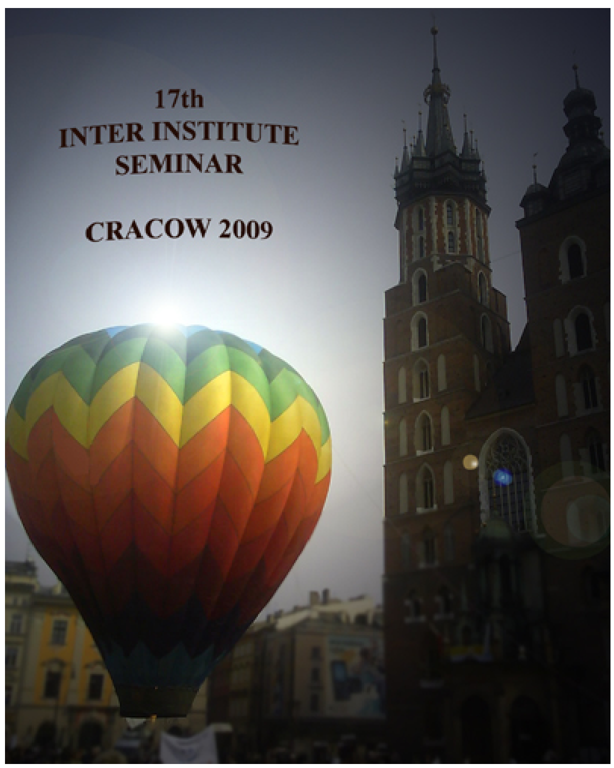
Cracow University of Technology
Institute for Computational Civil Engineering

Budapest University of Technology and Economics
Department of Structural Mechanics

Vienna University of Technology
Institute for Strength of Materials

17th Inter-Institute Seminar for Young Researchers



May 22-23, 2009, Kraków, Poland

Program

Abstracts

List of Participants

Organizing Committee:

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Time Schedule of the Seminar

Friday, May 22, 2009	Main building, room 310

9.00 - 9.35	Keynote lecture
9.35 - 10.50	Session (1)
10.50 - 11.10	Coffee break
11.10 - 12.50	Session (2)
13.00 - 13.50	Lunch (University canteen)
14.00 - 14.35	Keynote lecture
14.35 - 15.25	Session (3)
15.25 - 15.40	Coffee break
15.40 - 16.55	Session (4)
19.30 -	Banquet (Restaurant "Pod Wawelem", Św. Gertrudy 26)

Saturday, May 23, 2009	WIEiK building, room 414

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11.10 - 12.50	Session (6)
12.50 - 13.00	Final Discussion and Closure of the Seminar
13.00 - 14.00	Lunch (University canteen)

Program

Friday, May 22, 2009

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ABSTRACTS

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THE MECHANICAL MODEL OF A MATHEMATICAL COVERING PROBLEM

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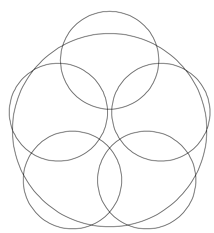
KEYWORDS: covering, cable, strut and triangular elements, large displacements, equilibrium paths

Connelly [1] posed a problem: How must the centres of *n* equal discs of given radius *r* be distributed in the unit circle so that, in the unit circle, the area covered by the discs will be a maximum? He considered the case of $n = 5$ as an example (see the figure), and wanted to know that, with a continuous increase in *r*, how the disc configuration changes in the transition from packing to complete covering. If *r* is only a little larger than the maximum packing radius then the discs have double overlaps (pairwise intersections). In such a case, the motion of the discs can be described as a function of a parameter, and the derivative of the area with respect to the motion parameter can be expressed with a formula of Csikós [2]. Connelly has provided a stress interpretation of Csikós's formula, and shown how a tensegrity framework can be associated to the maximum area configuration. However, if *r* is close to the minimum covering radius, then the discs have some triple overlaps for which Csikós's formula does not work, and it is not known how to set up an equivalent mechanical model to obtain the solution to the mathematical problem.



In this paper, we introduce triangular elements to model the triple overlaps of the circles. Edge forces of these elements can be calculated as functions of the coordinates of the vertices of the triangles. In the case of the optimum arrangement for a given *r*, the structure composed of cables, struts and in-plane loaded plates is in a state of self-stress. It is problematical, however, that in certain intervals, more states of self-stress can occur. First, changing the value of *r* in small steps in the investigated interval, we used the method of dynamic relaxation. At each step, the position obtained in the previous step is considered as the starting position. The symmetry properties of the solutions obtained in this way subdivided the investigated interval into several segments, but the end points of the segments cannot be exactly determined with this method. The stiffness matrix of the elements and that of the structure, however, can be constructed, by the help of which the locus and type of the points of bifurcation as well as the complete system of the equilibrium paths can be determined.

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ZERO-STIFFNESS POSTBUCKLING: A BORDERLINE CASE

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KEYWORDS: postbuckling analysis, zero-stiffness, imperfection sensitivity

Zero-stiffness postbuckling of a perfect structure is characterized by a secondary load-displacement path along which the load remains constant. In sensitivity analysis of the initial postbuckling behavior, it is considered to be a borderline case between imperfection sensitivity and imperfection insensitivity [1]. However, it is unclear whether zero-stiffness postbuckling as such is imperfection sensitive or insensitive. Attempting to remove this lack of clarity, Koiter's postbuckling analysis is used as a tool for sensitivity analysis based on the variation of a design parameter [2]. A disadvantage of this mode of analysis is the requirement to compute, at least in principle, infinitely many coefficients of a Taylor series of the load parameter $\lambda(\eta)$ where η denotes a path parameter, showing that all coefficients of this series are zero. This would render zero-stiffness postbuckling unpredictable [1]. It becomes predictable, however, e.g. for relatively simple problems that can be solved analytically. In the course of two sensitivity analyses, one design parameter each is varied. The potential energy along the zero-stiffness postbuckling path is found to be constant. Since this path represents a local minimum of the potential energy, the path is stable. Applying a small imperfection to the perfect structure, it is shown that the load-displacement path of the imperfect structure, corresponding to zero-stiffness postbuckling of the perfect strucuture, is monotonically increasing. On the basis of a comprehensive numerical investigation consisting of a variation of the imperfection, it is concluded that zero-stiffness postbuckling of the perfect structure implies imperfection insensitivity.

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BRIDGE FLUTTER ASSESSMENT WITH THREE-DIMENSIONAL FLUID-STRUCTURE INTERACTION SIMULATION

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KEYWORDS: FEM, CFD, three-dimensional dynamic response, fluid-structure interaction

In bridge designing practice, calculation of the wind loading on an arbitrary structure is always a difficult problem. In simpler cases, good approaches are offered by codes and standards [1] but if we consider a more complex structure, regularly wind tunnel tests are to be undertaken [2]. The main requested data are the force coefficients. In case of a very flexible structure, the critical wind speed is the most valuable information, at which the structure vibrates. During the design process, measures must be done against unpleasant motions of the structure.

