Short presentation of research projects supported by the Croatian Science Foundation.

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ASSESSMENT OF STRUCTURAL BEHAVIOUR IN LIMIT STATE OPERATING CONDITIONS - *STRUBECON*

Research summary

In the broad sense, the STRUBECON research can be divided into three groups: experimental, solid mechanics and structural mechanics. The goal of the experimental group is to determine material behavior in the environmental and loading conditions in which will the structure operate. These environment and loads are not the one intendent in the design procedure and take place due to some unforeseen event. In this research, a particular focus is set to the shorter exposure to elevated temperature and impact. In the line with this, short-time creep and Charpy impact tests are performed.

The second line of research is oriented toward solid mechanics. Two particular problems are analyzed. The first one is developing a multiscale tool that can predict the macroscopic behavior of a structure based on the microstructure of the considered material. Since such model must account both for thermal and mechanical processes, thermoplasticity material behavior is a suitable choice. The other solid mechanics problem being considered is the mechanics of the nanocomposite materials. As it is nowadays widely believed, the nanocomposite materials should be the dominant structural material in the future (beside metals). Such an opinion is attributed to the exceptional mechanical properties of the nanocomposites. This makes nanocomposite materials a logical choice for the application in the limit state conditions. Therefore, the research at hand should provide some useful models and guidelines for these applications.

Structural mechanics aspects are being analyzed in the third part of the research. The aims are twofold. One is going to provide a suitable methodology of structural connections modeling. The traditional approach is to consider these connections either as hinged or rigid, but in the reality the connection behavior is usually somewhere in between. Since at the limit operating conditions, this behavior can be crucial, it is of utmost importance to model the connection as realistically as possible. The other aim of this group is oriented toward buckling of the beam-type structures, composite materials being particularly interesting. Namely, especially in the high temperature regime, buckling of beams is likely to appear, so an accurate structural model should be known.

STRUBECON accomplishments in the first year of research

Within the domain of material behavior at extreme conditions, short time creep of steels 20MnCr5 and 42CrMo4 were investigated. In the case of 20MnCr5, it was found that the material can sustain high stresses [1], but the creep resistance is found only at temperatures below 723 K. Fracture toughness of this steel was also investigated. The latter material was compared to other steels (S275JR, S355JO, ASTMA618, 50CrMo4, X10CrAlSi25) in [2, 3]. It was found that 50CrMo4 steel has the lowest fracture toughness in this group of steels. Crack driving force of 20MnCr5 steel was analyzed in [5]. As for 42CrMo4 steel [4], short time creep tests points to the similar behavior as in the case of 20MnCr5 steel. This steel is creep resistant till 400 $^{\circ}$C, and at higher temperatures can be used only in the low stress regime and for the shorter time periods. Paper [6] is oriented toward modelling of plasticity effects in thermomechanical loading conditions.

As such, it is suitable for the description of development of permanent deformation at higher temperatures. It is shown that cyclic plasticity accompanied by the temperature change, i.e. low cycle fatigue can be successfully modeled by the proposed approach. The other two contributions in the solid mechanics group is aimed at the nanocomposite materials. In particular, behavior of reinforcements (carbon nanotubes) in the polymer matrix is analyzed at the atomic level. Special emphasis is set to proper modeling of carbon nanotube – polymer interface and the defects of carbon nanotubes. Among these defects, waviness and vacancies at the nanoscale level were of special importance [7]. A multiscale approach to the problem was proposed in [8]. Structural mechanics research group was concerned with the possibility of application of advanced materials, i.e. functionally graded materials in the beam-type structures. For the sandwich box beams they developed a model suitable for the analysis of stability problems in structural engineering.

Conclusion

To summarize, STRUBECON project resulted with significant findings in all planned research fields. The results were published in top journals in the field. For considered materials mechanical properties as well as creep behavior were investigated and also Charpy impact energy was determined.

Acknowledgments

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Research group's journal publications related to the project in 2014/2015.

