Characteristics of main research directions investigated at the institute and the achievements 2010−2014

Institute	Institute of Theoretical and Applied Mechanics of the CAS, v. v. i.

The presented characteristics follow the division of the research orientation of the Institute corresponding to the work in research teams which are subject of evaluation. However, these teams collaborate across borders of individual Departments or Laboratories both within the teams as well as between teams due to interdisciplinary character of some projects. The main directions of research in ITAM were defined in research and development plans with time overlapping till 2017. They were and are concentrated in three families of problems and solved in ad hoc created teams across the organizational structure of the Institute: i) section of dynamics, stochastic mechanics and theory of structures, ii) section of mechanics of materials, experimental mechanics and biomechanics and iii) section for interdisciplinary research of cultural heritage problems which was a nucleus of the built Centre of Excellence in Telč. Scientists in the first section developed stochastic dynamics of linear and non-linear systems, studied dynamic stability, bi-furcation and post-critical effects, further dynamics of non-conservative systems with moving inertial excitations. In the field of the oriented research they investigated seismic processes and types of response, interactions of systems with the air flow, tasks of wind engineering and dynamics of structures (bridges, pedestrian bridges, transmission TV and other towers). Another research group in this section continued in research of degradation processes in thin-walled vessels and pipes of gas lines and other media transportation lines made of modern steels at complex loads of internal stresses, temperature and aggressive environment. The results aim at reduction of degradation rates, serviceability prolongation, and achievement of required safety and integrity of such systems. This research involved also problems of fatigue on steel bridges of a new generation. The section operates a fatigue laboratory and a Centre for computation and informatics technology carrying out its own research in the field of numerical methods especially application of massive parallel algorithms on available GPU. A small group of scientists was focused on research of solid mechanics problems - mathematical tasks and mezo-mechanics. Selected results are presented in the following paragraphs.

Rational structural and material mechanics

The outputs of preliminary basic research are the scientific articles in respected impacted and international journals, other publications, software, methodologies and technological samples. The main subject of the research In the field of rational dynamics, theoretical (analytical/numerical) was to analyze dynamic stability, transition and post-critical states of Hamiltonian/non-Hamiltonian systems with non-conservative constraints and ability of energy absorption due to interactions with other systems and moving medium. Besides basic principles of stability criteria, bifurcation and solution methods, non-holonomic systems with part-cyclic symmetry, also auto-parametric systems with multi-component semi-trivial solution and self-excited systems were investigated. Mathematical formulations was based on nonlinear differential/algebraic systems subdued to additive/multiplicative deterministic/random excitation originating from interaction with moving medium and from implied energy flow in stable/non-stable regimes. Bifurcation mechanisms was dealt with focus to transition, quasiperiodic, chaotic and stable post-critical states respecting possible stochastic character of systems. Theoretical investigations were carried out together with the experimental background on the following results:

Multi-degree of freedom (MDOF) non-linear systems characterized by a number of response types and with the focus on Limit Cycles and Homoclinic Orbits. They are of the most important cases representing typical post-critical response type of many systems, and can be encountered in aeroelasticity, earthquake engineering, high speed traffic mechanics, etc. The research was focused on the aspects of stability and non-stability and the character of LC being possibly an attractor or a repulser. Exponential LC stability criteria were proposed on the first degree of the perturbation procedure. An approximate geometry of a subspace orthogonal to the LC trajectory has been introduced. It facilitates an effective investigation of an LC behavior in a close neighborhood of the basic trajectory. Theoretical considerations were illustrated using single and two degree of freedom systems already complex enough and being able to be generalized. Formulation with stochastic differential equations. The topic was further extended and formulated with stochastic differential equations. Mostly, the normal form of governing stochastic differential system with Gaussian white noise perturbations was considered. Stability investigation was carried out on the basis of relevant Fokker-Planck (FP) equation. Then, a stochastic differential system with multi-component additive and multiplicative perturbation was constructed and transformed into FP equation with respect to special toroidal coordinate system around the LC. Perturbation of Probability Density Function (PDF) stability was analyzed in the meaning of the mean value and variance using stochastic moments decomposition. As a demonstration, particular case of a single and two degree of freedom systems of the generalized Van der Pol type are discussed. Illustrating cases were studied because of their relevance with the aero-elastic post-critical response types of a slender beam in a cross-flow.

The stability problems analyzed on the case of a kinematically excited spherical pendulum. Double degree of freedom spherical pendulum as an auto-parametric system was used to demonstrate this effect. An analytical–numerical approach of these effects was developed using the original non-linear system. Relevant differential system in ‘‘slow time’’ was presented, which provided periodic, orbital and a few singular solutions separating basic response types. Response trajectories represent certain spiral curves in the horizontal plane, which repeat periodically including higher (thousands) or lower (tens or zero) number of elementary cycles. Trajectories have a shape of generalised hypo-cycloids and can be approximated in every moment by a virtual ellipse moving around its center with time dependent angular velocity and changing size of principal axes in ‘‘slow’’ time. The stability of the response in the vertical plane was analyzed experimentally in the theoretically predicted auto-parametric resonance domain. Three different types of the resonance domain were investigated the properties of which depended significantly on the dynamic parameters of the pendulum and the excitation amplitudes.

The unified linear variant of the general mathematical description of stability conditions. A double degree-of-freedom model for the initially independent heave and pitch self-excited motion is used. The properties of the response located at the stability limits and the tendencies of the response in their vicinity are analyzed by means of the Routh–Hurwitz theorem. The respective stability conditions are depicted in the frequency plane delimited by the frequencies of two principal aero-elastic modes. The application of this method to real bridges was demonstrated and compared with existing results from other approaches and experiments. This criterion enables to sort them roughly in three groups: (i) neutral models - aero-elastic forces are introduced as suitable constants independent from excitation frequency and time; (ii) flutter derivatives - they respect the frequency dependence of aero-elastic forces; (iii) indicial functions - they are defined as kernels of convolution integrals formulating aero-elastic forces as functions of time.

