@simet.hr

Abstract

The mathematical modeling of the phenomena appearing in the cohesive zone around crack tip in the ductile metallic materials is performed in this paper. Some of the well-known cohesive models are applied in those investigations, [1-2]. Some parameters of EPFM, such as, the stress intensity coefficient and the magnitude of cohesive zone are investigated, [1-3]. An *isotropic* and *non-linear* strain hardening of a plate material is assumed. Non-linear strain hardening of a plate material at uniaxial state of stress is described by the *Ramberg-Osgood equation*, [3]. The investigations were carried out for the several different values of the *strain hardening exponent n* which is changed among the discreet values n = 3, 5, 7, 10, 25 and ∞. In that way, it is going to be shown how different strain hardening of a material influences on the plastic zone magnitude. It is necessary to point out that the cohesive stresses within the plastic zone are not more *constant* in such isotropic strain hardening material. They are changed according to a *non-linear* law, [3]. The analytical methods were used in the analysis. The stress intensity coefficient from the cohesive stresses is calculated using *Green functions*, [3]:

$$K_{\mathrm{coh}}(b) = \sqrt{2r_{\mathrm{p}}} \cdot \sigma_0 \cdot \left\{ \Gamma\left[n/(n+1)\right] / \Gamma\left[(1/2)+n/(n+1)\right] \right\} \cdot$$
$$\cdot {}_2F_1\left[1/2;1/2;(1/2)+n/(n+1);r_{\mathrm{p}}/2b\right].$$

The results were obtained by means of software package *Wolfram Mathematica 7.0.*

References

[1] D. Pustaić, B. Štok. Crack Tip Plasticity Investigations using Dugdale Strip Yield Model Approach. In: J. Petit, J. de Fouquet, G. Henaff, P. Villechaise, A. Dragon, eds., Proceedings of 11th European Conference on Fracture (ECF-11), 151-156. Engineering Materials Advisory Services (EMAS), Poitiers-Futuroscope, 1996.

[2] D. Pustaić, B. Štok. Some Critical Remarks on the Dugdale Strip Yield Model for the Crack Tip Plasticity. In: M.W. Brown, E.R. de los Rios, K.J. Miller, eds., Proceedings of 12th European Conference on Fracture (ECF-12), 889-894. Engineering Materials Advisory Services (EMAS), Sheffield, 1998.

[3] X.G. Chen, X.R. Wu, M.G. Yan. Dugdale Model for Strain Hardening Materials. *Engineering Fracture Mechanics*, 41(6): 843-871, 1992.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

A Novel Approach in Multiscale Analysis of Quasi-brittle Softening Materials

Filip PUTAR, Jurica SORIĆ, Tomislav LESIČAR, Zdenko TONKOVIĆ

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {filip.putar, jurica.soric, tomislav.lesicar, zdenko.tonkovic}@fsb.hr

Abstract

It is well-known that the conventional homogenization approaches at microlevel are not appropriate for an objective multiscale analysis, because the averaging over the whole representative volume element (RVE) cannot adequately describe localization phenomena. There are some suggestions to overcome these problems, [1], where the converged results are obtained by averaging only over a loading zone where damage is rising. Derivation of an efficient and accurate multiscale method is still under development. In this contribution, a two-scale model presented in [2] is extended and transformed to the analysis of the softening materials. For this purpose, the damage model based on the strain gradient continuum proposed in [3] is employed at the RVE level, where the discretization is made by means of the C^1 continuity triangular finite elements. The two separate analyses are performed at the microlevel, one for the undamaged bulk, where the stress and constitutive operators are extracted using the conventional homogenization, and the other one for the softening material, where the localization is captured by a novel approach. Herein, due to a linear-elastic material, the bulk constitutive operators stay unchanged throughout the analysis and can be computed only once. The degradation of the macroscale stiffness is achieved using the isotropic damage law with the homogenized damage variable obtained from the softening RVE analysis. All the algorithms derived are implemented into the finite element software ABAQUS via user subroutines. The verification of the presented computational model is performed on several benchmark examples.

Acknowledgement: This work has been supported by Croatian Science Foundation under the project *Multiscale Numerical Modeling of Material Deformation Responses from Macro- to Nanolevel* (HRZZ-IP-2013-11-2516).

References

[1] V.P. Nguyen, M. Stroeven, L.J. Sluys. An Enhanced Continuous–discontinuous Multiscale Method for Modeling Mode-I Cohesive Failure in Random Heterogeneous Quasi-brittle Materials. *Engineering Fracture Mechanics*, 79: 78-102, 2012.

[2] T. Lesičar, Z. Tonković, J. Sorić. Two-scale Computational Approach Using Strain Gradient Theory at Microlevel. *International Journal of Mechanical Sciences*, 126: 67-78, 2017.

