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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*

Project summary

The studies in this project relate to the possible limit state operating conditions of the structure and by their nature are experimental and numerical. Structural design is usually based on the requirements relating to its use, safety, functionality and service life and at the same time meeting the requirements for strength, deformation, manufacturing technology and price. Structure may be sometimes exposed to unexpected conditions, let say adverse or hazard conditions. These conditions may cause failures making structure incapable to perform the function for which it has been designed. In such conditions the task is to make an assessment of the structure behavior if the structure is capable for further operation. This means the assessment should provide an answer if the structure has sustained irreparable damage. Therefore, the main objective is to provide an assessment of structure behavior, by comparing of the parameters such as stress, strain, crack occurrence, etc., caused by certain load level and temperature at this unexpected limit state with those allowed by material properties. To assess structural behavior in operation at limit state, the following research sub-objectives should be accomplished: testing of material properties for the different environmental conditions; definition of impact energy as well as the determination of the crack driving force and life assessment of structural elements; evaluation of the semi-rigid structural joints/connections behavior; development of a numerical algorithm for optimization of semi-rigid framed structures; creep buckling simulations of composite beam-type structures; proper constitutive modelling at limit operating conditions (i.e. plasticity, damage, thermomechanical coupling); application of new materials to be used at limit state – nanocomposites. Targeted structures may be single and multi storey steel buildings, high-power electrical transmission towers, ship structures, machines, etc.

Principal investigator

Prof. Josip Brnić, D. Sc., Faculty of Engineering, University of Rijeka

Team members

Prof. Goran Turkalj, D. Sc., Faculty of Engineering, University of Rijeka
Prof. Marko Čanađija, D. Sc., Faculty of Engineering, University of Rijeka
Assoc. Prof. Domagoj Lanc, D. Sc., Faculty of Engineering, University of Rijeka
Assist. Prof. Marino Brčić, D. Sc., Faculty of Engineering, University of Rijeka
Assist. Prof. Goran Vukelić, D. Sc., Faculty of Maritime Studies, University of Rijeka
Igor Pešić, D. Sc., Faculty of Engineering, University of Rijeka
Sanjin Kršćanski, D. Sc. (postdoc), Faculty of Engineering, University of Rijeka
Neven Munjas, D. Sc. candidate, Faculty of Engineering, University of Rijeka
Damjan Banić, D. Sc. student, Faculty of Engineering, University of Rijeka
Edin Merdanović, D. Sc. candidate, Euro Façade Tech, Kuala Lumpur

Introduction

The design and the manufacturing of the structure implies to be enough familiar with material properties determination as well as with manufacturing technologies. However, in engineering practice many types of structures as well as many kinds of design procedures exist. When types of structures are considered it can be mentioned, for example, mechanical structures, aircraft structures, ship structures, civil engineering structures etc. Also, regarding design procedures some different types can be mentioned, for example: design for unlimited structure lifetime, optimal structural design related to cost or to weight or to predicted lifetime, etc. However, in recent time, structure is usually designed to be optimal one and it means that this optimization need includes cost of the product but also requirements such as fulfilment of the purpose of the structure, factor of safety, stiffness etc. During structure service life many kinds of failures may arise. General failure causes should be mentioned: structural loading, corrosion, wear as well as some of latent defects. Common causes of failure may include: misuse, design errors, improper material, assembly errors, improper maintenance, manufacturing defects, unforeseen operating conditions, the transition of temperature effect, inadequate control, etc. If the structure has been designed with respect to permissible stress it is not guaranteed that any assessment of the structural behavior at possible adverse effects has been made. In this case, when structure is subjected to any case of overload or to any risk/hazard environmental conditions, some damage in the structure may occur. The analysis of failures in engineering structures is of utmost importance in an engineering approach to determine why and how an engineering component has failed. The knowledge and understanding of the root causes of failures provide a basis for improvements in design, manufacture and the use of structures, preventing us so from repeating similar mistakes in the future. Therefore, the main objective is to provide an assessment of structure behaviour which need to be based on comparing of the parameters like stress, strain, crack occurring, etc. caused by certain load level and temperature of this unexpected limit state with those allowed by material properties.