Problems of soil-structure interaction. This area of scientific interest especially in the field of seismic engineering has been studied recently. Although many studies have shown strong influence of interaction on the dynamic response, it is often in practice neglected. Similarly overlooked is the expression of non-classical damping structure, which is caused, e.g., by presence of a damping element and which can also significantly affect the overall dynamic behavior. The basis of the research is studying the combined effect of both these phenomena, i.e., soil-structure interaction and the non-classical damping on modal parameters and the overall response of the structure. The aim was to assess qualitatively and quantitatively their effects, both separately and especially in their combination. Based on the results of theoretical and experimental research the error rates that are caused by neglecting phenomena were studied and quantified.

Fracture mechanics

Important research of the team is in the field of development of an engineering method for application of fracture-mechanics principles to gas pipelines. This research is also related to problems of fatigue under corrosion pipeline steel for transportation of oil. We have developed the methods to detect micro-plastic limit in a structural steel by indirect measurement of magnetic permeability and the effect of stress corrosion on the fracture toughness, breathing-induced fatigue in thin-walled steel girders, fatigue life assessment of orthotropic bridge decks, and breathing-induced fatigue in the lamella flanges of steel bridges. Following results are summarized below:

Approximate expressions for determining fracture parameters. The method utilizes simple approximate expressions for determining fracture parameters K, J, concerning the axial part - through thickness cracks in a pipe wall, and it employs these parameters to determine the critical dimensions of a crack on the basis of equality between the J integral and the J-based fracture toughness of the pipe steel. The crack tip constraint is accounted here by the so-called plastic constraint factor C, by which the uniaxial yield stress in the equation for determining the J integral is multiplied. The results of the prediction of the fracture condition of the pipes were verified by burst tests on test pipes of various dimensions and materials. Only our team was engaged in solving the problem in question so that a full part of the deliverable was formed by our team.

The effect of stress corrosion (SC) on the fracture toughness. The main result of investigation into the effect of stress corrosion (SC) on the fracture toughness was that the fracture resistance of a component depends not only on the material of the component and on the crack tip constraint (the thickness of the wall of the component) but also on the origin of the crack (fatigue, stress corrosion) and thus on the corresponding crack growth mechanism. In contradiction with the opinion that low-C steels are not susceptible to SC cracking the results obtained showed that under conditions specified in the American NACE Standard stress corrosion cracks can be generated from fatigue cracks also in low-C steels such as ČSN 411353. Unlike a fatigue crack, the occurrence of a SC crack in a component means a significant decrease in the fracture toughness characteristics while the crack is exposed to SC conditions and a partial "recovery" of the fracture toughness when SC conditions are removed. In comparison with fatigue fracture toughness characteristics the SC ones were reduced for the low-C steel ČSN 411353 by a factor ranging between 4.5 (Jm value) and 5.7 (Jin value). However, a two-week recovery period made it possible to recover, to some extent, their fracture properties, namely the J integral Jm to almost 80%, the J integral J0.2 to about

60%, and the J integral Jin to about 22% of the fatigue crack J integral values. The result was achieved in collaboration with the team from the Czech Technical University Prague, Faculty of Nuclear Sciences and Physical Engineering. This team contributed to the result by fractographic investigation of fractured surfaces and by micro-hardness tests to determine the shape and size of an increased micro-hardness ahead of the SC crack tip. Our team was engaged in generating SC cracks, performing fracture mechanics tests, evaluating the results and drawing conclusions.

Solid mechanics

Geometrical setting of solid mechanics and its consequence for time-incremental analysis. While the position and shape of a deformed body take place in the usual three dimensional Euclidean space, a corresponding progress of deformation tensor makes up a trajectory in the space of all deformation tensors – a negatively curved Riemannian symmetric manifold. Since this space is not a linear vector space, we cannot simply employ the tools from the theory of small deformations, but in order to analyze deformation processes correctly, we have to resort to the corresponding tools from the differential geometry and Lie group theory, which are capable of handling the very geometric nature of this space. The key idea that the space of all deformation tensors of a body does have naturally defined on it a simple geometric structure – Riemannian metric, which plays a very interesting and important role in the development of the theory, has been so far overlooked. However, utilization of this fact results in a geometrically based approach to solid mechanics via simple Lagrangian system on the space of symmetric positive-definite matrices (deformation tensors). This approach is especially appealing since it enables to utilize the tools of differential geometry and Lie group theory for an analysis of finite deformation processes to provide geometrically justified, unambiguous answers to time-linearization, as well as to time-discrete integration. As a result one obtains natural stress rate, incremental principle of virtual power and generalized logarithmic strain. Further, by recognizing a well known relation as an evolution equation of Lie-type for the right Cauchy-Green deformation tensor, geometrically consistent time-discrete integration schemes for finite deformation processes (such as the Runge–Kutta–Munthe-Kaas methods) are developed, correcting thereby established practice – cf. Simo, J.C., Hughes, T.J.R.: Computational Inelasticity. Springer, Berlin (1997).

Aerodynamics and aero-elasticity

Experiments in aerodynamics, nonlinear aero-elasticity, and heat transfer phenomena. The research in the aerodynamics was significantly enlarged due to construction of unique wind tunnel in Centrum of Excellence Telč. This created the base for experiments in wind engineering aspect (creating special part of fluid dynamics) like simulation of atmospheric boundary layer, turbulence measurement, flow adjustment, vortex flow or vortex induced vibration of non-aerodynamic shapes. The research was also focused on other special effects originating from experiments or numerical investigation like for example large nonlinear response of the girders that showed memory (hysteresis) effects. This was demonstrated as the hysteresis phenomenon together with the separation curves determining the stability boundaries. Also, the solution of influence of the natural frequency ratio on the initiation of unstable vibration has been analyses on the experimental basis. Based on the experimental testing in the climatic wind tunnel, new simple method for unsteady heat transfer on elements of porous materials was developed. In the results, the overall heat transfer coefficient is evaluated together with transient conductive processes arising due to the forced heat transfer at various flow velocities.