Nowadays, with the widely used softwares aimed at advanced coupled fluid-structure simulation, there is a possibility to substitute the really expensive and tedious wind tunnel tests. Nevertheless, it is really challenging to validate these softwares in modelling really complex phenomena like a bridge flutter.

Our main goal is to assess a bridge structure due to wind loading with computational simulation. We want to involve the dynamic properties of the structure, the shape of the structure and the wind flow around the bridge. This approach assumes a fluid-structure interaction simulation of the whole system. For this purpose, we used the Ansys commercial software in case of a suspension bridge.

In the coupled analysis the FEM model of the bridge must be built up at first. This include the stiffness, mass and damping properties as well as the time step for the numerical integration process. Secondly the numerical grid must be created around the bridge body for the flow simulation. During the simulation process, at every single time step, the fluid flow around the bridge must be solved and the distributed pressure is desired to calculate the structural deformation.

Despite the impressive results of our three dimensional simulation, we need to survey the bridge by using simpler models for the better understanding of this really complex phenomenon. Usually, flutter assessement is carried out by solving a differential equation with two degrees of freedom which requires the so called aerodynamic derivatives. These derivatives are usually extracted with wind tunnel tests. In a series of two dimensional fluid-structure interaction simulation, we determined the aerodynamic derivatives in case of several bridge shapes. If we consider a simple flat plate, theoretical values are available, so entire comparison can be made. We found great coincidence between theoretical and numerical values. By calculating numerically the aerodynamic derivatives, ordinary structures can be investigated relatively easily, and a more detailed three-dimensional coupled simulation can also be controlled.

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DAMAGAE IDENTIFICATION OF CIVIL INFRASTRUCTURES WITH ARRAY SENSING UNDER LOCAL EXCITATION

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KEYWORDS: damage identification, frequency response function, steel bridge

In the recent years the interest in the structural health monitoring of highway bridges using damage identification techniques has been increasing. Developing the vibration-based damage detection theories and practices are necessary because of growing amount of aging bridges with risk of deterioration, serious failure or even collapsing. The research in the field of SHM aims to detect structural damage directly from frequency response functions or dynamic response measurements in the time domain. One of the algorithms used to detect damages, locate its position and monitor the increase of breaks using only measured data in the experiment is one based on changes in Power Spectral Density (PSD).

The aforementioned method was applied to the data obtained in the experiment on the steel bridge on an abolished railway in Japan. As an exchange student I had an opportunity to take part in that research in Kitami Institute of Technology in Hokkaido. The bridge model consisting of 2 main girders (I beams) and 4 cross beams (channels) was supported on two wooden blocks without fixation. It was equipped with 2 actuators and 14 accelerometers aligned in the horizontal direction.

The excitation force was directed horizontally with the sine sweep wave form, amplitude of 30Kgf, frequency 1-700 Hz and sampling rate 1600 Hz. Afterward the resonant frequencies with the highest magnitude at each channel located on the web were selected and used to excite the structure with the sampling rate 1600 Hz. The damages were introduced to the structure in 3 different places and each one was deepen twice. Sensor and damage location are shown in Fig.1.

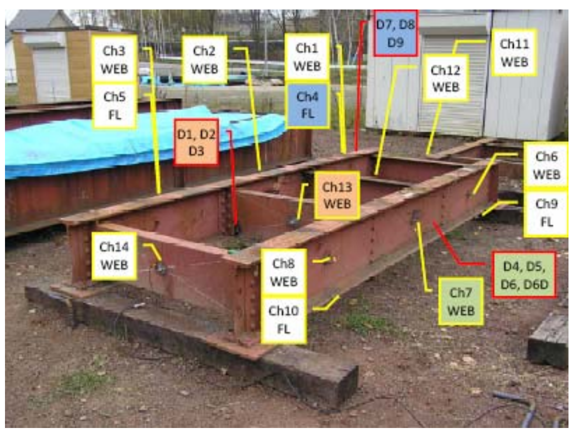

Fig.1. Sensor and damage location

The collected data in the experiment was analyzed using damage indicator and total changes in PSD. The results indicate that the information of damage existence is getting more accurate with the growth of the damage. However, by array measurement it is possible to receive clear information about defect even in case of the small one. Decision of the distribution of sensors in the suspected areas of the structure is very important. Using array distribution we can increase accuracy of the damage indication.

STOCHASTICALLY GENERATED FINITE ELEMENT BEAM MODEL FOR DENTAL RESEARCH

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KEYWORDS: Dental research, Bone mechanics, Trabecular bone, Finite element analysis

Dental implantation is currently the most commonly used and physiologically the most favourable procedure for tooth replacement in dental surgery. Implants can have either advantageous or destructive effect on the surrounding bone, depending on several physiological, material and mechanical factors. In the light of this, implants should be applied, that transfer occlusal forces to bone within physiologic limits and have geometry capable to enhance bone formation. To this, stress and strain distributions around different types of dental implants need to be assessed.

The most general method for estimating the biomechanical behaviour of the bone is Finite Element Analysis. In the aspect of oral implantation in the upper- and lower-jawbones the finite element models reported so far consider the trabecular bone substance as a continuum. The microstructural conformation of the trabecular bone – which can be modelled by the means of converting computed tomography images into micro finite element models or in a stochastic way – influences the overall mechanical properties of the bone tissue. Several microstructural models have been developed for simulating the mechanical behaviour of different types of bones in the human skeleton, usually for simulating the effect of bone diseases – such as osteoporosis – on the mechanical properties of the bone. In the majority of cases the models are from the vertebral or the femoral bone substance and not from the mandible or maxilla and include no implants in or cortical layer around the examined trabecular bone. In these models the micro-computed tomography images (3D high resolution images) are transformed into a finite element model by the means of different methods. The 3D reconstruction can be directly transformed into an equally shaped micro finite element model by converting all voxels to equally sized 8-node brick elements. The need of high computational capacity and time resulting from the large number of elements in models using volume elements can be reduced by creating frame models, in which each trabecula is represented by one beam element.

To avoid the use of computer tomography imaging and to create a repeatable and variable finite element model, a stochastically generated beam structure was accomplished that possesses the geometrical and mechanical microstructural properties – obtained from literature – of the trabecular bone substance of an average man from the edentulous mandibular region. The finite element beam model was submitted to compression tests, and the macro-structural elastic properties were computed from the result data obtained by the means of Finite Element Analysis. Several attempts have been made to achieve the possibly most accurate elastic properties. Considering the shell behaviour of the trabeculae by dividing each beam into three parts with different elastic properties proved to be the most effective and the most suitable for further investigations, in which the stability and the elastic properties of the thus received model are tested under other types of loading and with various boundary conditions and the finite element frame model of the trabecular bone is combined with screw type dental implants.