[3] F. Putar, J. Sorić, T. Lesičar, Z. Tonković. Damage Modeling Employing Strain Gradient Continuum Theory. *International Journal of Solids and Structures*, 120: 171-185, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Mechanical Characterization of Cellular Metals

Zoran REN [*], Miran ULBIN[*], Matej VESENJAK[*], Matej BOROVINŠEK[*], Nejc NOVAK[*], Lovre KRSTULOVIĆ-OPARA[+], Željko DOMAZET[+]

[*]University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia
E-mails: {matej.vesenjak, matej.borovinsek, miran.ulbin, n.novak, zoran.ren}@um.si

[+]University of Split, Faculty of Electrical Eng., Mech. Eng. and Naval Arch., Croatia
E-mail: {lovre.krstulovic-opara, zeljko.domazet}@fesb.hr

Abstract

Cellular structures have been increasingly used in modern engineering applications over the past decade due to their attractive combination of mechanical and thermal properties [1]. Their mechanical behaviour depends on the porosity, morphology, topology and the base material [1, 2]. The advantages of cellular materials in general are low density (lightweight structures), efficient damping, high rate of deformation, high energy absorption capability, durability at dynamic loadings and fatigue, high thermal and acoustic isolation [1, 2]. Their physical properties make them very suitable for use in engineering as filters, heat exchangers, isolators, core material in sandwich structures, implants, impact energy absorption and damping elements [3, 4]. However, to achieve adequate mechanical (strength, stiffness) of cellular materials, their design parameters and proper fabrication procedure have to be carefully chosen [5]. The conference contribution presents different types of cellular materials (Figure 1), focusing on their geometrical properties and mechanical behaviour, obtained by micro computed tomography, experimental testing and computational simulations.

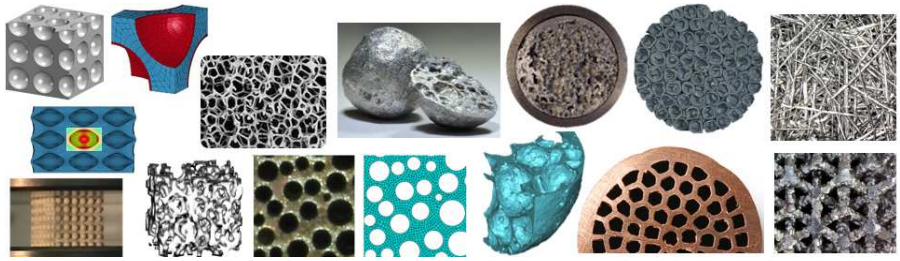


Figure 1. Different types of cellular metals

References

[1] M.F. Ashby, A. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley. *Metal Foams: A Design Guide*. Butterworth-Heinemann, Burlington, 2000.
[2] J. Banhart. Manufacture, Characterisation and Application of Cellular Metals and Metal Foams. *Progress in Materials Science*, 46(6): 559–632, 2001.
[3] L.-P. Lefebvre, J. Banhart, D.C. Dunand. Porous Metals and Metallic Foams: Current Status and Recent Developments. *Advanced Engineering Materials*, 10(9): 775–787, 2008.
[4] F. García-Moreno. Commercial Applications of Metal Foams: Their Properties and Production. *Materials*, 9(2): paper no. 85, 2016.
[5] D. Lehmhus, M. Vesenjak, S. De Schampheleire, T. Fiedler. From Stochastic Foam to Designed Structure: Balancing Cost and Performance of Cellular Metals. *Materials*, 10(8): paper no. 922, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Two-layered Plates with Assumed Shear Strain Fields

Dragan RIBARIĆ

University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia
E-mail: dragan.ribaric@uniri.hr

Abstract

We present a finite element model for a two-layered moderately thick plates based on the Mindlin plate theory [1]. Starting from the pure displacement-based approach and the general expressions for the shear strains, selective reductions for the shear are assumed and a new layered plate element is introduced based on the mixed formulation. In the bending part of the formulation the starting transverse displacement interpolation has a cubic order and the rotation interpolations are quadratic and they are linked in both fields following the problem-dependent linked-interpolation expressions [2]. In the membrane part the displacement interpolations are quadratic and also linked with the drilling nodal rotations. The element passes the general constant-bending patch test and has 30 degrees of freedom among which two are the internal bubble parameters. The layers can have different material characteristics, but these are assumed to be linear for each layer. The element is tested on a set of benchmark problems and compared with the results produced by the displacement-based layered elements without reduction in shear and which stiffness matrix is calculated by the reduced integration technique. The element is also compared with the other elements from the literature.

Acknowledgement: The results shown here have been obtained within the research project IP-06-2016-4775: *'Assumed strain method in finite elements for layered plates and shells with application on layer delamination problem - ASDEL'* financially supported by the Croatian Science Foundation.

References

[1] L. Škec, G. Jelenić. Analysis of a Geometrically Exact Multi-layer Beam with a Rigid Interlayer Connection. *Acta Mechanica*, 225(2)**:** 523-541, 2014.