Tools to be used

As it was previously said, experimental and numerical / computational methods will be used to achieve the expected objectives / results. To assess structural behavior in limit state operating conditions, the following research sub-objectives should be accomplished: testing/definition of material properties for the different temperature/environmental conditions; definition of impact energy as well as the determination of the crack driving force and life assessment of structural elements; evaluation/assessment of the semi-rigid structural joints/connections behaviour; development of a numerical algorithm for optimization of semi-rigid framed structures; creep buckling simulations of composite beam-type structures; proper constitutive modelling at limit operating conditions (i.e. plasticity, damage, thermomechanical coupling); application of new materials to be used at limit state – nanocomposites. In any case, experimental results will be of importance to verify computational results and, in general, to provide material data for the computations. In this sense, project work-packages may also be divided into experimental investigations related to previously defined materials and numerical investigations for defining considered behaviors.

Conclusion

It is expected that the results of the STRUBECON project will provide tools for more reliable estimation of the structural behaviour at the limit state conditions. Consequently, hazards to both human lives and material damage should be reduced at the benefit of the community and industry. Combination of experimental and computational techniques will ensure that the obtained results are verified and reliable. Also, the wide spectra of analysed materials, from classical metals to nanocomposites will also provide possible applications in different industries.

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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.

Principal investigator

Prof. Jasna Prpić–Oršić, D. Sc., Faculty of Engineering, University of Rijeka

Team members

Prof. Odd Magnus Faltinsen, D. Sc., Norwegian University of Science and Technology, Trondheim
Prof. Roko Dejhalla, D. Sc., Faculty of Engineering, University of Rijeka
Prof. Tomislav Mrakovčić, D. Sc., Faculty of Engineering, University of Rijeka
Prof. Vladimir Medica, D. Sc., Faculty of Engineering, University of Rijeka
Prof. Duško Pavletić, D. Sc., Faculty of Engineering, University of Rijeka
Prof. Igor Rudan, D. Sc., Faculty of Maritime Studies, University of Rijeka
Assoc. prof. Nikola Račić, D. Sc., Maritime Faculty, University of Split
Ozren Bukovac, D. Sc. (postdoc), Faculty of Engineering, University of Rijeka
Dunja Matulja, D. Sc. (postdoc), Faculty of Engineering, University of Rijeka
Marko Valčić, D. Sc. (postdoc), Faculty of Maritime Studies, University of Rijeka
Natalija Vitali, PhD student, Faculty of Engineering, University of Rijeka

Introduction

Basic characteristics of an efficient transportation are safety, cost effectiveness and friendliness with the environment. According to various environmental impact assessments, ocean-going vessels, as the most important part of maritime transportation industry, will have increasing influence on the global ecosystem in the near future. In the modern approach to ship-design the problems related to energy efficiency and environmental protection must not be left aside. Fortunately, in majority of the cases, they are related with the ship economic efficiency in a manner that does not require much compromise and measures undertaken are mainly in the same direction. Improving the energy efficiency of the ship means increasing profits and reducing the adverse impact on the environment.

Energy efficient strategy for greener shipping

The aim of the strategy proposed in this project is to reduce the GHG emissions from ships by adopting better hull designs, energy efficient technologies and energy efficient operations. The objective is to improve ship design and performance taking into accounts the environmental issue, creating aforementioned eco-efficient or "green" design. Within this strategy, several goals need to be accomplished. Since ship operates in a weather conditions that could not be predicted with the absolute certainty, the appropriate simulation method of the real weather conditions is essential part of a ship voyage scenario. Another very important segment of the methodology is the short and long-term ship speed estimation, which allows reliable prediction of fuel consumption as well as GHG emissions. The prediction of these values very much depends on the main engine model. Therefore, there is a need for the development of the appropriate dynamic model of the main engine, which could adequately predict fuel consumption and GHG emissions on various sea state conditions. If it's possible to create the more realistic scenario of ship behavior under the real weather conditions, then the ship design and operations can be improved in order to increase ship energy efficiency in "real life". It could be achieved by various concepts such as improvement of the ship hull form taking into account the resistance both on the calm water and under the real environmental conditions, selection of ship's engine/propulsion system, deployment of a novel approach to dynamic and adaptive weather route planning, etc.