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A VISCO-ELASTIC MYOSIN MODEL

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KEYWORDS: Motor protein, actin filament, myosin, lever arm, motor domain

Motor proteins are special enzymes capable of transforming chemical energy into mechanical work. One of the best known motor proteins is the (super)family of myosins which can be found in eukaryotic tissues. The most studied – and first discovered – type of myosin is the skeletal muscle myosin which is the motor protein responsible for the contraction of muscle tissue. Many models have been proposed for understanding the complicated behavior of this enzyme. Most of them use a description based on the existence of different discrete chemical states with different transition rates between them. These transition rates give the probability of chemical changes from one state to another, and in case of a system of many molecules, they give the speed of the reaction. The motivation of this study is the perception that every model requires an arbitrary selection between hypotetical states, which make their domain of validity quite ambigous. In the present study we propose a model of rigid bodies linked with springs and dashpots, leading to a continous model where the states are not strictly determined. The model provides exponential time-displacement curves which can be fitted to the exponential curves of experimental time-concentration mesurements. Based on the comparison with experimental data the validity of our model can be justified, which could give a good estimation of the rigidity of the complicated molecular subdomains of the myosin molecule. As the model is based on the significant difference of two spring's rigidity, which is responsible for the sequence of supsteps of the motion (binding to actin vs. lever arm swinging), further investigations can be made – by variation of this proportion and the refinement of other parameters- for application to other members of the myosin family.

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NUMERICAL ANALYSIS OF HUMAN BRAIN ANEURYSMS

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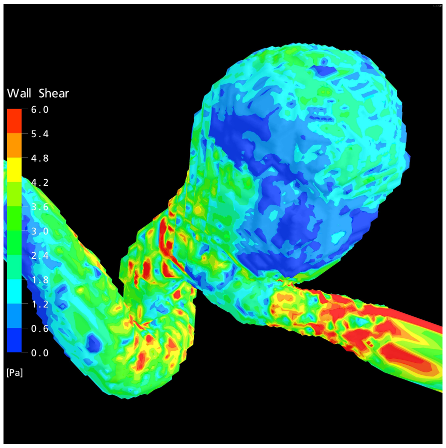
KEYWORDS: FSI, FEM, CFD, aneurysm



This letter describes the algorithms used in a software system for performing biomechanical analysis of blood vessels using finite-element methods from 3D angiographic images. The purpose of this software is the following:

- Calculate the time-dependent speed distribution brought about by the pulsating blood flow by haemo-dynamic analysis in the particular part of the vessel and in this way it draws attention to the existence of vortices and turbulent regions. Viewing the blood-flow data, the model can define the pressure and shear stress as an effect on the vessel wall.

- With the help of the loads acting on the wall resulting from the flood analysis the model carries out the static analysis of the vessel wall. By means of the available material parameters it gives an estimation of dislocations. Strains and internal stresses of the layered wall-structured part of the vessel are indicating the places of stress concentrations. That is the vessel parts, which are immensely susceptible for rupture: a damage in the vessel wall causing rupture.

The main processing steps performed by our software system:

- data transfer from the acquisition system;
- 3D finite element model based on the 3D angiography image;
- haemodynamic analysis taking into account the pulsating blood flow;
- strength analysis of artery walls taking into account the blood pressure and shear stresses;
- transfer of the results of the haemodynamic and strength analysis;

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Experimentally validated micromechanical model for elasticity and strength of hydroxyapatite biomaterials

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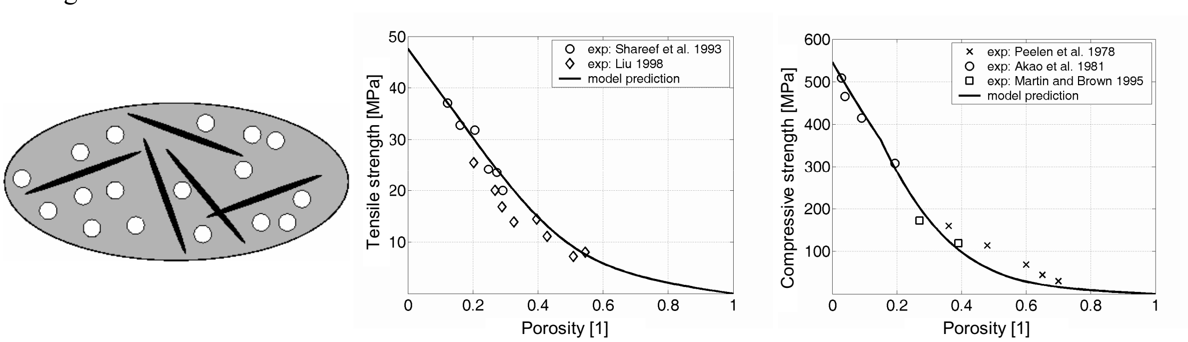
KEYWORDS: biomaterials, hydroxyapatite, continuum micromechanics, elasticity, strength

Hydroxyapatite biomaterials production has been a major field in biomaterials science and biomechanical engineering. As concerns prediction of their stiffness and strength, we propose to go beyond statistical correlations with porosity or empirical structure-property relationships, as to resolve the material-immanent microstructures governing the overall mechanical behaviour. The macroscopic mechanical properties are estimated from the microstructures of the materials and their composition, in a homogenization process based on continuum micromechanics. Thereby, biomaterials are envisioned as porous polycrystals consisting of hydroxyapatite needles and spherical pores. Validation of respective micromechanical models relies on two independent experimental sets: Biomaterial-specific macroscopic (homogenized) stiffness and uniaxial (tensile and compressive) strength predicted from biomaterial-specific porosities, on the basis of biomaterial-independent ('universal') elastic and strength properties of hydroxyapatite, are compared to corresponding biomaterial-specific experimentally determined (acoustic and mechanical) stiffness and strength values. The good agreement between model predictions and the corresponding experiments underlines the potential of micromechanical modeling in improving biomaterial design, through optimization of key parameters such as porosities or geometries of microstructures, in order to reach desired values for biomaterial stiffness or strength.



(a) (b) (c)

Fig. 1(a): Representative volume element of a porous biomaterial made of hydroxyapatite; Comparison between model predictions and experiments for uniaxial (b) tensile and (c) compressive strength of different porous biomaterials, as function of porosity. (Source: A. Fritsch, L. Dormieux, Ch. Hellmich, J. Sanahuja: *J Biomed Mat Res A, 88A, 149-161, 2009*.)

A-POSTERIORI ERROR ESTIMATES FOR APPROXIMATION BY SELECTED COMPUTER METHODS

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KEYWORDS: approximation error estimates, computer methods

Approximation error estimates enable assessing accuracy of numerical solutions and may be used to drive adaptive mesh refinements. Thus, they contribute to robustness and efficiency of the computer methods.