[2] D. Ribarić. Problem-dependent Cubic Linked Interpolation for Mindlin Plate Four-node Quadrilateral Finite Elements. *Structural Engineering and Mechanics*, 59(6), 1071-1094, 2016.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

A Simple and Efficient Three-node Planar Curved Beam Element Based on Linked Interpolation

Dragan RIBARIĆ, Edita PAPA DUKIĆ, Gordan JELENIĆ

[*]University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia
E-mails: {dragan.ribaric, edita.papa, gordan.jelenic}@uniri.hr

Abstract

We present a new three-node Timoshenko curved-beam finite element for in-plane actions constructed on expanded linked interpolation for a straight beam [1]. Only the displacements and the rotation of the cross-section are interpolated and the element is formulated in a pure displacement-based fashion. At first the displacement fields are enriched in polynomial order to the quartic form associated to two pairs of internal bubble parameters following the idea presented in [2]. Then the shear strain constraints are enforced on the displacement interpolations and these parameters are expressed in terms of the rotation degrees of freedom resulting in a new linked interpolation for a curved beam element. At the same time the geometry is approximated using Lagrangian interpolation, so that the element-stiffness assembly is very simple and can easily be implemented in a computer code. The beam kinematics is defined using the global displacement variables in contrast to the commonly used displacement unknowns in the local coordinates, thus avoiding the co-ordinate transformation for the nodal degrees of freedom. Polynomial geometry of the element can easily be adapted to a straight beam configuration as well as to any other curved beam form and naturally shows no numerical sensitivities for the extremely shallow arches. The element is tested on a set of benchmark problems and shows no shear or membrane locking.

Acknowledgements: The results shown here have been obtained within the research project IP-11-2013: '*Configuration-dependent Approximation in Non-linear Finite-element Analysis of Structures*' financially supported by the Croatian Science Foundation. The University of Rijeka support for ongoing research no. 13.05.1.3.06 '*Testing of Spatial slender Beam Structures with Emphasis on Model Validation*' is also acknowledged.

References

[1] G. Jelenić, E. Papa. Exact Solution of 3D Timoshenko Beam Problem using Linked Interpolation of Arbitrary Order. *Archive of Applied Mechanics*, 81(2): 171-183, 2011.

[2] D. Ribarić, G. Jelenić. Distorsion-immune Nine-node Displacement-based Quadrilateral Thick Plate Finite Elements that Satisfy Constant-bending Patch Test. *International Journal for Numerical Methods in Engineering*, 98(7): 492-517, 2014.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Modelling Fiber Pull-out in Heterogeneous Fibrous Composites

Tea RUKAVINA[*+], Ivica KOŽAR[*], Adnan IBRAHIMBEGOVIĆ[+]

[*]*University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia*
E-mails: {tea.rukavina, ivica.kozar}@uniri.hr

[+]*Université de Technologie de Compiègne – Sorbonne Universités, Centre de Recherche Royallieu, 60200 Compiègne, France*
E-mail: adnan.ibrahimbegovic@utc.fr

Abstract

To be able to properly describe the failure of heterogeneous fibrous composites, we have to take into account the material behaviour of every constituent. In the case of short fiber reinforced concrete (FRC), we deal with concrete, steel fibers and the bond-slip between them. Since the bond-slip along the concrete-fiber interface has a global representation, and is spanning more than one finite element, the chosen description is based on the extended finite element (XFEM) representation that exploits the partition of unity property of standard shape functions [1, 2]. According to that, the displacement field for a single element consists of a standard and an enriched part:

$$\mathbf{u}(\mathbf{x})|_{\Omega^e} = \sum_{a=1}^{n} N_a(\mathbf{x})\mathbf{d}_a^e + \sum_{a=1}^{n} N_a(\mathbf{x})\psi(\mathbf{x})\alpha_a \tag{4}$$

Here, $\mathbf{d}_a^e$ are concrete displacements, α_Q are the relative displacements between the fiber and concrete, $N_Q(x)$ are standard shape functions for the chosen finite elements, and $\psi(x)$ is the enrichment function describing bond-slip. This formulation, comprising the damage softening model for concrete, the linear elastic behaviour of fibers, and a bond-slip law that takes into consideration the complete pull-out of the fibers, is implemented in a finite element computer code that allows for a partitioned solving of the model equations using an operator split solution procedure, as in [3]. Numerical results for tension tests and three-point bending tests are presented and validated with experimental data.

References

[1] F. Radtke, A. Simone, L. Sluys. A Partition of Unity Finite Element Method for Obtaining Elastic Properties of Continua with Embedded Thin Fibres. *International Journal for Numerical Methods in Engineering*, 84(6): 708-732, 2010.

[2] M.G. Pike, C. Oskay. XFEM Modeling of Short Microfiber Reinforced Composites with Cohesive Interfaces. *Finite Elements in Analysis and Design*, 106: 16-31, 2015.

[3] A. Ibrahimbegovic, A. Boulkertous, L. Davenne, D. Brancherie. Modelling of Reinforced-concrete Structures Providing Crack-spacing Based on X-FEM, ED-FEM and Novel Operator Split Solution Procedure. *Int. J. for Numerical Methods in Engineering*, 83(4): 452-481, 2010.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Analysis of In-plane Vibrations of Tattoo Gun

Filip SARBINOWSKI[*], Roman STAROSTA[+]

[*]***Poznan University of Technology, Department of Applied Mechanics,***
Jana Pawła II 24, 60-965 Poznan, Poland
E-mail:.filip.j.sarbinowski@doctorate.put.poznan.pl

[+]***Poznan University of Technology, Department of Applied Mechanics,***
Jana Pawła II 24, 60-965 Poznan, Poland
E-mail: roman.starosta@put.poznan.pl