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DEVELOPMENT OF EVOLUTIONARY PROCEDURES FOR CHARACTERIZATION OF BIOLOGICAL TISSUES BEHAVIOR-BIOMAT

Project summary

Optimal material selection is very important for the proper product design, whereby special attention should be paid to the behavior of materials under actual conditions of use. In order to enhance and improve product features, increasing attention is paid to enhancing the properties of conventional and especially the development of innovative materials and creating conditions for their technical applications. Although the materials research is still to a large extent focused on metallic, polymeric materials, glass, ceramics, composites, etc., increasing interest is devoted to the study of the biological and the like materials with excellent properties and behavior under different conditions and loads. The motivation for the research lies in the fact that many biological systems have mechanical characteristics which are greatly above those that can be achieved using conventional and synthetic materials. As a consequence, mechanical properties and behavior of materials present in, for example, clams, mussels, bone, spider silk, the muscles and the like are intensely studied. Within the project, for the characterization and modeling of biological materials, the data obtained through experimental testing of samples of cervical ligaments of the human spine has to be used. In order to more efficiently obtain the precise values of the material parameters for the proposed nonlinear hyperelastic material model, the techniques for determining the parameters of material behavior based on genetic algorithm have to be developed. In order to develop the best genetic algorithm and to optimize it for the given material or group of materials, and to achieve desired solutions as soon as possible, complex genetic algorithm procedures and its operators have to be developed, by applying the appropriate objective function for the optimization procedure. The procedure can be automated by using the appropriate mathematical and numerical methods. This project proposes setting innovative foundations in the interdisciplinary field of engineering sciences and biomedicine, allows the connection of members of the proposed scientific groups and ensures their international visibility and contributes to the overall development of the field of material research.

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Introduction

The behavior of the biological material under the loading influence is very complex, but, as well as modeling of the conventional material, it is based on the knowledge of its mechanical properties, such as the interdependence between the stress and strain of the material. Some of these characteristics may be determined by experimental methods, such as tensile loading of samples to their cracking. In addition to the knowledge of mathematical and material model, which can be well described by the aforementioned interdependence, a basic prerequisite for modeling the behavior of biological materials, is certainly the identification of their parameters on the basis of physical laws that apply to them.

Due to the complexity of the model of biological materials and a large number of material parameters that appear in it, conventional calculation methods are not sufficient for their determination. In preliminary studies, it was found that for the identification of parameters of biological materials needed for modeling and simulation of their behavior, it is advisable to apply the evolutionary methods, especially genetic algorithm.

Material behavior modelling

Parameter identification of biological materials for modeling their behavior would be well advised to be conducted by applying evolutionary methods, especially genetic algorithm, which has been recognized as an advanced tool to achieve this objective. In order to more efficiently obtain the precise values of the parameters, a technique for determining the parameters of materials behavior needs to be developed for the proposed material model. In order to develop better procedures of genetic algorithm for a given material or group of materials, or as soon as possible achieve the desired solution, it is necessary to develop a procedure for a complex genetic algorithm and properly develop its operators with the development of an adequate objective function for the optimization procedure. In order to achieve this, it is essential to automate the process with the appropriate mathematical and numerical methods.

The application of previously acquired knowledge on modeling the behavior of metallic materials and evaluation of their lifetime in modeling the behavior of biological materials, as materials that have a completely different structure, and thus their mechanical characteristics, would allow the creation of a unified methodology for the identification of parameters for modeling the behavior of materials. Consequently, characterization of a large number of innovative materials and an assessment of their lifetime would be enabled, along with their optimal use in engineering practice. The development of complex genetic algorithm to identify the parameters of material behavior would allow a fast adaptation and further development of specific functions and operators for application to a wide variety of materials.

Conclusion

The proposed methodology of material characterization, has so far proved to be very applicable for parameters identification of material with different microstructure and mechanical properties. It is expected that because of its flexibility and robustness, besides for the modeling of the biological material it can be applied to characterize the behavior and other non-conventional and innovative materials of complex behavior. For this purpose, collection and systematization of relevant results of experimental tests of advanced types of materials and information on the methodology and material models is foreseen and planned. This will create the basis and foundation for the further improvement of the developed solutions and the creation of a unified methodology for the characterization of a large number of innovative materials and facilitate their application in engineering practice.