We will focus on a model elliptic problem that will be formulated in various ways i.e. as a direct statement of a balance principle, as a system of partial differential equations or a variational principle, including the mixed approach as well as by the boundary integral equations in a strong and weak forms.

These formulations are basis of the well known solution approximations by the Finite Volume, Finite Difference, Finite Element and Boundary Element Methods. A-posteriori error estimates, theirs reliability and example applications will be presented for the aforementioned methods.

The following error estimates will be discusses briefly: heuristic two-grid (Runge) method, post-processing based (Zienkiewicz-Zhu) approach, explicit and implicit residual estimates, interpolation error assessment. Generally these approaches enable assessing global error norms. However, an appropriate modification turns these techniques into, valuable from practical point of view, goal-oriented error estimates.

The presentation is based on works by Answorth and Oden [1], Babuska [2], Steward and Hughes [5], Verfurth [6], Gratsch and Bathe [4] as well as on the own experience[3].

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GLOBAL FORMULATIONS OF THE MULTIPOINT MESHLESS FDM

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KEYWORDS: multipoint approach, higher order approximation, meshless finite difference method

The work presents a significant modification and extension of the original multipoint FD method proposed by L. Collatz [2] more then fifty years ago, and forgotten since then. The multipoint concept is based on raising the order of approximation of the unknown function u by introducing additional degrees of freedom in the star nodes, taking into account e.g. the right hand side of the considered differential equation or any required operator. It improves the FD solution without increasing the number of nodes in the mesh. Two basic versions of the Multipoint MFDM – general and specific are consider here.

For the purpose of high order approximation [4] this multipoint meshless method is based on the MWLS technique [3] instead of the polynomial interpolation, proposed by Collatz [2]. Moreover unstructured, totally irregular meshes may be used here.

Besides development of the MMFDM for analysis of b.v. problems given in the local (strong) formulation, the multipoint method was also extended to the global formulations. In this research, for the first time, appropriate algorithms and corresponding software were developed. Various chosen 1D and 2D variants of the method were tested as well as compared with the corresponding results obtained for the weak formulations. Taken into account were some versions of the global formulation including the variational Galerkin, local Petrov-Galerkin (MLPG), and minimum of the total potential energy. The main objective of this research is to show that multipoint approach to b.v. problems, given in the global formulation, is practically possible and it may provide valuable results.

Preliminary tests of application of the new multipoint method in the b.v. problems globally formulated were carried out. Tested were applications of the MMFDM in the Galerkin formulations as well as in the MLPG5 [1], and in minimization of the potential energy functional. A variety of 1D and 2D tests done show that the new MMFDM may be a useful solution tool for analysis of b.v. problems globally formulated in a similar way, like it was demonstrated before [5, 6] for the local formulation. Numerical results obtained for both formulations are closed enough. Further research is planned.

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HIGHER ORDER A'POSTERIORI ERROR ANALYSIS IN THE MESHLESS FINITE DIFFERENCE METHOD – STATE OF THE ART

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KEYWORDS: a'posteriori error analysis, higher order approximation, meshless methods

Recent advances in the Higher Order approximation ([2,3]) in the Meshless Finite Difference Method MFDM are presented. MFDM is based on arbitrarily irregular clouds of nodes, and the MWLS approximation [2]. It belongs to the wide class of the so called meshless methods [1,2], which are strongly developed nowadays. The MFDM being in fact the oldest, and therefore, one of the most developed meshless methods, is one of the basic tools for analysis of boundary value problems nowadays.
Expansion of the unknown function u into the Taylor series, used in the MWLS approach, produces additional higher order correction terms Δ [3]. Those terms include HO derivatives, that may be calculated using appropriate formulae composition inside the domain, as well as singularities, and jump terms of the function u, and / or its derivatives. Correction terms modify the right hand sides f of the MFD equations. The final HO solution $u^{(H)}$ depends only on the truncation error of the Taylor series. The whole solution process needs only two steps, both using the same MFD operator L. Thus the order of local approximation of u is raised without introducing new nodes into the MFD operator L.
Special emphasis is laid upon improved a'posteriori error estimation [2,3], where the HO terms may be used in several ways. Examination of the local solution error e or the local residual error r at specially chosen points of the domain is considered. Error estimation may use the HO terms: for both the solution error $e \approx u^{(H)} - u$ and the residual error $r \approx Lu^{(H)} - \Delta - f$. Especially, the improved residual error estimation r is worth stressing and may be applied in the error based generation criteria of the new clouds of nodes, during the *h*-adaptation process. Additionally, it uses the multigrid [1] solution approach, which allows reducing the calculation time on a set of arbitrarily irregular cloud of nodes.
Various integral type error estimators are used in the Finite Element Method, e.g. hierarchic or smoothing $\|e\|$ as well as residual type - $\|r\|$, where $\|\cdot\|$ denotes appropriate integral norm. HO approximation done here by means of the HO correction terms, provides the superior quality estimation of the exact solution, when compared to those widely used in the FEM.
Very promising results were observed after execution of variety of 1D and 2D benchmark tests, as well as selected engineering problems, using the HO approximation approach. Recent research is focused on HO discretization of various b.v. problems formulations, especially the Meshless Petrov-Galerkin ones [1]. Future research plans include error estimation analysis of the large boundary value problems, as well as development of a special mesh generator, based on the mesh density control, the HO terms and the multigrid approach.

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CONTINUUM MICROMECHANICS BASED MULTISCALE MODEL FOR ASPHALT – APPLICATION TO STRUCTURAL SAFETY ASSESSMENT OF FLEXIBLE PAVEMENTS

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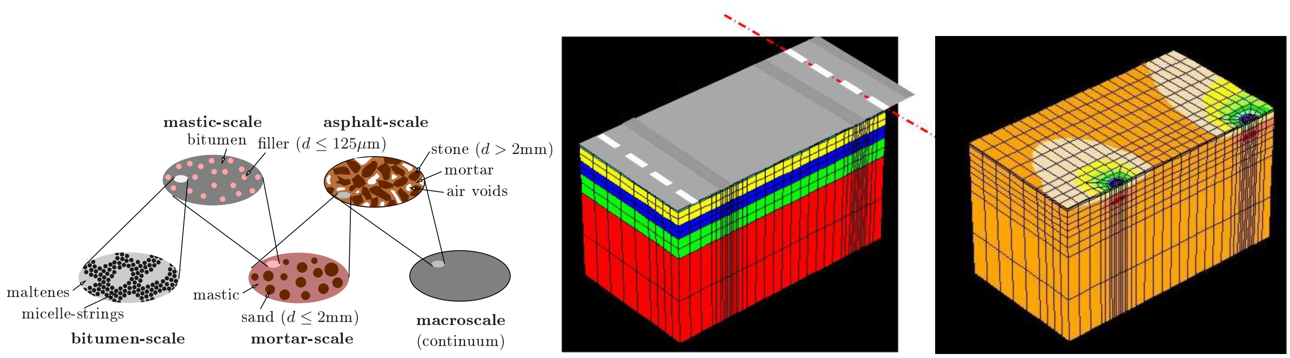
KEYWORDS: multiscale model, continuum micromechanics, creep, asphalt concrete, finite element model