Abstract

As rightly noted in [1], for several years the dynamic development of tattoo art can be observed. In connection with the above, the requirements for devices for tattooing [2] are naturally increasing, and the key feature affecting the comfort of such a device is the magnitude of its vibrations. These are mainly limited by the use of more and more complex kinematic systems of power transmission or precisely manufactured elements, which makes the prices of *tattoo guns* with reduced vibrations takes extreme values. An alternative to this trend may be the design of simple structures with rational dynamic properties determined on the basis of detailed analysis of mechanical phenomena occurring in the device. To carry out this type of research, knowledge of models of device interaction with the operator and the body of the tattooed person is required, which is in vain to find among scientific studies. In this work, the methodology for determining dynamic parameters for the bi-axial model of a tattooing device with five degrees of freedom will be presented. This model contains damping-elastic quantities describing the device's interactions the environment as well as dynamic factors of the motor foundation and the model of the needle's properties, as well as the set of forces acting on the system. On the basis of the obtained model, equations of motion will be derived, the solution of which will determine the behaviour of the system. In addition, the role of individual parameters will be examined for machine vibrations, including the analysis of bifurcation, the appearance of which is transferred due to the numerous nonlinear parameters occurring in the system. There will be also presented a method of optimizing the structure, the aim of which is minimization of vibrations.

References

[1] K.J. Leader. Occupy your Body: Activating 21st-Century Tattoo Culture. *The Journal of Somaesthetics*, 3(1-2): 44-57, 2017.

[2] *Technology Takes Tattoos into the Future.* [open access: https://www.asme.org/engineering-topics/articles/design/technology-takes-tattoos-into-future]

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Application of Genetic Algorithms to Optimize Geometry of a Resonator

Filip SARBINOWSKI[*], Roman STAROSTA[+]

Poznan University of Technology, Department of Applied Mechanics,
ul. Jana Pawła II 24, 60-965 Poznań, Poland
[*]E-mail: filip.j.sarbinowski@doctorate.put.poznan.pl
[+]E-mail: roman.starosta@put.poznan.pl

Abstract

Due to the increasingly common implementation of the innovative concept of the *Internet of Things* [1], the requirements for autonomous measuring devices are increasing - their task is not only to acquire data but also to process, analyze and transfer them to higher-level devices, hence their energy demand increases dramatically. According to that, there is a need to develop more efficient devices that are able to recover energy from the environment, including mechanical vibrations [2]. The devices of this type are using resonators as an active element - units whose natural frequency should be as close as possible to the frequency of excitation. Regarding to a very large diversity and commonness of vibrations, resonators should indicate high amplitudes and accelerations of vibrations in the widest range of excitation frequencies - this is a feature of non-linear systems [3]. The work is devoted to the optimization of the geometry of resonator, which can be an active element of energy harvesting devices. The goal function of the implemented genetic algorithm is to maximize amplitudes and vibration accelerations at the widest range of excitation frequencies. The analysis starts with the identification of features that cause nonlinearity of the structure. On this basis, an algorithm will generate random elements exhibiting these features. This population will be processed by the author's genetic algorithm, evaluating individuals on basis of FEM analysis, considering both: the target functions and durability of the generated element.

References

[1] M. Lampi. Internet of Things - Ambient Energy Harvesting. [open access: https://wiki.aalto.fi/download/attachments/59704179/lampi-iot-ambient-energy-harvesting.pdf]

[2] F. Cottone. Introduction to Vibration Energy Harvesting. NiPS Energy Harvesting Summer School, August 1-5, 2011. (pdf presentation) [open access: http://www.nipslab.org/files/file/nips%20summer%20school%202011/Cottone%20Introduction%20to%20vibration%20harvesting.pdf]

[3] Ch. Hayashi. *Nonlinear Vibrations in Physical Systems*, Mc Graw Hill, New York, 1964.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Nonlinear Static Analysis of Cable Structures Based on Isogeometric Analysis

Damir SEDLAR, Željan LOZINA, Ivan TOMAC

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Ruđera Boškovića 32, HR-21000 Split, Croatia
E-mails: {damir.sedlar, zeljan.lozina, ivan.tomac}@ fesb.hr

Abstract

Cable structures attitude well known demanding problems and the modelling of such structures has always been a subject of research and invention. Cable structures are light, very flexible and do not involve bending and compression stiffness. Therefore, cable structures show a high non-linear behavior. The main source of this nonlinearity is appearing large displacements which correspond to geometric nonlinearity. Total Lagrangian method [1] is used to solve this behavior. This method is based on an iterative process that modifies step by step the geometry of cable structures from one configuration to another fulfilling the equilibrium equations. Another important problem of cable structures is the determination of the initial equilibrium configuration. The isogeometric analysis method (IGA) is used to find equilibrium configuration and for modeling cable structures. The IGA is developed by Hughes et al. [2] to overcome discrepancy between computer aided design and structural analysis using traditional finite element method (FEM). Compared with FEM, IGA uses a different mathematical description of the geometry which enables it to preserve the exact geometry which is especially important for complex structures such as cable structure. Furthermore IGA provides a flexible way to make refinement and degree elevation. This paper deals with the static behavior of two and three dimensional cable structures [3]. The accuracy and efficiency of proposed algorithms are verified on several cable structures benchmark problems. The h and k refinement strategies are carried out to examine its influence to convergence and accuracy. The obtained results are compared with results given by other authors who have used different approaches. By comparing the obtained results the effectiveness of IGA is confirmed because the results are the same or even more precise. IGA provides accurate results when using the lowest degree of the polynomial, however in that case it is necessary to apply greater number of elements.