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EVOLVING SOFTWARE SYSTEMS: ANALYSIS AND INNOVATIVE APPROACHES FOR SMART MANAGEMENT - EVOSOFT

Project summary

Evolving complex software systems (EVOSOFT) have become a central part of a rapidly growing range of applications, products and services supporting daily human activities from all economic sectors. As they are often distributed, heterogeneous, decentralized and inter-dependent, and operating in dynamic and unpredictable environments, availability and reliability become key properties for its operation and future evolution. The novel and still unexplored area of research addressed in this project is to understand how abstract software structures and local system properties influence fault distributions, thus affecting mission critical system properties, among which availability and reliability and to develop innovative approaches for smart management of their operation and evolution. We are facing with completely new phenomena, similar to human evolution, but produced by human intellect. Foundations and theories from other disciplines aiming to understand complex system behavior, evolution and human reasoning could be applied. New findings would open new opportunities in many scientific fields, especially in complex systems theory and its applications, thus interacting with a wide spectrum of sciences, from natural sciences such as biomedicine to social sciences. Industrial experience gathered by systematic Empirical Software Engineering approach is extremely important for further evolution of software engineering discipline. New theories cannot provide effective means for industry without fundamental understanding of EVOSOFT behavior. The main aim of this project is to fulfill this gap between empirical evidence and theoretical models. In that aim we combined empirical and theoretical skills aiming to:

- replicate studies and confirm empirical principles and methods and define a solid base to ground new theories
- define structural dependencies for applicability of empirical principles, methods,
- define formal models and innovative approaches for smart management

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Introduction

Modern society is increasingly dependent on large-scale EVOlutionary developed SOFTware systems – EVOSOFT and the importance of software in the era of rapidly growing new technologies cannot be underestimated. These systems are central in supporting majority of human daily activities (telecommunications involving television, radio, Internet; financial transactions and e-commerce, medical systems, automotive industry, energy production, public transport, etc.). They evolved in series of development cycles to large-scale systems and gradually have become too complex to be easily managed and further developed under reasonable productivity and quality limits. This may represent a significant obstacle for its future evolution and technological innovation. Current software engineering technologies are not good enough to accommodate challenges of *EVOlving complex SOFTware systems* (EVOSOFT). Huge efforts are devoted to development of new and innovative solutions that would efficiently and effectively address productivity and software quality in these systems within number of projects: *BETTY* action funded by European Cooperation in Science and Technology foundation, *Enabling growing software systems* funded by Swedish Foundation for Strategic Research, *CloudScale*, *Q-Impress* funded by the European Community's Framework Programme Seven (FP7), etc. This is also the main research challenge of Horizon2020, introduced by *Networked European Software and Services Initiative*[1] (NESSI, 2013), that needs to be addressed so that Europe can develop competitive advantages in the Software and Services as well as in other technology areas and its applications.

Innovative approaches engineering evolving software systems

This project brings together the skills of University of Rijeka (Croatia), Lund University (Sweden), IT University of Copenhagen (Denmark), and industrial partner Ericsson Nikola Tesla, Zagreb (Croatia) to better understand the fault distributions and its underlying influencing effects and to propose innovative solutions for smart management. Faults are local system properties connected to particular line of code and are directly influencing global system quality properties such as reliability and availability. The properties of the system that we refer to as global are impossible to describe using simple rule with collection of local properties. Another problem is that in engineering EVOSOFT there is limited understanding of local software properties. Our recent findings of several replications on fault distribution show fundamental behaviour that seems to apply to any EVOSOFT. In this project we study industrial closed source software systems (IS) and open source systems (OSS) and investigate commonalities from the fault distribution perspective and relations to other software properties. Main aims of the project are:

Aim 1. To replicate studies aiming to confirm empirical principles and methods proposed and used in software engineering community and to define solid base to ground new theories.

Aim 2. To define structural dependencies between various empirical principles.

Aim 3. To define formal models and innovative approaches that would enable accurate modelling of fault distributions and smart quality management of EVOSOFT systems.

Conclusion

Our previous studies in this context were already published in leading software engineering journals. Deep industrial involvement enables us to further explore the effects in industrial context and to define inputs for theoretical development of sound formalisms. These theoretical foundations will be driven with real needs then used for development of verification and simulation tools that are to be integrated within software development environments. Diverse skills of project team members from empirical software engineering and theoretical sciences provide unique team that is able to better understand the EVOSOFT behaviour and generate innovative approaches to smart EVOSOFT management.