Research in dynamics effects on industrial structures, bridges, footbridges, masts, towers, and historical structural elements. The research in the evaluated period was focused on analysis and mitigation of excessive vibration and eventual collapse of structure or bearing parts, which is one of the adverse effects. Dynamic response was used also for the identification of structure properties as a non-destructive way; nowadays an important part of wide research branch discussed in many journals and conferences. The importance of assessment from the engineering perspective was considered from the point of view of requirements for safe design of special structures such as bridges, towers and chimneys or their details. Origin and effects of vibration by wind and other random impulses (transport, technical seismicity) can hardly be explained solely on the basis of experimental research without special numerical solution. The research was focused on the general methodology for response of structures under dynamic excitation and reliability of its important structural components and details. It lead to application in the form of methodologies, publications, software aimed at specific calculations coherent with existing standards. The result was also a prototype of a counting device intended for long-term record of cumulative and the commentaries and changes of existing standards for engineering practice. Practical outputs from the analysis, in situ measurements and laboratories lead to the design of vibration absorbers on several documented examples.

The section of mechanics of materials, experimental mechanics and biomechanics was concentrated on development of micro-structural FEM models of trabecular bones for reliable assessment of their qualities by means of combination with microCT models and mechanical characteristics determined on the level of individual trabeculas. The scientists here developed methods for contactless measurement of deformation behaviour of other biological tissues and their replacements, especially trabecular bone and a hyalline cartilage. Another group studied mechanical characteristics of composites subjected to time variable forces in environments accelerating degradation taking advantage of hybrid experimental numerical methods. The characteristics quantified as parameters of constitutive relations were determined by resolving inversion tasks resulting from synergy of combined physical principles in the developed non-invasive experimental methods which are applied in a range from mezo- to micro-scales. The last group is more focused on development of various special experimental devices which are designed for testing of materials, fracture mechanics investigations and building diagnostics. Some important results are illustrated below.

Biomechanics

Analysis of mechanical properties of trabecular bone at the tissue level. To describe mechanical properties of the compact phase of the spongy bone which serve in material models in further numerical simulations of complex bone structures, a testing methodology was developed and employed for testing base structural elements of the bone. A custom modular loading device was developed which provides a possibility to test micro-scale specimens (smaller then 2mm in length) in different loading modes (tension and three-point bending) and in conjunction with X-ray micro-radiography. The specimens of single trabecula were extracted from several anatomically different locations and were tested in tensile and bending mode. During the loading, radiographs of the loading scene were captured continuously. Real-time control of the testing setup enabled a sufficiently low loading rate, which was crucial in order to capture radiographs with a favourable signal-to-noise ratio. The specimens' surface was equipped with gold plated micro-spheres (diameter 5 to 15 microns), which served in the radiographs as tracking features. The deformation behaviour was described tacking advantage of displacement tracking of these features using digital image

correlation method. This technique enables to track the displacement on the specimen surface with sub-pixel accuracy. Additionally, in the radiographs, strain evolution was tracked and relationship between strain and change in attenuation for X-rays was analyzed.

Advanced experimental mechanics in material research

Experimental evaluation of contour J integral and energy dissipated in the fracture process zone. The direct calculation of the J integral, CTOD and separation energy based on experimental full field displacement measurement was successfully implemented and tested for specimen with completely yielded ligament. X ray radiography served for identification of the fracture process zone (FPZ) and newly developed crack. It was proven that the obtained dependence of the J integral on the loading displacement does not have any indication of the critical value Jc. The results show that the J integral is independent of the integration path although the integration paths tested crossed completely yielded ligament. It was documented, that simple calculation of the JCTOD integral from the CTOD gives similar results. However, obtained dependence JCTOD on loading displacement has such different shape than these calculated directly, that it cannot be reliable corrected using some conventionally used multiplication coefficient only. Contrary with J integral evolution, the experimentally obtained dependence of the specific separation energy on the loading displacement has a sharp maximum, which corresponds to the intensive evolution of the separation area. Maximal value of the specific separation work (specific work of fracture) is significantly lower than J integral at the same loading state. Values of the specific work of external forces are in good correlation with measured J integral. We can conclude from this reason that evaluated specific plastic work is approximately equal to the fraction of the plastic work comprised in the calculated J integral as predicted by the theory of separation energy or essential work of fracture.

Quasi-static compressive deformation characteristics of a closed-cell metal foam. To evaluate mechanical characteristics of a closed-cell metal foam uni-axial compressive experiments were carried out using in-house developed loading device optimized on minimal attenuation of X-rays for the feasibility of radiographical imaging of specimens under loading. The device was designed geometrically and structurally with respect to dimensions of the representative volume element of the studied material that was determined by statistical image and signal processing methods. Using the device time-lapse X-ray micro-tomography under gradual loading was performed to obtain volumetric image data in every loading step and thus detailed response of the specimens' microstructure to applied load. High resolution strain fields were derived from the image data acquired in individual loading steps by digital volumetric correlation (DVC) of the deforming microstructure. The resulting displacement and strain fields were then used to calculate elastic characteristics of the specimens inversely using numerical simulations of the experiments based on detailed voxel finite element models of the non-deformed specimens. Displacement of the top face of specimens calculated by DVC was used in the FE simulations as a boundary condition to evaluate total reaction force inversely at the constrained nodes for assessment of the specimens' effective elastic characteristics.

The last section research activities were strongly tied to the established infrastructure that covers three specific areas of research, grouped into three work packages of the original CET project proposal. They are primarily activities related to the climatic “Vincenc Strouhal” wind tunnel, which were shortly described above. The research has been supported by SADeCET project as part of the national sustainability programme, the Czech-Taiwan bilateral GAČR