References

[1] K.J. Bathe. *Finite Element Procedures*. Klaus-Jurgen Bathe, Watertown, 2006.

[2] J.A. Cottrell, T.J.R Hughes, Y. Bazilevs. *Isogeometric Analysis: Toward Integration of CAD and FEA*. Wiley Publishing, 2009.

[3] S. Thai, N.-I. Kim, J. Lee. Isogeometric Cable Elements Based on B-spline Curves. *Meccanica*, 52(4-5): 1219-1237, 2017.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Residual Control Phase-field Staggered Algorithm for Brittle Fracture Modelling of Heterogeneous Microstructure

Karlo SELEŠ, Tomislav LESIČAR, Zdenko TONKOVIĆ, Jurica SORIĆ

University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, HR-10000 Zagreb, Croatia
E-mails: {karlo.seles, tomislav.lesicar, zdenko.tonkovic, jurica.soric}@fsb.hr

Abstract

The phase-field approach to fracture is a diffusive method based on the variational principle of the free energy minimization. It introduces fracture induced dissipation energy term in the total free energy functional, corresponding to the Griffith's fracture theory. A scalar damage parameter continuously varies over the domain approximating the sharp crack topology, thus eliminating the need for the numerical tracking of the crack displacement discontinuity inherent to the discrete fracture methods. Consequently, the phase-field approach is successful in solving the complex fracture processes even in the three-dimensional settings [1]. A length scale parameter is introduced to regulate the width of the approximated fracture band and govern the regularization of the free energy functional. Therefore, very fine mesh is required to resolve thin crack approximation. Combination of the thick mesh with the commonly used single-iteration staggered solution scheme for the phase-field fracture problem [1, 2] can be computationally very expensive, due to small loading increment requirement, which is essential to provide an accurate solution. In this work, an iterative staggered phase-field fracture model with the stopping criterion based on the control of the residual norm is implemented in the commercial finite element software Abaqus. It utilizes Abaqus advanced convergence control, automatic incrementation and built-in line search algorithm making the implementation more efficient. The model is verified on the several benchmark tests in terms of robustness, accuracy and computational cost. Moreover, a porous microstructure exhibiting crack nucleation and complex crack paths is analyzed. The proposed implementation demonstrates an improvement in the computational efficiency. Additionally, an accurate solution can be obtained independently of the loading increment size.

References

[1] G. Molnar, A. Gravouil. 2D and 3D Abaqus Implementation of a Robust Staggered Phase-field Solution for Modeling Brittle Fracture. *Finite Elements in Analysis and Design*, 130: 27–38, 2017.

[2] Ch. Miehe, M. Hofacker, F. Welschinger. A Phase Field Model for Rate-independent Crack Propagation: Robust Algorithmic Implementation Based on Operator Splits. *Computer Methods in Applied Mechanics and Engineering*, 199(45-48): 2765–2778, 2010.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Analysis of Plate Strips with Initial Transverse Cracks Subjected to Tension

Paulo ŠĆULAC, Gordan JELENIĆ

University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia
E-mails: {paulo.sculac, gordan.jelenic}@uniri.hr

Abstract

In this paper plate strips including initial defects subjected to uniaxial tensile stresses will be investigated. Both internal and external initial transversal cracks will be considered. The problem will be modelled using a novel beam finite element with embedded transversal crack; according to the strong discontinuity approach the displacement field will be enriched with an additional degree of freedom in order to take into account the jump in the displacement field at the crack position. The element will be treated as multilayered, thus enabling the crack to propagate through the depth of the plate. Several common problems will be analyzed: (i) centered cracked; (ii) single; or (iii) double edged notched strip plates and compared with analytical or numerical results [1-3].

References

[1] T.L. Anderson. *Fracture Mechanics: Fundamentals and applications.* 3rd edition. CRC Press - Taylor & Francis Group, Boca Raton, 2005.

[2] Z.P. Bažant, J. Planas. *Fracture and Size Effect in Concrete and Other Quasibrittle Materials*. CRC Press, Boca Raton, 1998.

[3] P.C. Paris, G.C.M. Sih. Stress Analysis of Cracks. In: *Fracture Toughness Testing and its Applications*, 30-83. ASTM & NASA, Baltimore, 1965.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

On Characterizing Fracture Resistance in Mode-I Delamination

Leo ŠKEC[*], Giulio ALFANO[*], Gordan JELENIĆ[+]

[*]*Brunel University London, Kingston Lane, Uxbridge, Middlesex UB8 3PH, England, United Kingdom*
E-mails: {leo.skec, giulio.alfano}@brunel.ac.uk

[+]*University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia*
E-mail: gordan.jelenic@uniri.hr