[1] www.nessi-europe.hr

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GREENER APPROACH TO SHIP DESIGN AND OPTIMAL ROUTE PLANNING - GASDORP

Project summary

The accurate calculation of attainable ship speed at actual sea is essential from economical and also environmental aspects. Reliable ship speed loss estimation under real environmental conditions allows a more accurate prediction of the power increase and fuel consumption as well as gas emissions from ships. Nowadays this second issue becomes very important because of the problem of global warming. Following the increasing awareness of the environmental and human health concerns of shipping, legislative actions have been taken on global and national levels making mandatory (from January 1st 2013) that new ships over 400 gross tonnage, to comply with the regulations, should have emissions of CO_2 under limiting value. Technological enhancement to ships like improved hull designs as well as improvement in power and propulsion systems could potentially reduce CO_2 emission up to 35 %. These measures could effectively be combined with several other operational measures, such as weather routing and voyage planning, in order to ensure that fuel consumption and CO_2 emissions from ships are minimized on every voyage.
The proposed research will be conducted in three main areas: 1. Improvement of the methodology of ship speed, fuel consumption and greenhouse gases (GHG) emissions (especially CO_2) calculation on actual weather conditions, 2. Optimization of the ship hull (bow and stern) and ship propulsion system operating in actual weather condition, 3. Optimization of ship route by taking into account all relevant parameters: weather prediction, attainable ship speed on waves, main engine performance and navigation constrains.
The objective is to improve ship design and performance taking into accounts the environmental issue, creating a so called eco-efficient or "green" ship design. The project team consists of the scientists who are experts in the naval architecture, mechanical engineering and marine engineering field which allow solving this problem multidisciplinary.

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Natalija Vitali, PhD student, Faculty of Engineering, University of Rijeka

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OPTIMISATION AND MODELLING OF THERMAL PROCESSES OF MATERIALS - OMOTPOM

Project summary

Main objective of this project is development of models and computer simulations of thermal processes and study of optimizing the application of tools and dies in thermal processing of materials. Computer programs for simulation of heat transfer, microstructural transformations, mechanical properties, distortions and residual stresses will be analysed considering required workpiece shape, mechanical property and microstructure distribution with avoidance of cracking and reduction of distortion and residual stresses.

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Introduction

To make achievement of predicted project goals more efficient, project team members, as well as their tasks are divided in two research groups. First one is from University of Rijeka, and second one from University of Split. In the first year of the project, research group from Rijeka had tasks of development of 3D model of steel quenching, as well as optimisation of electroless coatings and increasing of adhesiveness of coatings on substrates, while research group from Split had task of optimisation of thermo-mechanical behaviour of thermal processing dies and casting alloys. Tasks of both groups also included organisation of workshops, field researches, publishing of achieved results in journals and on conferences, setting up infrastructure that will enable conducting of proposed research and working meetings to harmonize tasks of both groups for better and faster achievement of results predicted by work plan for the first year of the project.

First phase in optimisation and modelling of thermal processes of materials

During working meeting on FESB in Split all tasks, necessary equipment, specimens and materials which will provide conditions to start with project activities have been defined. Infrastructure has been set up to provide all necessary conditions for both research groups. Industrial problems have been defined on field researches and project activities have started.

Main task of research group from Rijeka is to develop 3D model of steel quenching. First step towards achievement of this goal was to examine and study existing literature. With gained knowledge about microstructure transformations, heat transfer and all phenomena which occur during thermal processes, development of algorithm for microstructure transformations could start. After defining critical temperature intervals for microstructure transformations, algorithms for estimation of kinetic coefficients of decomposition of austenite to ferrite, pearlite, bainite and martensite based on TTT diagrams have been developed. Based on developed algorithms, first simulations have been done. Next step is development of algorithms for estimation of mechanical properties after thermal processing.

Second subgroup from Rijeka has the task of optimisation of electroless coatings and increasing of their adhesiveness on substrates. With knowledge gained from existing literature, researchers were able to define starting parameters for practical realization of applying the coatings on substrates. To ensure satisfactory adhesivity, electropolishing and substrate activation is necessary. Other important factors have shown to be chemical composition, temperature, pH value, filling and age of bath. Since application of Ni-P coating directly on austenitic steel substrate is not yet possible, electrolytic nickel layer must be applied primarily by nickel strike. Technological procedure of electroless process has been fully defined, but there is a lot of room for adhesivity increasing and optimisation of electroless coatings on austenitic steel substrates.