According to everything stated so far, the strategy for improvement of ship design and routing optimization that aims toward environmental friendly green ships should be based on:

- Improved ship motion modelling based on mathematical modelling and historical data;
- Improved models for environmental loads (wind, waves, ocean currents) as well as their forecasts;
- Improved ship hull (bow and stern) and ship propulsion system operating in actual weather conditions;
- Improved main engine dynamic model;
- Determination of a relationship between environmental disturbances and fuel consumption and GHG emissions;
- More precise method for prediction of ship speed and ETA with respect to environmental disturbances and ship motions;
- Attainable ship speed loss due to wind, waves and ocean currents;
- Deployment of ship seakeeping capability based on historical data and weather forecast uncertainties;
- Implementation of novel optimization methods for determination of the optimal route with minimum fuel consumption and GHG emissions in a time-efficient way while not exceeding the safe operating boundaries and constraints.

Conclusion

Introduction of novel ship designs and propulsion systems, together with increased fuel costs and the increasing conscience about environmental protection requires detailed research. Moreover, the necessity for respecting the strict safety requirements and increasingly demanding marine operations to be performed in the heavy sea conditions is growing. The results of proposed strategy will improve a very important segment of maritime transport technology, i.e. green ship design and shipping which assumes decreasing of fuel consumption and GHG emissions and at the same time much safer navigation for crew, passengers and the ship herself.

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OPTIMISATION AND MODELLING OF THERMAL PROCESSES OF MATERIALS - *OMOTPOM*

Project summary

Thermal processing of materials is one of the most important factors in production and reliability of engineering components. All varieties of material thermal processing technology, from heat treatment, casting and hot metal forming, to the welding, not only manufactures workpieces of required shapes but also optimizes their final properties. Objective of the optimisation of thermal processes of materials is development of models and computer simulations of thermal processes of materials and study of optimizing the application of tools and dies in thermal processing of materials.

During the thermal processing, physical processes and material properties such as: heat transfer, microstructure transformations, mechanical properties and distortions and residual stresses will be studied primarily. To solve these tasks, joined thermo-mechanic-metallurgical approach will be required. The computer program for simulation of heat transfer, microstructure transformations, mechanical properties, distortions and residual stresses during the thermal processes will be analyzed.

To meet the needs of industry to control and optimize the thermal process parameters, developed computer programs for simulation of the thermal processes will be accomplished by considering the achievement of: Required workpiece shape; Desired mechanical property distribution; Desired microstructure distribution by: Avoidance of cracking; Reduction of both, distortion and residual stresses.

Principal investigator

Prof. Božo Smoljan, D. Sc., Faculty of Engineering, University of Rijeka

Team members

Prof. Branimir Lela, D. Sc., Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split;
Prof. Dražen Živković, D. Sc., Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split;
Prof. Domagoj Rubeša, D. Sc., Faculty of Engineering, University of Rijeka;
Prof. Loreta Pomenić, D. Sc., Faculty of Engineering, University of Rijeka;
Prof. Zvonimir Kolumbić, D. Sc., Faculty of Humanities and Social Science, Rijeka;
Assist. Prof. Dario Iljkić, D. Sc., Faculty of Engineering, University of Rijeka;
Sunčana Smokvina Hanza, D. Sc., Adriainspekt d.o.o.;
Neven Tomašić, D. Sc. Student; Hara d.o.o.;
Hrvoje Novak, D. Sc. Student; NMP Produkt d.o.o.;
Mauro Maretić, D. Sc. Student, Technical High School, Pula;
Goran Salopek, D. Sc. Student, Faculty of Humanities and Social Sciences, University of Rijeka;
Zvonimir Dadić, D. Sc. Student, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split;
Nikša Čatipović, D. Sc. Student, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split;

Lovro Štic, D. Sc. Student, Faculty of Engineering, University of Rijeka.