Abstract

In this work we focus on the mode-I quasi-static crack propagation in adhesive joints or composite laminates. For these problems a number of different standards have been approved [1]. The most widely used are based on the double cantilever beam (DCB) test and on linear elastic fracture mechanics (LEFM) but differ in some aspects of the testing procedure and the recommended data-reduction schemes. The applicability of these methods is still a matter of debate in the scientific community, particularly in the case of ductile interfaces. We revisit the accuracy of the most used standards and compare it with other methods based on either LEFM or J-integral theory [2]. All the methods analyzed in our work are based on either Euler-Bernoulli or Timoshenko beam theories. We present a number of numerical examples where we compare different expressions for fracture resistance obtained with different methods. The input for the analysis, which includes applied load, cross-head displacement and rotation, crack length and cohesive zone length, is obtained from the numerical model which simulates real experiments. In these simulations, we use a Timoshenko beam model with a bi-linear CZM [3, 4] which allows us accurate comparison with analytical formulas for fracture resistance based on Euler-Bernoulli and Timoshenko beam theory.

References

[1] BS ISO 25217:2009: *Adhesives - Determination of the mode 1 adhesive fracture energy of structural adhesive joints using double cantilever beam and tapered double cantilever beam specimens*. British Standard, Geneva, 2009.

[2] T.L. Anderson. *Fracture Mechanics: Fundamentals and Applications. Third Edition*. CRC Press, Boca Raton, 2005.

[3] L. Škec, G. Jelenić, N. Lustig. Mixed-mode Delamination in 2D Layered Beam Finite Elements. *International Journal for Numerical Methods in Engineering*, 104: 767-788, 2015.

[4] G. Alfano, M. Crisfield. Finite Element Interface Models for the Delamination Analysis of Laminated Composites: Mechanical and Computational Issues. *International Journal for Numerical Methods in Engineering*, 50(7): 1701-1736, 2001.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Process of Tungsten Wire Explosion and Synthesis of Carbide by Pulsed Wire Discharge

Shigeru TANAKA, Hayato ODA, Kazuyuki HOKAMOTO

Kumamoto University, Institute of Pulsed Power Science,
Kumamoto 860-8555, Japan
E-mail: ***tanaka@mech.kumamoto-u.ac.jp***

Abstract

A pulse large current was made to flow through the tungsten wire existing in liquid paraffin. During the discharge, the melting and evaporation (explosion) phenomenon of tungsten wire was observed by using a high-speed video camera, at the same time, the discharging current/voltage was measured. When the electric energy more than the evaporation of W wire was applied on the W wire, the cubic WC_{1-x} was synthesized. The grain size of the spherical WC_{1-x} particle ranged from several ten nm to several μm. The carbon ration of the cubic WC_{1-x} was within around 0.72-0.76. When the electric energy lower than the evaporation of W wire was applied, large sized spherical particles were recovered. One of the particles larger than 100 μm was composed of core W_2C and core coating WC.

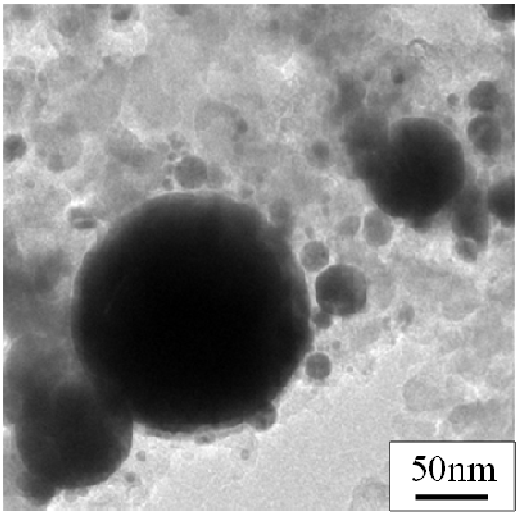


Figure 1. TEM image of recovered powder particles

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Application of Impact Resonance Method for Estimation of Steel Fiber Distribution in Concrete

Neira TORIĆ MALIĆ, Natalija BEDE, Ivica KOŽAR

University of Rijeka, Faculty of Civil Engineering, Radmile Matejčić 3, HR-51000 Rijeka, Croatia
E-mails: {ntoric, natalija.bede, ivica.kozar}@uniri.hr

Abstract

Fiber reinforced concrete (FRC) shows improved performance in cracking and shrinkage, as well as high ductility and tensile strength. However, one of the major drawbacks of FRC is determination of fiber volume fraction as well as achievement of uniform distribution of fibers in the concrete mixtures. Non-uniform distribution can cause weak zones with just a few fibers or even none. On the other hand, if fiber content is very high or fibers are too large, during concrete casting they can easily group into fiber balls and form areas only filled with fibers and air. Purpose of this work is experimental investigation of steel fiber distribution in concrete with impact resonance method (IRM) [1] in order to assess casting defects such as fiber segregation, non-uniform distribution of fibers or different kind of cracks. The IRM is based on determination of resonant frequencies of vibration on specimens excited by impact hammer. Experimental tests are performed on steel fiber reinforced concrete (SFRC) prismatic specimens of different concrete mixtures and with cracks known in advance. Additionally, possible internal cracks and other defects in SFRC mixtures are explored. Prior to testing, SFRC prisms are exposed to x-rays in order to validate reliability of test results. By use of discrete Fourier transform, acceleration in time domain is transformed into frequency domain. Further, resonant frequencies are determined as frequency response peaks. From fundamental resonant frequency, dynamic modulus of elasticity of FRC is calculated according to standards ASTM C215 [2] and EN 14146 [3]. Based on the reduction of dynamic modulus of elasticity and change of frequency response curve some conclusions about local damage or defects are made. Smaller defects (e.g. air voids, inhomogeneity) are indicated with change in frequency response curve shape, while larger defects (such as cracks) are indicated with reduction in resonant frequency, and consequently reduced dynamic modulus. Further, with softer impact hammer tip smaller defects and voids can be detected. On the contrary, stiffer tip is more convenient for detection of local failures. These conclusions are verified with x-ray scans of SFRC prisms.