Research group from Split has the task of optimisation of thermo-mechanical behaviour of thermal processing dies and casting alloys. Main problem in industry is damaging of dies due to thermal fatigue. Research group has started defining mechanisms of damaging as well as defining and optimisation of parameters for heat treatment of austempered ductile iron casting. Experiments have been conducted to define dependence of hardness on heat treatment temperatures and holding times. The design of a prototype device that can simulate damaging of moulds due to thermal fatigue has also begun. Basic idea in its design is to immerse specimens with high speed into molten alloy instead of casting the alloy into the moulds. With this device, research cost should be reduced. By the end of first project year, device design was in final stage.

Accomplished results have been presented throughout the year in the following conference proceedings:

- Smoljan B., Iljkić D., Pomenić L.; Mathematical Modelling and Computer Simulation of Steel Quenching; Proceedings of the 24th International Conference on Metallurgy and Materials; 03.-05.06.2015; Brno, Czech Republic.
- Smoljan B., Iljkić D., Smokvina Hanza S.; Computer Simulation of Mechanical Properties of Quenched and Tempered Stamping Punch; European Conference on Heat Treatment & 22nd IFHTSE Congress, 20-22 May 2015.; Associazione Italiana di Metallurgia; Venice, Italy.
- Čatipović N., Živković D., Dadić Z., Sučić A., Ljumović P.; Influence of Isohermal Temperature and Holding Time on Microstructure and Hardness of Austempered Ductile Iron; MTSM 2015; ISSN 1847-7917, 2015.; HDST, Split, 23-35.
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Conclusion

Division of project team in two main groups and division of project tasks allows faster and more efficient accomplishment of project goals. There are three main goals to be accomplished: development of 3D model of steel quenching, optimisation of electroless coatings and increasing of adhesiveness of coatings on substrates and finally, optimisation of thermo-mechanical behaviour of thermal processing dies and casting alloys. By acting with respect to project working plan, first year has resulted in well-established foundations which will allow achievement of one common goal – optimisation and modelling of thermal processes of materials.

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CONFIGURATION-DEPENDENT APPROXIMATION IN NON-LINEAR FINITE-ELEMENT ANALYSIS OF STRUCTURES

Project summary

This research explores configuration-dependent interpolation as a novel and unorthodox expansion of the framework within which the non-linear finite-element method has been traditionally contained. The basic idea underlying the project stems from an apparent disparity between the rather advanced extensions of the traditional linear finite-element principles to non-linear problems and a fairly rudimentary application of interpolation of the unknown functions – which is surprisingly kept mostly configuration-independent.

Development of configuration-dependent approximation is presented as a general concept providing viable novel development paradigm. During the design process, the following two basic principles will be consistently adhered to: (i) in the limiting case where the non-linear mechanical problem becomes linear, the configuration-dependent approximation sought must coincide with a known reference interpolation for linear analysis (reference linear solution – RLS) and (ii) in a general non-linear situation, the configuration-dependent approximation should preserve a set of selected mechanical or mathematical properties of equilibrium or motion defined beforehand (property preservation – PP).

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Project work-packages

WP1. Configuration-dependent interpolation for homogeneous straight and curved 3D beams.
WP2. Configuration-dependent interpolation for homogeneous plates as well as flat and curved shells.
WP3. Configuration-dependent interpolation for straight layered 2D beams including discontinuities.
WP4. Configuration-dependent integration of equations of motion.

Outline of 1. year project results

Within the first year of the project life-span, specific attention has been paid to providing reference linear solutions (RLS) for multi-layered bars and beams with rigid and elastic-slip conditions between layers [1-5] as well as Mindlin plates [6].

The requirement of property preservation (PP) has been applied to 3D geometrically exact beams based on the so-called fixed-pole approach [7-10] as well as to central-force-field dynamical problems [11].