project "Random vibration of beam structures caused by a combination of moving load and wind ", standard GAČR project "Thermally stratified atmospheric boundary layer developing over a complex surface modelling in climatic wind tunnel" and postdoctoral GAČR project "Solution of dynamic stability of nonlinear systems with multiple degrees of looseness and random excitation using the Fokker-Planck equation ". Thematically these include projects with possible application development in building industry. It blends basic and applied research with the predominance of basic research. Within the start-up program short-term pilot projects have been developed, aimed at preparing new grant proposals, e.g.: features of the current and atmospheric boundary layer in the aerodynamic section and suggestions for modification by means of screens; methodology of ice and frost formation on carrying cables of a suspended bridge; stability of one or two parallel U-beams and suppression of their large vibrations; testing pressure distribution on a standardized cube, irregular bodies and comparison with numerical procedures; distribution of the heat transfer coefficient near a cylinder in air flow; flow visualisation methods, their comparison and computer simulations and processing. The climatic wind tunnel is designed as a regional infrastructure in terms of the ESFRI road map. Another important group of laboratories is the radiography and corrosion workshop. The micro-tomography laboratory is a unique facility with a wide research potential and development possibilities, and it is closely shared with the section above. The group of laboratories for biodegradation, chemical and physical analyses, mobile diagnostic laboratory, monitoring networks and databases and laboratory for sustainability of monuments are used exclusively for a focused research of interdisciplinary issues of cultural heritage. The group includes an experimental lime kiln with the firing capacity of up to one ton of limestone. The laboratories are equipped with a comprehensive set of analytical, diagnostic and testing equipment, thus achieving very specific concentration of infrastructure for interdisciplinary research on cultural heritage under a single roof, which has no parallel in the world. The research was supported by 12 grant projects of NAKI MK ČR programme, one grant project of the GAČR Centre of excellent research, one postdoctoral GAČR grant project and two cross-border Czech-Austrian projects. This area has also been supported by the SADeCET project of the national sustainability programme. The topics of projects in basic research include a study of cumulative time-dependent processes in building materials and structures, and a study of the kinetics and CaCO3 polymorphs in the course of lime carbonation. In applied research it concerns research on damage of immovable monuments and development of a knowledge-based system for analysis, proposed interventions and prevention; development of high performance and compatible lime mortars for extreme applications in the restoration, repair and preventive maintenance of architectural heritage; development of the methodology and instruments for protection and preservation of cultural heritage at risk from flooding; research on traditional lime technologies of historic buildings and their use in the present; research and development of new materials and technologies for preservation of the surfaces of historical buildings and for preventive preservation; research and development of the technology of maintenance and preservation of the mosaic of the Last Judgment and methods of restoration-conservation of Medieval glass; research on the conditions and requirements of compatible care of historical porous inorganic materials; a comprehensive methodology for the selection and processing of a stone intended for replacements and repairs of the ashlars masonry of historic buildings; development of a unified modular system of remote on-line monitoring of environmental parameters of depositories and expositions; research on selected preservation methods to improve care for sculptures and monuments; research and assessment of wooden carpentry joints of historical structures; research on application of colloidal nano-particles of lime for consolidation of Leitha limestone and development of procedures to diagnose and preserve unused religious monuments. Within the start-up program pilot projects were launched to develop new

materials with a significant overlap to the topic of the proposed project, i.e. outside the scope of historical materials and materials for their preservation and conservation, e.g. the study of production of magnesium phosphate cement using toxic asbestos-cement waste. In total, the start-up programme (next to the grant projects) dealt with other 25 pilot projects. Some illustrative examples of the work, which attracted a wider attention or have an application potential are presented.

Climate change and global change problems

Comprehensive flood protection of monuments. A collection of comprehensive works covering the damage analysis caused by floods on monuments enabled a processing of proposals for measures to reduce or completely mitigate damages on cultural heritage during floods was a result of a EC supported CHEF project and a national NAKI project. Scientific findings for assessing the historic materials and structures affected by floods or excessive water ingress include examples of a behaviour of typical monuments during and after flooding. The results are important for a flood risks mapping and also contain recommendations and guidelines for the use of non-destructive methods for monitoring the behaviour of historical materials after a flood (drying, desalination, biological control). Various forces and actions during flood situations were sorted according to their ability to cause damage into the following categories: horizontal static pressure of raised, upward hydrostatic pressure, dynamic low velocity stream, dynamic high velocity stream, dynamic impact of waves, dynamic impact of floating objects, compacting of soils or infill, change of subsoil conditions, saturation of materials with water, contamination of materials with chemical and biological agents, creation of barriers, ice floe and post-flood effects. An analysis of key factors influencing the quality of the indoor environment during flooding was carried out. A penetration of flood water into a building, along with other symptoms, causes deterioration of parameters of the internal environment - heat and moisture, odor, microbial, aerosol and toxic. The surveys and analysis of flooded structures engaged in finding species of moulds occurring in buildings immediately after flooding with a view to their possible influence of health complications of persons staying or working in affected buildings. The research study documents that a flood means for architectural heritage and the indoor environment in buildings a significant amount of risk factors, each requiring a specific approach remediation.

Protection of built heritage against earthquake. During a European project NIKER project a new integrated methodology aiming at improving the general safety level for CH assets and at reducing the loss of artistic value has been developed. On a basis of a multidisciplinary approach innovative materials and systems for low-intrusiveness and compatible interventions were proposed. ITAM scientists investigated wooden elements in masonry structures and developed energy absorbers for roof frames and floor joists anchoring. They were responsible for the final "guidelines".

Compatible dilation limits of masonry joint mortars. The effects of joints on the behaviour of masonry and on the damage processes have been investigated in various studies. The typically observed damage to some water-sensitive stone in ashlar masonry has usually been explained as a consequence of increased moisture and possible frost damage in the vicinity of impermeable mortar joints. A new numerical model describes the compatibility limits in relation to coefficients of thermal expansion and moduli of elasticity of two adjacent materials creating a composed structure.

Calibration Eurocode 7-1 (Geotechnical design). Two long-term experiments E5 / 0.2 (April, 8th – October, 13th 2010) - 5 phases of movement, max. displacement at the bottom u = 226.89 mm, speed of 0.005 mm / min, E6 / 0.2 (March, 25th -December 13th 2011) - 5 phases of movement, max. displacement at the bottom u = 212.32 mm, speed of 0.005 mm / min - showed a different behaviour of a granular body than assumed by a current theory. A follow up numerical analysis of the experimental data confirmed the different behaviour of an ideal granular body than that of the considered by the current theory and its application in practice (Eurocode 7-1, Annex C). When such behaviour is fully demonstrated the development of an advanced theory with subsequent modifications of Eurocode 7 - 1 is going to be proposed.