References

[1] V.M. Malhotra, N.J. Carino. *Handbook on Nondestructive Testing of Concrete*. 2nd edition, CRC Press, Boca Raton, 2004.

[2] ASTM C125: Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens, 2002.

[3] EN 14146: Natural Stone Test Methods - Determination of the Dynamic Modulus of Elasticity (by Measuring the Fundamental Resonance Frequency), 2004.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Computational Strength Analysis of Closed-cell Aluminium Foam

Miran ULBIN[*], Janez KRAMBERGER[*], Matej VESENJAK[*], Isabel DUARTE[+], Srečko GLODEŽ[*], Zoran REN[*]

[*]*University of Maribor, Faculty of Mechanical Engineering, Maribor, Slovenia*
E-mails: {miran.ulbin, janez.kramberger, branko.necemer, matej.vesenjak, srecko.glodez, zoran.ren}@um.si

[+]*Department of Mechanical Engineering, University of Aveiro, Aveiro, Portugal*
E-mail: isabel.duarte@ua.pt

Abstract

Metal foams [1] are investigated for using in several applications, such as light-weight structures, energy absorption applications and thermal management. One approach is by the computational simulations, which are usually more cost effective methods compared to experimental testing. Metal foams are usually non-homogenous materials [2], since the pores are commonly randomly positioned and are different in shape and size throughout the base material. The base CAD model of such advanced geometrical material is often obtained by the micro computed tomography (μCT) scanning. The CAD model is then transformed to a volumetric model, where each voxel could then be converted to a discretisation element. Building a computational model can thus be quite challenging, often resulting in numerical models with huge number of finite elements, which are very difficult to process. In some cases, it is possible to create the 2D models for plane symmetry problems [3]. In the presented work, the computational model of the closed-cell aluminium foam was created by means of a reverse engineering methodology, rather than creating the model directly from the μCT-scan. The μCT images were first analysed by own developed methodology to obtain basic geometrical features [4]. The computational model was then built by applying random positioning of the equivalent spherical pores in the representative volume with retaining the same geometrical features (porosity, size and number of pores). The model was used for nonlinear computational analysis of the stress-strain state of the metal foam, when subjected to tensile loading.

References

[1] M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley. *Metal Foams: A Design Guide*. Butterworth-Heinemann, Woburn, 2000.

[2] I. Duarte, M. Vesenjak, L. Krstulović-Opara. Variation of Quasi-static and Dynamic Compressive Properties in a Single Aluminium Foam Block. *Materials Science and Engineering: A*, 616: 171-182, 2014.

[3] J. Kramberger, M. Šori, M. Šraml, S. Glodež. Multiaxial Low-cycle Fatigue Modelling of Lotus-type Porous Structures. *Engineering Fracture Mechanics*, 174: 215-226, 2017.

[4] M. Ulbin, M. Borovinšek, Y. Higa, K. Shimojima, M. Vesenjak, Z. Ren. Internal Structure Characterization of AlSi7 and AlSi10 Advanced Pore Morphology (APM) Foam Elements. *Materials Letters*, 136: 416-419, 2014.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

The Pian-Sumihara Element and its Extension to Hyperelasticity – Basic Ideas

Nils VIEBAHN, Jörg SCHRÖDER

[*]University of Duisburg-Essen, Institute of Mechanics, Department of Civil Engineering, Universitätsstrasse 15, D-45141 Essen, Germany
E-mails: {nils.viebahn, j.schroeder}@uni-due.de

Abstract

Non-mixed finite element formulations are not sufficient in the case of highly constrained material properties. In the situation of (nearly) incompressibility the ensuing deficiencies, as for example stress oscillations and hourglassing modes, have been analyzed in the last decades and are now well understood. In the framework of linear elasticity, a variety of mixed finite element formulations are nowadays available, which are well suited for the incompressible regime. In this framework the formulation proposed by Pian and Sumihara [1] is still one of most efficient formulations available. This mixed finite element is based on Hellinger-Reissner principle. Unfortunately, due to the use of a complementary energy, the formulation is only available in the linear elastic case and very special and limited cases of nonlinear elasticity [2]. In this work we will propose some basic ideas on the extension of the Pian-Sumihara element into a general hyperelastic framework. It will be shown that, depending on the choice of your interpolating stress-quantity, hourglass modes may occur and stabilization is necessary.