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MULTI-SCALE CONCRETE MODEL WITH PARAMETER IDENTIFICATION – *CONCRETEMUSCID*

Project summary

In complex numerical models, the calibration can only be achieved through interaction of measured data with the underlying mathematical model. Especially difficult situation occurs when loading is stochastic (e.g. wind, earthquake, traffic) since there is no direct relation between loading (input) and displacements (output). System parameter identification will be based on inverse mathematical formulation so to present a reliable and theoretically sound procedure for identification of required parameters. One of the main goals of the system identification procedure is representative volume identification. It will be necessary to consider non-Gaussian stochastic processes with heavy tails characterizing dangerous rare events. Regarding material parameters, this project advocates the hypothesis that the fracture energy of a material is approximately constant and that the material constitutive law should not incorporate "rate effect". The idea of (approximately) constant fracture energy for all loading rates is new and important in models of concrete under the dynamic loading. In addition, the inclusion of the viscous parameter in the existing 3D microplane model for concrete is of vital importance for fatigue analysis since it connects creep and shrinkage (internal material loading) with dynamic loading (external structural loading). In the end, the developed concrete model will account for corrosion by coupling the mechanical properties of concrete and properties affecting the transport of humidity, oxygen and chloride (chemo-hygro-thermo-mechanical model). The calibration of the 3D model and its verification will be performed based on the simulation of the corresponding experimental tests from the laboratory and the available literature according to the procedure for system parameter identification described above.

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Introduction

The main motivation for this work is illustrated with concrete behaviour under high-cycle loading: after (very) long exposure of concrete structures to cyclic loading of rather low intensity a sudden loss of integrity occurs. It is planned to obtain the answer to the question by combining material models with structural and material parameter investigation. The main tool of the proposed procedure is inverse analysis that enables us to determine model parameters that could not be directly measured.
Three main concrete models will be investigated: i) damage model for concrete under dynamic loading, ii) influence of thermal, hygroscopic and chemical process on mechanical properties of concrete, iii) system identification procedure for determination of the representative volume element for concrete.

Multi-scale Concrete Model with Parameter Identification

The material under investigation in the project is a special variant of concrete: steel fibre reinforced high performance concrete, a concrete with supposedly "bright" future due to its very good properties compared to the "classical" concrete used in today's structures.
High cyclic loading is tightly connected with material behaviour under dynamic loading. This project plans to extend the existing non-linear dynamic viscoelastic material model. The current model is based on a system of differential and algebraic equations and is not suitable for large structures, some kind of discretization and linearization procedure is required. The main characteristic of the model is presence of the viscous parameter that can be used for material characterization under high-rate and dynamic loading. Here advocated approach is that the material rate-effect does not have to be adapted to the load rate if structural inertial effects are properly taken into account. This results in the principle that the fracture energy of concrete is (approximately) constant for all load rates.
The existing models of steel corrosion in concrete are mainly one or two-dimensional. However, there is a 3D model developed at the Institute for Materials, University of Stuttgart. The existing 3D thermo-hygro-mechanical model for concrete will be improved with introduction of coupling between non-mechanical (heath, moisture, creep and shrinkage) and mechanical loading. The applications of the improved numerical model that will be developed and implemented into the 3D FE code are extremely broad. Since the model can replace time-consuming and costly experiments to a large extent, it can be very effectively employed in research, teaching and industry.
System parameter identification is to be undertaken in the first part of the project. There are two levels of system identification: first order model and second order model.
The first order model deals with identification of parameters based on input/output recorded time histories, the so-called "black-box" model used primarily in control theory. Being based on non-physical parameters it is not suitable for the purpose of material parameter detection but is valuable as a starting point. Here, Kalman filtering will receive special attention since it can be completely designed in the time domain. Numerical structural model will be divided into appropriate sections and a suitable parametrization of the system will be looked for.
The second order system is used for identification of physical parameters of the structure or material. Starting from the determined first order system the second order system can be recovered by using proper linear algebra transformations. One of the main goals of the system identification procedure is representative volume (RVE) identification. It is especially difficult to determine RVE for nonlinear material models like the one proposed here since RVE is different for different material properties. System parameter identification will be based on the inverse mathematical formulation so to present a reliable and theoretically sound procedure for identification of required parameters

Conclusion

Regarding the feasibility of the outlined scientific approach, it should be stressed that this is an extension and continuation of the previous work of the principal investigator: the IPA3C project "Centre of Excellence for Structural Health" (2013 - 2015) where Ivica Kožar was coordinator (and researcher) for the University of Rijeka Faculty of Civil Engineering. Research in the proposed project is highly applicable in the field of wind power plants, nuclear power plants, analysis of dams and bridges.