The macroscopic behaviour of bituminous mixtures is defined by the underlying material phases, namely aggregates, air, and bitumen. In order to assess and finally optimize the performance of bituminous materials, a multiscale framework of material description is proposed (see Figure 1(a)), allowing us to relate the material properties at the structural scale (macroscale) to finer-scale characteristics such as material composition and behavior of the constituents [1]. Upscaling of viscoelastic properties is performed in the framework of continuum micromechanics, making use of the so-called ”correspondence principle” [2] relating the elastic parameters, present in well known homogenization schemes, to viscoelastic parameters (namely the creep compliance function J(t)) in the Laplace-Carson space. Hereby, the viscoelastic properties which can be described by a fractional dash-pot, are assigned to the matrix via the initial creep compliance rate and the exponent of the fractional dash-pot whereas elastic material behavior is assssigned to the inclusions. The viscous properties of bitumen and bituminous mixtures are characterized by means of static and cyclic loading experiments on bituminous samples at different length scales, providing access to the material response at different temperature and cyclic-loading regimes.

Via upscaling, the presented multiscale model provides access to the viscous properties of asphalt concrete as a function of the mix design, serving as input for a numerical analysis tool for the performance assessment of flexible pavements (see Figure 1(b)). Respective results obtained from recent applications of this analysis tool to pavements subjected to combined thermal and traffic loading will be presented.



(a) (b)

Figure 1: (a) Multiscale model for asphalt and (b) numerical assessment of flexible pavamanets

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NUMERICAL HOMOGENIZATION BY $hp-$ADAPTIVE FINITE ELEMENT METHOD

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KEYWORDS: adaptive finite element method, homogenization, multiscale modeling

Modeling of heterogeneous materials, especially beyond the elastic range, results in very time consuming computations. The direct analysis, that would take into account all the details of heterogeneous domain and behavior of the material components, is extremely difficult and would require an enormous computer cost. Thus, the computer homogenization technique [2, 3] and up to date numerical methods are employed to replace the heterogeneous structure by, in a sense, equivalent body with effective material parameters. The $hp-$adaptive FEM is used to improve efficiency and reliability of such an analysis.

Two-scale approach is applied for periodic metal matrix composites. We present application of the adaptive discretization at both scales. At the micro-scale special attention has to be paid to error estimation. At macro-scale each adaptive mesh refinement introduces new Gauss points (3D *representative volume elements* RVE), so certain history-depended micro-quantities have to be transfered to new meshes, what is a particularly demanding task. Thus, we use a fixed set of points that are attributed to RVE. A rough initial elastic analysis of the whole loading history, based on only one RVE is used to predict the optimal positions of the RVEs. Such an approach slightly enhanced convergence of the 1D results.

Properties of metal matrix composites reinforced with metallic inclusions with different shapes (balls, fibers etc.) were modeled by 3D analysis. The adaptation process was driven by mesh optimization presented in [1]. A faster reduction of approximation error for adaptively refined meshes was observed. We compared effective parameters obtained by analysis with adaptively refined meshes that initially either accounted for material distribution of heterogeneous microstructure or not. Some results were compared with numerical as well as experimental tests presented in [4]. The coincidence is very good.

Certain initial tests that account for inelastic deformations will be also presented.

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Numerical multi-scale simulation strategy for fracture in quasi-brittle heterogeneous materials

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KEYWORDS: Multi-grid method, Hybrid Trefftz Method, Quasi-brittle Material

Multi-scale analysis aims to predict the macroscopic constitutive behaviour of materials with heterogeneous microstructures. Homogenization of the microscale constitutive response can be undertaken analytically or computationally, whereby effective continuum material properties are obtained via averaging of the constitutive behaviour on the finer scale, utilising a representative volume element (RVE). However, there is a strong connection between material instabilities on the fine-scale and loss of ellipticity of the governing PDE at the coarse-scale. Fine-scale instabilities such as nucleation and propagation of cracks may induce coarse-scale instability phenomena in the form of strong or weak discontinuities. Loss of ellipticity at the coarse scale, whereby zero thickness localization bands may be created, imply no separation of scales and it is no longer possible to define an RVE. In such situations, analysis of the fully resolved heterogeneous microstructure is required and this results in a very large system of algebraic equations that needs to be solved efficiently. Miehe and Bayreuther [1] have developed a numerical multi-scale approach for problems involving poor scale separation using a multi-grid solution strategy that is inspired by the formulations, and in particular the scale transition techniques, of computational homogenization. This paper focuses on an extension of this work for the simulation of fracturing in quasi-brittle materials, such as concrete at the meso-level (1-10cm) of observation. Although the focus of attention is on concrete, the presented approach can also be applied for a range of problems with softening or fracturing materials.

The analysis of fracturing and softening phenomena in materials can typically be categorized into two main types: smeared and discrete. The former is attractive from the point of view that the problem can be solved within a continuum setting. However, as strain localization occurs, the governing equations become ill-posed, which causes numerical difficulties and requires regularization of the continuum model to overcome this. On the other hand, discrete approaches describe fractures in a more straightforward manner in terms of displacement jumps and tractions, rather than in terms of stresses and strains. In this paper a hybrid two-mesh (fine and coarse meshes) strategy is adopted. For the fine mesh, that fully resolves the heterogenous structure, the cohesive crack methodology is utilized and for the coarse mesh a non-local gradient approach is adopted.

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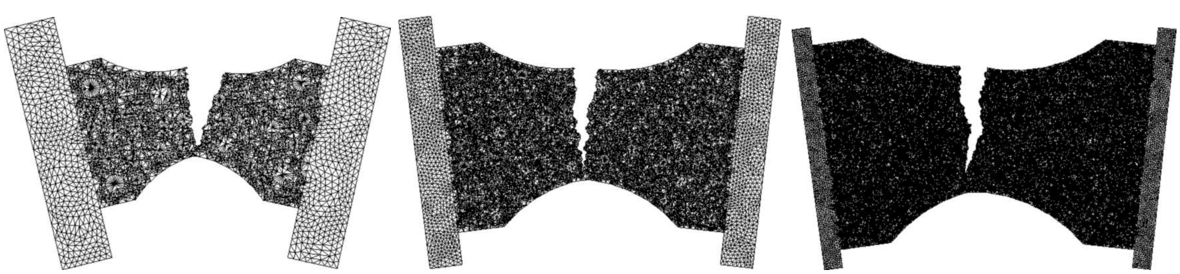

Figure 1: Deformation dog-bone, on the left 50mm, in the center 100mm and on the right 200mm. Displacement magnification x100.