Materials - analysis, replication, consolidation and testing

Research and valorisation of traditional materials. The knowledge and understanding of differences between the modern and historic materials based on the characterisation and diagnostic work led to new research topics. Knowledge about historic technologies and materials is very important in the protection and conservation of cultural heritage. However, the modern materials differ from the originals and sometimes even do not exist or are not available on the market. One of the typical examples is Natural hydraulic lime. Natural hydraulic lime (NHL) binders are nowadays not produced in the Czech Republic however they had been historically well spread and used. Well known was the Staroměstké lime. The experimental re-evaluation of the traditional lime binders provided a new technical knowledge for their use for repair of monuments and also it was an inspiration for a development of new alternative binders. In relation to the valorisation of traditional historic binders an experimental lime kiln was designed and built. This new unique facility allowed to study the traditional production processes. The kiln was used for research and development of "copies" traditional lime binders, that are no longer produced, and which could find their use in conservation of build heritage. A GIS geodatabase comprising data about current and historic limestone quarries including chemical composition of the main geological stratigraphic layers and data about historic technologies related to lime production was designed and is in operation. It holds about 1000 records related to quarries in the Czech Republic. It serves as a research tool, as well as, it is a basic data source for publication of specialised maps related to this field including WMS maps.

Research and development of new materials. The Institute's laboratories are involved in the research and development of new building materials mainly for applications in repairs and maintenance with a special care for cultural heritage applications. Some employees are members of RILEM TCs that deals with testing and requirements for design of new repair materials, e.g. RILEM203 RHM Repair mortars for historic masonry and TC SGM Nonstructural grouting for architectural surfaces. Involvement in the RILEM TCs and other similar groups provides an international collaborative framework for testing and design of new materials. Important result of the past research was the assessment of the effect of an addition of a small amount of linseed oil on lime and lime-metakaolin mortars. Significant durability improvement of both lime and lime-metakaolin mortars enriched with linseed oil was achieved: remarkable capillarity reduction and consequently higher resistance to NaCl cycles. Linseed oil had a different effect on the two studied mortars: mechanical strength was slightly reduced for lime+oil (LO) and slightly raised for lime-metakaolin+oil (LMO). The study proved that 1.5 wt. % of linseed oil is a good proportion to achieve satisfactory performance on tested mortars.

Pilot research on asbestos transformation. Another, research topic evolved in relation to the widened possibilities in the Centre of Excellence in Telč where a topic of preparation of magnesium phosphate cement by recycling the product of thermal transformation of asbestos containing wastes was introduced. An experimental production process carried out represents a viable recycling opportunity for this class of hazardous wastes. Simultaneous destruction of asbestos minerals and formation of reactive MgO during thermal treatment, bring benefits in terms of energy requirements and preservation of natural resources in cement manufacturing.

The structure and material composition of ossified aortic valves identified using a set of scientific methods. Aortal valve mineralization very frequently causes a genesis of aortic stenosis, which is the most often surgically treated heart disease. Hydroxyapatite deposits have been identified as one of the causes leading to the loss of elasticity of the aortic valves. It is known that phosphates/calcium is accumulated in valve tissues during mineralization, but the mechanism of this process remains unclear. The work is focused mainly on the study of protein composition of mineralized aortic valves by nano-liquid chromatography electrospray ionization in a quadrupole orthogonal acceleration time-offlight mass spectrometry. New methodological approach based on direct enzymatic digestion of proteins contained in hydroxyapatite deposits was developed for the study of pathological processes connected with osteogenesis.

Evaluation of the consolidation effect of lime water and other consolidants on lime based porous substrates. The effectivity of various strengthening substances was assessed by especially designed tests and procedures. No consolidating effect of distilled water on the compressive strength of the tested mortar specimens with a low lime binder content (1:9) was observed. The mechanical characteristics of the tested mortar specimens were also not improved by a treatment of a lime water with added metakaolin. The lime water treatment was proven to be effective only after a sufficiently large number of applications (160 saturations). Barium water treatment significantly increased mainly the tensile strength of the tested mortar specimens. In addition, also other substances used in conservation to restore the cohesion and reinforcement of natural stone and plaster were evaluated. These were especially substances based on silicic acid ester and nanoparticle suspensions of calcium hydroxide in ethanol or isopropyl alcohol. The suspension of lime particles in alcohols allows application of a much higher concentration of active ingredient than is possible in the case of an aqueous solution, moreover, in many cases the use non-aqueous suspension is also advantage. In terms of time and the strengthening effect the experiment proved that the combined use of dilute silicic acid esters followed by a multiple application nano-lime suspension in ethanol could be a very effective approach. Testing of mechanical properties of historic building materials before and after treatment is the basic method enabling to experimentally determine the consolidation effect of strengthening substances impregnated into age-damaged surfaces of historic buildings.

Characterisation of historic materials. Several studies and historic material characterisations were carried out during the monitored period as a part of research projects or as a contractual research. The laboratories of the institute routinely carries standard tests as well as involve in development of modified tests and procedures. For example a set of non-standard techniques have been developed or modified for testing mechanical characteristics of mortars on small specimens extracted from existing structures. And also a methodology comprising of several non-destructive testing methods for use to diagnose historic materials was proposed. It includes test for assessment of a surface cohesion of stone and renders and determination of the rate of water penetration into material. A modified standard methodology for testing

strength of mortars was used for the diagnosis of historic mortars on an Italian ancient bridge. The measured characteristics can be also used to study building history and technology, or to assess the effectiveness of conservation methods.

Development of devices for testing mechanical properties of wood (2 patents). Two devices were designed, developed, tested and patented: (i) a diagnostic device for field and laboratory measurement of conventional strength and modulus of deformation during pushing jaws into sides of a drilled hole, and (ii) a device for measuring mechanical resistance of wood against pushing in a needle or pulling out a screw. The first device may be also used in situations where it is not possible or appropriate to use a resistance drilling but it is necessary to determine the mechanical properties of wood throughout the diameter of the element. The second device is used for determination of mechanical properties of built in wood in order to assess reliability of timber structures or for their design modifications, strengthening, load capacity, etc. A significant result was achieved in the field of wood diagnostics as the correlation relationship between the conventional strength derived from the newly-designed instrument and the mechanical properties of wood determined according to standards. The verification of the applicability of the new instrument was based on experiments and numerical simulations. The tested semi-destructive methods produced relatively low damage of wood and they can be used to assess all types of wooden structures.

Research Report of the team in the period 2010–2014

Institute	Institute of Theoretical and Applied Mechanics of the CAS, v. v. i.