Introduction

During the thermal processing of materials, phase transformation, evolution of microstructure, diffusion, heat conduction, and mechanical stressing and distortion are at once taking place inside of material. Mathematical models of thermal processes of materials should integrate fundamental theories of materials science and engineering, including chemistry, heat transfer, fluid mechanics and thermo-plastic mechanics to define physical phenomena which occur during thermal processing. Many of important research works in the field of thermal process modelling materials have recently been done. Despite that, the existing models are excessively simplified in comparison with real thermal processes and do not describe all industrial thermal processes. Computer simulation of thermal process of materials up to now has been limited because of simplifying these postulations, and their subsequent limited computational accuracy. Because of it, objective of this project is divided into development of models and computer programs for simulation of thermal processes of materials in macro and micro levels.

Development of a computer program for simulation

Creation of mathematical model and simulation of all physical processes which are taking place in a material during thermal processing requires joined thermo-mechanic-metallurgical approach and usage of finite volume method (FVM) to create the numerical model. FVM has showed to be the most suitable method for creating our own integrated computer program for simulation of transient temperature field, microstructure transformations, mechanical properties, residual stresses and distortions by additional development of special software 'BSquenching' for simulation of quenching and tempering. Just like every method, FVM is expected to show as inappropriate at some point so when necessary, the finite element method (FEM) will be used instead. To fulfill all project tasks, other professional software packages will have to be used.

To achieve a good quality simulation of heat transfer using the experimentally evaluated heat transfer coefficient relevant parameters of heat transfer process must be similar in simulation and experimental evaluation. New inverse method based on results of steel quenching will be developed and heat transfer properties will be obtained according to microstructure and hardness achieved by quenching or tempering of steel. Procedure of establishing inverse relations is in accordance to the question: what were the thermal properties of materials and the environment in order to achieve realized results of applied thermal process. The best way to resolve this inversion problem is through the application of computer modelling and simulation. Fully developed computer program will enable the prediction of results of decomposition of austenite in terms of continuous cooling, based on chemical composition of steel and to confirm the accuracy of simulated results, they will be verified by comparison with experimental results.

In the following phases of this project, computer simulations of microstructure evolution during thermal process of steel will be tested by experimental verification of results, mechanical properties of material during the thermal processes will be analyzed regarding to the phase composition and temperature because all aspects in predicting relevant mechanical properties of metal materials during thermal processes are still not fully explained in theoretical debate.

Conclusion

Numerical methods, such as, FVM and FEM are types of methods which allow development of different mathematical models and they have shown to be the best ones for simulation of thermal processes of materials. To make results of this kind of simulation as realistic as possible, it must include all relevant parameters which should be as similar as possible in simulation and in experiments. By establishing inverse method through application of computer simulation it will be possible to fully develop a computer program which enables prediction of results of thermal processes of materials which will later on be compared to experimental results. Establishing this method through application of computer simulation will allow successful achievement of all predetermined project goals.

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

Project summary

This research, supported by the Croatian Science Foundation under the research project IP-11-2013-1631, explores the configuration-dependent interpolation as a novel, unorthodox and remarkably promising 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 the fact that the key finite-element concept – that of interpolation of the unknown functions – is surprisingly kept mostly constant, i.e. configuration-independent.
Enabling the finite-element approximation to become configuration-dependent is motivated by the existing need to improve the current non-linear finite-element procedures, in particular for mechanical problems defined on non-linear manifolds. This principle is presented as the general concept providing viable novel development paradigm with obvious benefits for a wider class of mechanical problems. The configuration-dependent approximation shall obey the essential convergence requirements, with its extra flexibility (arising from the potential of the new approximation to vary with the configuration) employed to improve the solution in some clearly defined manner. In particular, 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.

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.

These principles define the sets of requirements which the solution sought should be reasonably expected to satisfy in any case. Nonetheless, this is not necessarily so and, in the design of the solution algorithm, particular care should be taken to this effect. In particular, it will be shown that, for certain classes of problems, configuration-dependent interpolation is instrumental for preservation of such a key mechanical principle as the objectivity of the approximated strain measures and provides ample space for development of more accurate solutions than those obtainable using the standard configuration-independent interpolation.