STRENGTH EVOLUTION IN HYDRATING SHOTCRETE: FROM MICROMECHANICAL MODELING TO STRUCTURAL ANALYSES

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KEYWORDS: cement paste, sprayed concrete, elastic limit criterion, tunneling, structural sensitivity analyses

Early-age strength evolution of shotcrete (sprayed concrete) is studied in the framework of continuum micromechanics. This is the motivation for employing two separated representative volume elements (RVEs): One of them relates to cement paste with a spherical material phase representing clinker, needle-shaped hydrate phases with isotropically distributed spatial orientations, a spherical water phase, and a spherical air phase, with all phases being in mutual contact. The second RVE relates to shotcrete with a spherical aggregate phase, embedded into a matrix phase made up by cement paste. Elasticity homogenization follows (i) self-consistent schemes at the cement paste level and (ii) Mori-Tanaka estimates at the shotcrete level.

Stress peaks in the hydrates related to quasi-brittle material failure are estimated by second-order stress averages over hydrates, derived from the elastic energy stored in the RVE, see e.g. [1]. Inserting hydrate stress peaks into a microscopic elastic limit criterion permits upscaling from the hydrate strength to the strength of cement paste [3], and further up to the shotcrete strength [4]. Experimental data from resonant frequency tests, ultrasonics tests, adiabatic tests, uniaxial compression tests, and nanoindentation tests suggest that evolving elasticity and strength of hydrating shotcrete can be reasonably well predicted from mixture- and hydration-independent mechanical properties of aggregates, clinker, hydrates, water, and air, and from the strength properties of the hydrates [4].

The developed strength model is applied to structural simulations related to tunneling according to the New Austrian Tunneling Method. Knowledge of the stresses in shotcrete tunnel shells is of great importance for assessing their safety against severe cracking or failure. Tunnel shell stresses are estimated by means of so-called hybrid analyses [2] in which measurements of the 3D displacements of the real tunnel shell are prescribed as geometric boundary conditions for a Finite Element model in which the tunnel shell is discretized only. This way, the simulated shotcrete shell undergoes the same deformations as the real tunnel shell. Running hybrid analyses based on realistic material models for shotcrete allows tunnel engineers to look inside the tunnel shell: to compute stresses, and to compare them with the evolving strength of the shotcrete, rendering safety assessments possible.

Within the framework of hybrid analyses, it is beneficial that micromechanics-based material models for shotcrete are capable to account for variations of the water-cement and the aggregate-cement ratio without raising the need for parameter identification. This way, structural sensitivity analyses become possible. The structural simulations predict that a decrease of the water-cement ratio increases the safety of the shotcrete tunnel shell.

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INFLUENCE OF SLENDERNESS RATIO λ_x / λ_y ON LOAD CAPACITY OF HSC COLUMNS IN BIAXIAL BENDING

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KEYWORDS: biaxial bending, high strength concrete columns, capacity, slenderness

Columns subjected to combined axial loads and biaxial bending are common structural elements in buildings and engineering objects. Dilatations in building are usually located in distances that significantly exceed code limit values. Hence, it is necessary to take into consideration thermal and shrinkage actions that induce additional bending moments in columns. Designed building structures have frequently irregular shapes - in such cases even internal columns may be subjected to combined axial loads and biaxial bending.

In recent years high strength concrete have been widely applied in structures, especially for columns. That allows for reduction in column cross-section and the structural dead-load, decrease in the concrete creep and increase in the structural durability [3]. But cross-section reduction results in slenderness increase of the elements. Design of slender RC columns constitutes a complicated task due to material and geometrical non-linearity. Methods of non-linear analysis are rather seldom used by designers as they require the solving of the great number of complicated equations. Thus the simplified methods are usually applied in engineering design practice [1], [2].

Information from literature concerning behaviour and design methods for biaxial bending in high strength concrete columns are limited, especially in the domain of experimental research. Load bearing capacity and behaviour of such columns are influenced by many different factors. The question of influence of column slenderness ratio λ_x / λ_y onto the load bearing capacity of HSC columns in biaxial bending is presented in the paper. Conducted analysis for some selected cases indicated that simplified methods included in codes are quite accurate for columns with the value of λ_x / λ_y close to 1,0. For higher values of this parameter application of simplified design methods results in significant underestimation of capacity in comparison with the real values obtained from tests.

The planned research program for testing the high strength concrete columns in biaxial bending for the slenderness ratio λ_x / λ_y range from 1.0 to 4.0 is also presented in the paper.

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NON-REINFORCED JOINT OF PRESTRESSED SLAB ELEMENTS UNDER THERMAL LOAD

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KEYWORDS: prestressed slab, joint, precast tank, thermal load

Precast cylindrical tanks for liquids, prestressed with internal, unbonded tendons are erected in Poland since 1997 year. In some solutions, in vertical structural joint between prefabricated shell elements, horizontal reinforcement aren't being used. Analysis of the structure under thermal loads and watertightness of the tank are ones of essential EC-2 [1] requirements. In this paper, the influence of non-reinforced joint on behavior the prestressed slab elements under thermal load was presented. During the experiment four slab elements about dimensions 3,6 x 1,0 x 0,18 m were tested. Every set was consisted of two elements: slab with joint and slab without it. Both elements were tested in the same static and kinematic boundary conditions. The test setup is illustrated in figure 1. Increment of horizontal displacement, measured at cross section of the joint, as a function temperature difference is presented in figure 2.

Fig. 1 Test setup and the view of joint between slab elements.

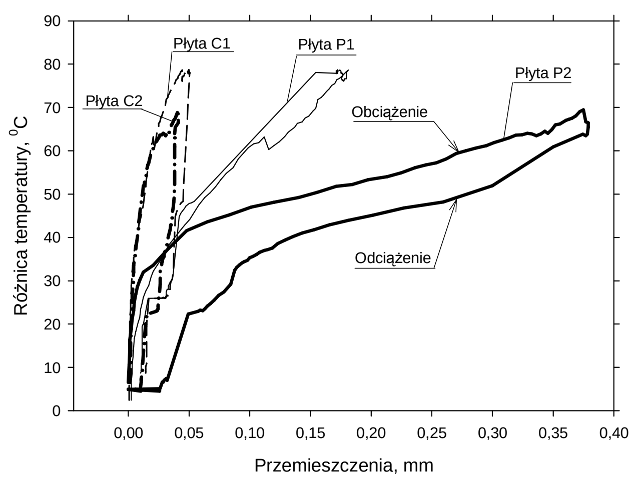

Fig. 2 Increment of horizontal displacement at cross section of joint (P) and continuous slab (C).