Scientific team	Engineering mechanics

Rational structural mechanics, dynamics, industrial aerodynamics

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Multi-degree of freedom (MDOF) non-linear systems characterized by a number of response types and with the focus on Limit Cycles and Homoclinic Orbits. They are of the most important cases representing typical post-critical response type of many systems, and can be encountered in aeroelasticity, earthquake engineering, high speed traffic mechanics, etc. The research was focused on the aspects of stability and non-stability and the character of LC being possibly an attractor or a repulser. Exponential LC stability criteria were proposed on the first degree of the perturbation procedure. An approximate geometry of a subspace orthogonal to the LC trajectory has been introduced. It facilitates an effective investigation of an LC behavior in a close neighborhood of the basic trajectory. Theoretical considerations were illustrated using single and two degree of freedom systems already complex enough and being able to be generalized.

Formulation with stochastic differential equations. The topic was further extended and formulated with stochastic differential equations. Mostly, the normal form of governing stochastic differential system with Gaussian white noise perturbations was considered. Stability investigation was carried out on the basis of relevant Fokker-Planck (FP) equation. Then, a stochastic differential system with multi-component additive and multiplicative perturbation was constructed and transformed into FP equation with respect to special toroidal coordinate system around the LC. Perturbation of Probability Density Function (PDF) stability was analyzed in the meaning of the mean value and variance using stochastic

moments decomposition. As a demonstration, particular case of a single and two degree of freedom systems of the generalized Van der Pol type are discussed. Illustrating cases were studied because of their relevance with the aero-elastic post-critical response types of a slender beam in a cross-flow.

The solution of non-linear mechanical systems subjected to the stochastic processes. Multiplicative and additive types of Gaussian and non-Gaussian random excitation were introduced and solved using the Fokker-Planck equation and originally developped variant of Finite Element Method. The proposed probabilistic method was applied to particular problems of flow-structure interaction, where oscillatory phenomena and their character with respect to the stochastic approach were examined, both qualitatively and quantitatively.

The stability problems analysed on the case of a kinematically excited spherical pendulum. Double degree of freedom spherical pendulum as an auto-parametric system was used to demonstrate this effect. An analytical–numerical approach of these effects was developed using the original non-linear system. Relevant differential system in ‘‘slow time’’ was presented, which provided periodic, orbital and a few singular solutions separating basic response types. Response trajectories represent certain spiral curves in the horizontal plane, which repeat periodically including higher (thousands) or lower (tens or zero) number of elementary cycles. Trajectories have a shape of generalised hypo-cycloids and can be approximated in every moment by a virtual ellipse moving around its center with time dependent angular velocity and changing size of principal axes in ‘‘slow’’ time. The stability of the response in the vertical plane was analyzed experimentally in the theoretically predicted auto-parametric resonance domain. Three different types of the resonance domain were investigated the properties of which depended significantly on the dynamic parameters of the pendulum and the excitation amplitudes.

The unified linear variant of the general mathematical description of stability conditions. A double degree-of-freedom model for the initially independent heave and pitch self-excited motion is used. The properties of the response located at the stability limits and the tendencies of the response in their vicinity are analyzed by means of the Routh–Hurwitz theorem. The respective stability conditions are depicted in the frequency plane delimited by the frequencies of two principal aero-elastic modes. The application of this method to real bridges was demonstrated and compared with existing results from other approaches and experiments. This criterion enables to sort them roughly in three groups: (i) neutral models - aero-elastic forces are introduced as suitable constants independent from excitation frequency and time; (ii) flutter derivatives - they respect the frequency dependence of aero-elastic forces; (iii) indicial functions - they are defined as kernels of convolution integrals formulating aero-elastic forces as functions of time.

Experiments in aerodynamics, nonlinear aeroelasticity, and heat transfer phenomena. The research in the aerodynamics was significantly enlarged due to construction of unique wind tunnel in Centrum of Excellence Telč. This created the base for experiments in wind engineering aspect (creating special part of fluid dynamics) like simulation of atmospheric boundary layer, turbulence measurement, flow adjustment, vortex flow or vortex induced vibration of non-aerodynamic shapes. The research was also focused on other special effects originating from experiments or numerical investigation like for example large nonlinear response of the girders that showed memory (hysteresis) effects. This was demonstrated as the hysteresis phenomenon together with the separation curves determining the stability boundaries. Also, the solution of influence of the natural frequency ratio on the initiation of

unstable vibration has been analyses on the experimental basis. Based on the experimental testing in the climatic wind tunnel, new simple method for unsteady heat transfer on elements of porous materials was developed. In the results, the overall heat transfer coefficient is evaluated together with transient conductive processes arising due to the forced heat transfer at various flow velocities.

Research in dynamics effects on industrial structures, bridges, footbridges, masts, towers, and historical structural elements. The research in the evaluated period was focused on analysis and mitigation of excessive vibration and eventual collapse of structure or bearing parts, which is one of the adverse effects. Dynamic response was used also for the identification of structure properties as a non-destructive way; nowadays an important part of wide research branch discussed in many journals and conferences. The importance of assessment from the engineering perspective was considered from the point of view of requirements for safe design of special structures such as bridges, towers and chimneys or their details. Origin and effects of vibration by wind and other random impulses (transport, technical seismicity) can hardly be explained solely on the basis of experimental research without special numerical solution. The research was focused on the general methodology for response of structures under dynamic excitation and reliability of its important structural components and details. It lead to application in the form of methodologies, publications, software aimed at specific calculations coherent with existing standards. The result was also a prototype of a counting device intended for long-term record of cumulative and the commentaries and changes of axisting standards for engineering practice. Practical outputs from the analysis, in situ measurements and laboratories lead to the design of vibration absorbers on several documented examples.

Problems of soil-structure interaction. This area of scientific interest especially in the field of seismic engineering has been studied recently. Although many studies have shown strong influence of interaction on the dynamic response, it is often in practice neglected. Similarly overlooked is the expression of non-classical damping structure, which is caused, e.g., by presence of a damping element and which can also significantly affect the overall dynamic behavior. The basis of the research is studying the combined effect of both these phenomena, i.e., soil-structure interaction and the non-classical damping on modal parameters and the overall response of the structure. The aim was to assess qualitatively and quantitatively their effects, both separately and especially in their combination. Based on the results of theoretical and experimental research the error rates that are caused by neglecting phenomena were studied and quantified.