Principal investigator

Professor dr Gordan Jelenić, Faculty of Civil Engineering, University of Rijeka

Team members

Assistant Professor dr Dragan Ribarić, Faculty of Civil Engineering, University of Rijeka

Assistant Professor dr Edita Papa Dukić, Faculty of Civil Engineering, University of Rijeka
Dr Leo Škec, Faculty of Civil Engineering, University of Rijeka
Dr Paulo Šćulac, Faculty of Civil Engineering, University of Rijeka
Dr Maja Gaćeša, Faculty of Civil Engineering, University of Rijeka
Dr Mohammad Reza Moosavi, Faculty of Civil Engineering, University of Rijeka
Sara Grbčić, doctoral student, Faculty of Civil Engineering, University of Rijeka

Introduction and methodology

Although pertaining only to linear analysis, the quest for the reference linear solution is worth considering in its own right. This is due to the fact that in many situations the reference approximation is yet to be found, or an existing reference interpolation needs to be put in a form suitable for the configuration-dependent generalisation. Within the project, specific attention will be paid to providing such reference linear solutions for beams with off-set reference axis, beams of constant spatial curvature, and multi-layered bars and beams with rigid and elastic-slip conditions between layers as well as the reference linear solution for the problem of motion of pseudo-rigid bodies. Where analytical solutions exist, but cannot be cast in a closed form (e.g. beams of non-constant curvature, plates and shells, multi-layered beams with interlayer uplift) the reference linear solution will be sought in a form of a polynomial approximation to the infinite-series analytical solution up to a chosen degree.
The requirement of property preservation (PP) is the core subject of the project and most of the allocated resources will be dedicated to performing it. This requirement, or rather its specific manifestations, has been at the heart of most of the existing attempts in the literature aimed at resolving certain specific problems, without necessarily recognising the configuration-dependent character of the ensuing interpolation. In different classes of problems (e.g. 3D beams, shells, time integration) preservation of certain properties in the non-linear analysis (e.g. consistent interpolation, higher-order convergence, momentum and energy conservation) will become particularly demanding in a very clear correspondence to the solution space of the problem to be considered. Within the project, a variety these problems will be investigated in detail.

Project work-packages

The project is divided into following work-packages:

WP1. (Jelenić, Ribarić, Papa Dukić) Configuration-dependent interpolation for homogeneous straight and curved 3D beams (based on strain-invariance, path-independence and kinematically consistent interpolation in non-linear analysis and exact polynomial and non-polynomial solution and their approximation to a chosen degree in linear analysis).

WP2. (Jelenić, Ribarić) Configuration-dependent interpolation for homogeneous flat and curved shells (based on kinematically consistent interpolation and higher-order convergence in non-linear analysis and an approximation of the exact infinite-series solution to a chosen degree in linear analysis).

WP3. (Jelenić, Škec, Šćulac) Configuration-dependent interpolation for straight layered 2D beams including discontinuities (based on kinematically consistent interpolation in non-linear analysis and exact non-polynomial solution for polynomial loading in bending, exact non-polynomial solution for point loading in uniaxial state and linear fracture mechanics results in linear analysis).

WP4. (Jelenić, Gaćeša, Moosavi, Grbčić) Configuration-dependent integration of equations of motion (based on kinematically consistent time integration, momentum conservation, preservation of relative equilibria, time symmetry, energy conservation and non-group dissipation in non-linear analysis and closed-form solutions for motion of rigid and pseudo-rigid bodies and kinematic consistence of integration of the translational and rotational parts of the motion).

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

Principal investigator
Prof. Ivica Kožar, D. Sc., Faculty of Civil Engineering, University of Rijeka

Team members
- Prof. Joško Ožbolt, D. Sc., Faculty of Civil Engineering, University of Rijeka and Institute for Materials University of Stuttgart
- Prof. Gojko Balabanić, D. Sc., Faculty of Civil Engineering, University of Rijeka
- Prof. Boris Podobnik, D. Sc., Faculty of Civil Engineering, University of Rijeka and Visiting Researcher at Boston University and National Univ. of Singapore
- Doc. Silvija Mrakovčić, D. Sc., Faculty of Civil Engineering, University of Rijeka
- Dr. Neira Torić Malić, Faculty of Civil Engineering, University of Rijeka
- Dr. Anamarija Perušić Pribanić, Faculty of Civil Engineering, University of Rijeka
- Natalija Bede, Faculty of Civil Engineering, University of Rijeka
- Tea Rukavina, doctoral student on the Project, Faculty of Civil Engineering, University of Rijeka

Objectives of the Project

A. Damage model for concrete under dynamic loading

The main goal in this phase of the research is extension of the existing nonlinear viscoelastic model (Kožar and Ožbolt, 2010) based on algebraic differential equations into three-dimensional model suitable for large problems. The inclusion of the viscous parameter in the existing 3D micro-plane model for concrete (Ožbolt et al., 2001) 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, it will enable more precise modeling of concrete durability.