[1] EN 1992-3:2006 Eurocode 2 – Design of concrete structures – Part 3: Liquid retaining and containment structures.

NUMERICAL ANALYSIS OF REBAR CORROSION PROCESS IN CONCRETE

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KEYWORDS: FEM, rebar corrosion

The paper presents mathematical model describing physical mechanism of rust formation and its increase in volume. The volume expansion of rust induces stress increase in concrete, exceeding the concrete tensile strength at one or more points on the concrete cover, and causing crack initiation. The presented model has been used in finite element (FE) analysis with updated Lagrangian approach [2].

The case of pitting corrosion is especially considered, since it is confirmed experimentally but it is difficult to describe its geometry and propagation. The model of pitting corrosion, proposed in the paper, is based on theoretical consideration, and its effectiveness should be verified by experiments. The rust formation is described as a result of phase conversion of steel into rust that is treated as a nearly incompressible material. The process involves the necessity of continuous updating of the domains occupied by the changing volume of the rebar, the forming corrosion product and finally, the rust itself. The rebar corrosion model is presented in Fig.1 where Δd_r is the thickness of rust, d_{sf} is the thickness of a band where phase conversion from steel to rust takes place, and d_r is the sum of thicknesses of rust and corroding steel.

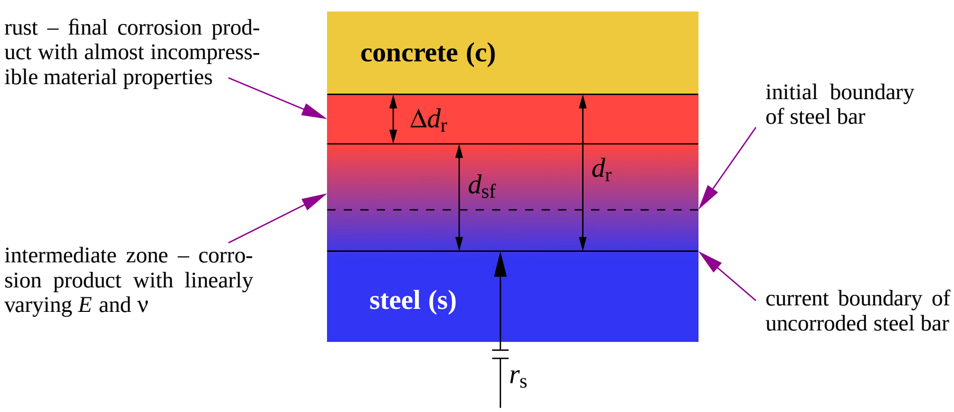

Figure 1: Rebar corrosion model.

The paper is limited to the analysis of mechanical effects of rust formation in rebar cross–section, which reduces the real 3D problem of mechanics to a plane strain problem.

The final result is the description of displacement and stress fields in a concrete structure, particularly in the concrete cover, pointing towards the possibility of developing primary and secondary cracks [1].

Solutions for the concrete stress are known from the literature on the subject, but only for uniform corrosion, and they use the linear theory of elasticity for a concrete ring model subjected to uniform pressure [3]. All calculations have been made with the use of a program developed in MATLAB 6.5 system.

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PREDICTING THE THERMAL IMPACT OF FIRE ON STRUCTURES BY MEANS OF COMPUTATIONAL FLUID DYNAMICS

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KEYWORDS: Fire, Temperature loading, Structures, Computational fluid dynamics

Fire accidents in recent years caused numerous casualties as well as an immense economic loss. The aim of this work is the assessment of the thermal impact on structures during fire accidents by means of Computational Fluid Dynamics (CFD). Starting with the heat release rate (HRR) of the fire load, which represents an important input parameter, the temperature distributions at the surface of the load-carrying structure is determined (see Figure 1). CFD simulations provide evolutions and spatial distributions of surface temperatures replacing the commonly used standard temperature-time curves of design codes. As fire-specific parameters enter the simulation process, the proposed approach leads to more realistic results: beside the individual geometrical properties of the structure, the calculation also accounts for an appropriate thermal load as well as its spatial distribution.

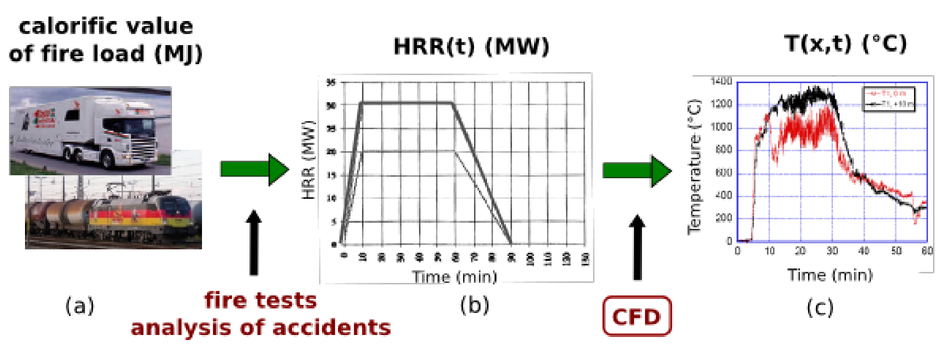

Figure 1: Application of CFD simulations in fires: (a) type of fire load, (b) evolution of HRR and (c) evolution of surface temperature

Based on an extensive literature study (e.g. [1; 2]), a comprehensive set of HRR-curves was collected. Furthermore, different CFD-codes designed to simulate fires in enclosures where investigated [3]. A pre-selection according to specified criteria was carried out to find the most appropriate tool for the current study, suggesting the two codes *Fire Dynamics Simulator (FDS)* and *OpenFOAM*. In order to study *FDS* and *OpenFOAM* in more detail, reference examples were designed and analyzed. The obtained numerical results are compared among each other and with respective experimental data.

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RELIABILITY BASED ANALYSIS AND OPTIMUM DESIGN OF FRAMES

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KEYWORDS: reliability analysis, limit analysis, shakedown analysis, residual strain energy

A general approach is presented for the reliability-based analysis and optimum design of steel frames under multi-parameter static loading and probabilistically given conditions with taking into consideration the influence of the limited load carrinng capacity of the connections. In addition to the plastic limit design to control the plastic behaviour of the structure, bound on the complementary strain energy of the residual forces is also applied (see e.g.[1, 2]). This bound has significant effect for the maximum of the load multipliers. If the design uncertainties (manufacturing, strength, geometrical) are expressed by the calculation of the complementary strain energy of the residual forces a reliability based extended limit design problem is formed. The formulations of the problems yield to nonlinear mathematical programming which is solved by the use of sequential quadratic algorithm by applying direct integration or Monte Carlo simulation. The bi-level optimization procedure is governed by the reliability index calculation.
Several solution techniques are considered. In Fig 1 the investigation on the optimal cross sections of the structure can be seen. In Fig 2 one can see the results of Monte Carlo simulation with sample of n = 500 000 realizations.