Fracture mechanics, solid mechanics

Important research of the team is in the field of development of an engineering method for application of fracture-mechanics principles to gas pipelines. This research is also related to problems of fatique under corrosion linepipe steel for transportation of oil. We have developed the methods to detect microplastic limit in a structural steel by indirect measurement of magnetic permeability and the effect of stress corrosion on the fracture toughness, breathing-induced fatigue in thin-walled steel girders, fatigue life assessment of orthotropic bridge decks, and breathing-induced fatigue in the lamella flanges of steel bridges. Following results are summarized below:

Approximate expressions for determining fracture parameters. The method utilizes simple approximate expressions for determining fracture parameters K, J, concerning the axial part -

through thickness cracks in a pipe wall, and it employs these parameters to determine the critical dimensions of a crack on the basis of equality between the J integral and the J-based fracture toughness of the pipe steel. The crack tip constraint is accounted here by the so-called plastic constraint factor C, by which the uniaxial yield stress in the equation for determining the J integral is multiplied. The results of the prediction of the fracture condition of the pipes were verified by burst tests on test pipes of various dimensions and materials. Only our team was engaged in solving the problem in question so that a full part of the deliverable was formed by our team.

Fatigue behaviour in zero-to-tension loading of pipeline steel. L485MB was investigated in various environments typical for crude oil processing and transport: crude oil, water separated from the crude oil phase, and a mixture of crude oil with rain water. For a reference, fatigue tests were also made in air. The results proved that crude oil had no negative effect on the fatigue properties of the steel. This contrasted with the effect of separated water, which exhibited corrosion aggressivity towards this steel. The corrosion aggressivity of the separated water was found to be formed by its saturation with oxygen and by a high content of chlorides. However, the presence of acid carbonates in high concentrations reduced its aggressivity. Under the conditions of the crude oil pipeline, the separated water can contain only a limited amount of oxygen, but under the conditions of long-term storage separated water can become saturated with air. This environment can then be considered as the most aggressive really possible environment. In other words, due to the low pH value and the high [c(Cl) + c(SO4)] / [c(HCO3)] ratio, separated water is an environment characterized by the highest chemical corrosion activity. The effect of the crude oil environment on the fatigue properties of the steel was found to be comparable to that of an inert environment, since it manifested itself by blocking the surface towards air oxygen (fatigue tests in air). The result was achieved in collaboration with the team from the Institute of Chemical Technology in Prague. This team participated in the chemistry work associated with the chemical activity of the environments towards the steel and our team was engaged in fatigue testing of specimens in these environments, evaluation of the results and drawing conclusions.

Cyclic stresses below the fatigue limit. It is generally accepted that not all cyclic stresses below the fatigue limit are non-damaging. Particularly in spectrum loading, the inclusion of some cyclic stresses below the fatigue limit can reduce the fatigue life of a component. It is believed that the boundary between damaging and non-damaging stresses is the so-called micro-plastic limit (MPL) defined as a macro-stress at which dislocation pile-up stresses begin to obstruct the magnetic domains in rotation to the direction of the tensile stress. Our research showed that MPL can be determined from changes in magnetic permeability during tensile loading which were measured indirectly – by measuring changes in electrical impedance (a.c. resistance and inductance). Measurements were performed on normalized low-C steel CSN 411375, and the microplastic limit was determined by evaluating the appropriate records. The MPL values were found to be greater than the friction stress needed for unlocked dislocations to move in the lattice, but to be less than the fatigue limit in symmetrical reverse loading. Block test - based informative results proved that the microplastic limit (MPL) separates damaging stresses and non-damaging stresses below the fatigue limit. The result was achieved in collaboration with the team from the University of West Bohemia, Faculty of Mechanical Engineering, Pilsen. This team contributed to the result by ensuring basic cyclic tests to generate a required damage to a specific group of specimens, and a special investigation regarding the variation of dislocation density during application of stress cycles. Our team was engaged in special measurements of changes in a.c. resistance and inductance of specimens during monotonic as well as cyclic loading, evaluation of results, drawing conclusions.

The effect of stress corrosion (SC) on the fracture toughness. The main result of investigation into the effect of stress corrosion (SC) on the fracture toughness was that the fracture resistance of a component depends not only on the material of the component and on the crack tip constraint (the thickness of the wall of the component) but also on the origin of the crack (fatigue, stress corrosion) and thus on the corresponding crack growth mechanism. In contradiction with the opinion that low-C steels are not susceptible to SC cracking the results obtained showed that under conditions specified in the American NACE Standard stress corrosion cracks can be generated from fatigue cracks also in low-C steels such as CSN 411353. Unlike a fatigue crack, the occurrence of a SC crack in a component means a significant decrease in the fracture toughness characteristics while the crack is exposed to SC conditions and a partial "recovery" of the fracture toughness when SC conditions are removed. In comparison with fatigue fracture toughness characteristics the SC ones were reduced for the low-C steel CSN 411353 by a factor ranging between 4.5 (Jm value) and 5.7 (Jin value). However, a two-week recovery period made it possible to recover, to some extent, their fracture properties, namely the J integral Jm to almost 80%, the J integral J0.2 to about 60%, and the J integral Jin to about 22% of the fatigue crack J integral values. The result was achieved in collaboration with the team from the Czech Technical University Prague, Faculty of Nuclear Sciences and Physical Engineering. This team contributed to the result by fractographic investigation of fractured surfaces and by microhardness tests to determine the shape and size of an increased microhardness ahead of the SC crack tip. Our team was engaged in generating SC cracks, performing fracture mechanics tests, evaluating the results and drawing conclusions.

The fatigue life estimation of orthotropic steel bridge. Fatigue life estimation of decks using the finite element method is most frequently associated with the application of the structural hot spot stress approach or the effective notch stress approach, rather than the traditional nominal stress approach. The application of these approaches to a welded joint with cut-out holes in orthotropic bridge decks, where it is not easy to distinguish the non-linear stress caused by the notch at the weld toe from the stress concentration effect emanating from the hole in the detail, was investigated. The results of the finite element calculations were compared with the results of the fatigue tests which were carried out on full-scale specimens. The results of the finite element analyses revealed that the structural hot spot stresses obtained from the shell element models were unrealistically high when the welds were omitted. Moreover, the way in which the welds were represented had a substantial influence on the magnitude of the hot spot stress. The results of the analysis when using the effective notch stress approach showed that the agreement between the estimated fatigue life using this approach and the fatigue life obtained from the fatigue tests was good.