Prevailing attitude in modeling concrete structures under dynamic loading is the hypothesis that the material constitutive law should incorporate "rate effect" (dependence of material properties on the loading rate). In Kožar and Ožbolt, 2010; Travaš et al., 2009; Ožbolt et al., 2011, 2013; Ožbolt and Sharma, 2012 this concept has been disapproved and substituted with an approach that the inertial forces from the dynamical model are sufficient for describing the rate effect. Also, possibility of the viscous regularization of the material model will be considered. Here, regularization is correction in the softening material model so that it is independent of the discretization (finite element mesh size and orientation). In later stage of development homogenization procedure based on the two scale convergence approach will be investigated. Suitable time integration method (symplectic integrator) will be developed as an extension of time integration procedure developed in Kožar, 2009. The idea of (approximately) constant fracture energy for all loading rates is new and important in models of concrete under the dynamic loading.

B. Influence of thermal, hygroscopic and chemical process on mechanical properties of concrete (coupled mechanical problem)

To build safe and economic structures, it is important that the behavior of concrete under extreme load conditions (explosions, fire, earthquake, fatigue, creep and shrinkage, etc.) is known. In these areas there are still many open questions. Particularly, the modeling of concrete under high loading rates (impact), creep and shrinkage of concrete and its interaction with damage has with regard to the durability of concrete structures great importance. Moreover, the fatigue of concrete due to constantly changing loads in, for instance, bridge or offshore structures is of enormous importance. Therefore, the development of the model that is able to predict behavior of concrete and reinforced concrete structures under such extreme conditions is of great importance for the community.

The existing 3D hygro-thermo-mechanical model will also be extended in a way that for given boundary conditions simulation of physical and electrochemical processes and their interaction with reinforcement (corrosion) and mechanical properties of concrete will be accounted for. This means that corrosion will influence the mechanical properties of concrete and that the mechanical properties will have an effect on the transport of humidity, oxygen and chloride. Such a models are in the literature known as chemo-hygro-thermo-mechanical models.

Most of known model of reinforcement steel corrosion in concrete are solved in one or two dimension, neglecting the influence of mechanical damage (cracks) in the concrete. In order to enable realistic modeling of service life of the reinforced concrete structures exposed to chlorides and mechanical damage it is necessary to develop a unique three-dimensional chemo-hygro-thermo-mechanical model which will realistically simulate both initiation and propagation phase depending on the mechanical damage.

C. System identification procedure for determination of the representative volume element

Numerical models of materials and structures are not self-sufficient, calibration of (material) parameters is of great importance for model reliability. In complex 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). Inverse procedures for determination of material parameters have to be modified to take into account the stochastic nature of the process.

We will concentrate on application of inverse mathematical methods in dynamic system identification and will assume that there is a finite element model of the structure and some input-output (force-accelerations/displacement) measurements. Some FEM models and related measurements will be obtained through the existing IPA3C project but some additional models and measurements will have to be performed. However, there is a major difficulty in dealing with real structures since force (loading) cannot be precisely measured if it is stochastic in nature. Dynamic loading on structures is generally stochastic in nature. In laboratory measurements, loading will be controlled but developed procedure has to be applicable to real structures under stochastic loading as well.

One of the main goals of the system identification procedure is representative volume identification. The representative volume element is a key element of the mechanics of random heterogeneous materials; it is a volume of heterogeneous material sufficiently large to be statistically representative and is different for different material properties (e.g. one size for elastic material properties like modulus and Poisson and the other size for thermal properties etc.). It is especially difficult to determine RVE for nonlinear material models like the one used by this research group (3D thermo-hygro-mechanical model (Ožbolt et al., 2008) based on micro-plane material model for concrete (Ožbolt et al., 2001)). System parameter identification will be based on inverse mathematical formulation so to present a reliable and theoretically sound procedure for identification of required parameters.