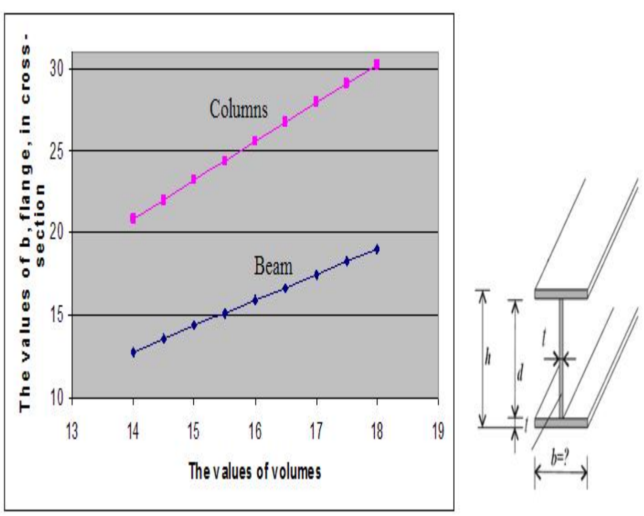

Figure 1: Optimal volumes

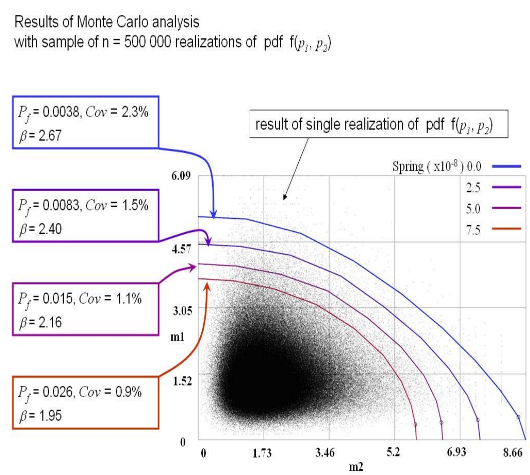

Figure 2: Plastic limit curves

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INVESTIGATING THE EFFECT OF KNOTS ON THE MECHANICAL BEHAVIOR OF WOODEN BOARDS BY MEANS OF NUMERICAL SIMULATIONS

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KEYWORDS: Numerical Simulation, Wood, Knots, Fiber Deviation, Continuum Micromechanics, Stiffness

Unlike the man-made materials steel and concrete with a macroscopically homogenous appearance, wood is a naturally grown material that shows growth irregularities, primarily knots and site-related defects. Knots result in a pronounced reduction of stiffness and strength of wooden boards. Due to the highly anisotropic material behavior of wood, the influence of the grain orientation on the mechanical properties of a board is very pronounced. The fiber deviations in the vicinity of knots therefore cause a high variability in strength and stiffness. The latter is a major difficulty in solid wood utilization and brings about the need for wood grading.
This motivated investigation of the effects of growth irregularities on the mechanical behavior of boards by means of physically-based numerical simulations. Such simulations provide insight into the internal stress and strain fields and contribute to an enhanced understanding of the internal stress transfer in wood with growth defects. By analyzing various knot configurations, relations between the morphological knot characteristics and wood strength can be assessed.
Previous modeling efforts in relation to wood with growth irregularities focused on the geometric task of determining the fiber course around a knot [1,2]. Existing physical models quantifying the effect of knots on mechanical properties of timber are generally based on very simple mechanical theories such as the rule of mixture [3]. They are not capable of reproducing the complex effect of a knot in terms of fiber deviations and local variations of tissue stiffness and density in the vicinity of knots.
To close this gap, the presented numerical model is based on the combination of the Finite Element (FE) Method with sophisticated models for the fiber course and the material behavior. The model takes into account the global fiber deviation caused by spiral grain and the local fiber deviation caused by the presence of a knot. For the latter a mathematical algorithm [1] based on a fluid flow approach and polynomial functions fitted to the annual ring course was implemented into the model. The algorithm is evaluated at every integration point of the FE model and provides the local three-dimensional fiber orientation there. With respect to the mechanical material behavior, a micromechanical model developed by the authors is used [4]. This model is based on homogenization strategies such as continuum micromechanics and unit cell theory and allows to predict macroscopic mechanical properties of wood from the chemical composition and microstructural features. It is also evaluated at integration point level and permits consideration of local variations of tissue stiffness resulting from local variations of density and microscale properties in the vicinity of knots.
The newly developed numerical multiscale-model enables the virtual recreation of a timber board with knot inclusions and the estimation of the stiffness and strength reduction caused by the knots by means of FE simulations. The validation, which is done by comparison of model-predicted and experimental results for the mechanical behavior of boards with knot inclusions, confirms the practicability of the model.
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GRADIENT DAMAGE IN DYNAMIC ANALYSIS

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In dynamics we take into consideration wave propagation problems when a loading pulse has the largest influence on the response of the structure. For softening materials waves have imaginary wave speeds, hence they do not propagate, i.e. standing waves appear. When propagating waves are stopped, strain localization occurs. In local approach the zone of intense deformation is limited to a discrete line or plane, the initial boundary value problem (IBVP) loses hyperbolicity and the finite element solution reveals mesh sensitivity. Different well-known regularization techniques to overcome this problem have been suggested, for example in [3].

The gradient-enhancement approaches employ an additional regularizing equation in order to remove the ill-posedness. In this model the equation of motion is coupled with the averaging Helmholtz equation, for example as proposed in [2]. This equation for the nonlocal equivalent strain involves the second gradients of this quantity and is responsible for the well-posedness of IBVP. Therefore, simulations of localization in dynamics become free from spurious discretization sensitivity.

The gradient damage theory is formulated in the strain space. We assume a loading function in which the averaged equivalent strain (involving the first and second strain invariants) governs the damage evolution. The damage growth law can represent a linear or an exponential softening uniaxial stress-strain relation. Small strains and no damping are assumed.

Independent interpolations of the displacements and the averaged strain measure are employed in the semi-discrete linear system. The nodal values of the displacements and the averaged strain measure are computed using implicit time integration which is based on the standard Newmark algorithm for nonlinear problems. Within each time step we apply the Newton-Raphson method to retrieve equilibrium. The consistent mass matrix is present in the first of the coupled equations, while the nonsymmetric tangent operator combines both the approximated fields.

As a simplest test we present a bar which is extended in one dimension. Wave propagation and damage localization in a two-dimensional direct tension test for plain and reinforced concrete is analyzed, cf. [1]. The split in the Brazilian test under impact loading is also considered. Finally, the simulation of reinforced concrete beam under dynamic four-point bending is reproduced following [4]. The mesh insensitivity of the results is verified.

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