References

[1] T.H.H. Pian, K. Sumihara. Rational Approach for Assumed Stress Finite Elements. *International Journal for Numerical Methods in Engineering*, 20(9): 1685-1695, 1984.

[2] P. Wriggers. Mixed Finite Element Methods - Theory and Discretization. In: C. Carstensen, P. Wriggers, eds., Mixed Finite Element Technologies, 131-177. CISM Courses and Lectures, vol 509, Springer, Vienna, 2009.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

Finite-discrete Element Modelling of Spatial Reinforced Concrete Structures

Nikolina ŽIVALJIĆ, Željana NIKOLIĆ, Hrvoje SMOLJANOVIĆ

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Matice hrvatske 15, HR-21000 Split, Croatia
E-mails: {nikolina.zivaljic, zeljana.nikolic, hrvoje.smoljanovic}@gradst.hr

Abstract

Monitoring of the behaviour of the structure before and after the failure, including the transition from continuum to discontinuum, is very important in the modelling of the load capacity and collapse of reinforced concrete structures subjected to extreme loads. Numerical model presented in this paper was developed with the aim of modelling and monitoring the behaviour of reinforced concrete spatial structures exposed to static and dynamic loads. The model is based on combined finite-discrete element method (FDEM) [1] which has become an excellent tool to address a wide range of problems involving fracturing and fragmentation of solids. In presented numerical model, four-node tetrahedron finite elements of concrete and two-node finite elements of reinforcing bar are used to model the behaviour of the material up to the cracking of concrete. Fracture and fragmentation as well as material nonlinearity are described with contact elements for concrete and contact element for reinforcing bars which are implemented within the finite element mesh. The continuity between the reinforcing bar finite elements and concrete tetrahedron finite elements in the pre-failure stage is ensured through the penalty method. The model, implicates few numerical algorithms which are based on approximation of the experimental curves for material behaviour of the concrete and steel and are important for description of main non-linear effects in reinforced concrete structures [2]. Verification and validation of the presented model are shown in several examples.

Acknowledgement: This work has been fully supported by Croatian Science Foundation under the project *Development of numerical models for reinforced-concrete and stone masonry structures under seismic loading based on discrete cracks* (IP-2014-09-2319).

References

[1] A. Munjiza. *The Combined Finite-discrete Element Method*. John Wiley & Sons, Chichester, 2004.

[2] N. Živaljić, H. Smoljanović, Ž. Nikolić. A Combined Finite-discrete Element Model for RC Structures under Dynamic Loading. *Engineering Computations*, 30(7): 982-1010, 2013.

9th International Congress of Croatian Society of Mechanics
18 - 22 September 2018
Split, Croatia

On a Gradient Based Transversely Isotropic Damage Model for Laminated Composite Structures

Werner WAGNER, Jonas LÄUFER

Karlsruhe Institute of Technology, Institute for Structural Analysis,
Kaiserstrasse 12, D-76131 Karlsruhe, Germany
E-mails: {w.wagner, jonas.laeufer}@kit.edu

Abstract

In order to reduce weight and to create efficient constructions fibre reinforced plastics (FRP) are of general interest. In comparison to classical materials, which basically have isotropic properties, a single FRP layer with unidirectional oriented fibres behaves transversely isotropic. FRP laminates consist of several layers with different orientation angles. Having in mind the failure behaviour maximum utilization of the material is possible. Furthermore, the post-failure behaviour may be of special interest because some failure types even allow an increase in load. Failure can be classified into different failure modes, e.g. fibre failure and inter fibre failure. Classical failure criteria, like Hashin or Puck criteria [1] are developed to determine the occurrence and specific type of damage. They do not consider the whole laminate at once but the single layers. Furthermore, degradation models are used to simulate the loss of material stiffness. These damage models allow the description of the failure process in a structure, including the failure criteria and the degradation model. Using finite element techniques to simulate the damage process, classical damage models usually show strong mesh dependence due to localization effects. This mesh dependence is characterized by a stress concentration which results in the occurrence of the damage only in a small area. The area generally corresponds with an element row and thus with the mesh refinement. In order to develop a regularized damage model for transversely isotropic materials a gradient enhancement method based on the Helmholtz free energy function is used [2, 3]. With the introduction of a new variable field, coupled with the inelastic variables, the model gets a non-local character. Furthermore, a gradient enhancement for transversely isotropic damage in laminated materials is shown. The damage model is integrated in the layered theory. This includes the consideration of the single layer with enhanced damage and the stacking of the gradient enhanced model. Finally, the influence of the regularized damage model on the mesh-dependence of the results of FE calculations is shown via examples. As a consequence, a comparison of the non-regularized and the enhanced damage model is presented.

References

[1] A. Puck, H. Schürmann. Failure Analysis of FRP Laminates by Means of Physically Based Phenomenological Models. *Composites Science and Technology*, 62(12-13): 1633-1662, 2002.

[2] B.J. Dimitrijevic, K. Hackl. A Method for Gradient Enhancement of Continuum Damage Models. *Technische Mechanik*, 28(1): 43-52, 2008.

[3] J. Läufer, V. Becker, W. Wagner. Gradient Enhancement of a Transversely Isotropic Continuum Damage Model. *Composite Structures*, 181: 138-144, 2017.

Author Index

ISSN 2584-7716