Thin-walled systems. With the view to create all necessary pre-conditions for a successful application of thin-walled systems, and thereby for saving steel and fabrication expenses, in steel bridgework and other steel structures subjected to many times repeated loading, an investigation was carried out at ITAM ASCR on thin-walled steel girders under the action of various kinds of repeated loads. The main objective was to study, and map, the "erosion" of the post-buckled behaviour of the slender webs of the girders, which is generated by the cumulative damage process and comes to being under the many times repeated loading cycles to which the girder is exposed. The experiments were carried out in the Laboratory of ITAM ASCR, the influence of several kinds of repeated loading being studied. It was found out that the main impact of the cumulative damage process generated by the repeated buckling (so-called breathing) of the slender web under the many times repeated loads was

the initiation and propagation of fatigue cracks. They initiate in the crack-prone areas at the toes of the fillet welds connecting the breathing web with the girder flanges and stiffeners, and thereafter propagate so that in the end they cut off the tension diagonal in the buckled web, which is the main element of the beneficial post-buckled behaviour of the web. Then, of course, a significant "erosion" of the postbuckled performance of the web and of the ultimate strength of the whole girder occurs, which ought to be taken into account in design. In establishing a suitable and user-friendly method of design, compatible with the conclusion drawn hereabove, the authors based their reasoning on the requirement that, in the course of the useful life of the girder, either no or very small fatigue cracks can develop, such as to be easily kept under control or easily retrofitted in case of need. To serve this purpose, they established, based on the results of their research, S-N curves and formulae which can successfully be used for governing inspections of the structure concerned for the occurrence of breathing-induced fatigue cracks.

Model of lamella flanges. The models of lamella flanges were then subjected to many times repeated loading - compatibly with the situation encountered on every bridge structure. It was observed during the test that, as a result of the existence of unavoidable initial imperfections, a gap formed between the two lamellas of the model, and consequently the directly loaded lamella was repeatedly pressed into this gap. This situation generated pronounced "breathing" of the flange lamellas and a cumulative damage phenomenon in them. Breathing-induced fatigue cracks then initiated in the boundary fillet welds connecting the lamellas, which afterwards propagated under further loading cycles, and in the end brought about a complete failure of the welds. So the experiments demonstrated that the lamella-breathing phenomenon can considerably imperil the safety and limit the useful lifetime of this type of bridge structures and cannot therefore be disregarded in design.

Geometrical setting of solid mechanics and its consequence for time-incremental analysis. While the position and shape of a deformed body take place in the usual three-dimensional Euclidean space, a corresponding progress of deformation tensor makes up a trajectory in the space of all deformation tensors – a negatively curved Riemannian symmetric manifold. Since this space is not a linear vector space, we cannot simply employ the tools from the theory of small deformations, but in order to analyze deformation processes correctly, we have to resort to the corresponding tools from the differential geometry and Lie group theory, which are capable of handling the very geometric nature of this space. The key idea that the space of all deformation tensors of a body does have naturally defined on it a simple geometric structure – Riemannian metric, which plays a very interesting and important role in the development of the theory, has been so far overlooked. However, utilization of this fact results in a geometrically based approach to solid mechanics via simple Lagrangian system on the space of symmetric positive-definite matrices (deformation tensors). This approach is especially appealing since it enables to utilize the tools of differential geometry and Lie group theory for an analysis of finite deformation processes to provide geometrically justified, unambiguous answers to time-linearization, as well as to time discrete integration. As a result one obtains natural stress rate, incremental principle of virtual power and generalized logarithmic strain. Further, by recognizing a well-known relation as an evolution equation of Lie-type for the right Cauchy-Green deformation tensor, geometrically consistent time-discrete integration schemes for finite deformation processes (such as the Runge– Kutta–Munthe-Kaas methods) are developed, correcting thereby established practice – cf. Simo, J.C., Hughes,T.J.R.: Computational Inelasticity. Springer, Berlin (1997).

Research team cooperation with abroad institutions. The research team was and is a part of the community involved in the domain of linear and non-linear dynamics including dynamic stability many years with an important role in international context. The research team approved its long-term stability solving several projects awarded by Czech Scientific Foundation and other agencies either domestic (MPO, MK, etc.) or international. Wide contacts, official international cooperation and joint projects make possible to realize some selected experimental analyses in the framework of running international projects, like FP7, COST, KONTAKT, Access to Large Facilities and others. Following workplaces are considered: Tamkang University Taipei (prof. J.D. Yau), TU Wien-Fac.Mech.Eng. (prof. H. Steinrück), Ruhr University Bochum- Institute of Structural Aerodynamics (prof. R. Hoeffer), Faculty of Mechanical Engineering and Naval Architecture and Faculty of Science-University of Zagreb (prof. H. Kozmar), CRIACIV-University of Florence (prof. C. Borri), Nort-Eastern Univ. - Boston (prof. L. Caracoglia), Tu Delft (prof.A. Metrikine), Univ. Notre Dame - Illinois (prof. A. Kareem), University of Tokyo (prof.N. Yoshikawa), Nat.Univ. Yokohama (prof. Y. Tamura), CSTB Nantes, Jules Verne CWT (Dr. P. Delpech), University of Bristol (Prof. C. Taylor), Polytechnic Opole (Prof. Z. Zembaty, Dr. P. Gorski) and others. The concept of development of the international cooperation in future years is essentially based on the CET project. In the sense of the ESFRI roadmap of the year 2008 should the Centre of Exclelence Telč and Climatic wind tunnel serve as a regional partner facility for large infrastructure climatic tunnel "Jules Verne" in Nantes, France, as well as for the European Joint Research Centre Ispra (Italy) and Bristol BLADE Laboratory (UK). This conception of SADeCET is still being honored: the climatic tunnel of CET has been designed with the assistance of the "Jules Verne" scientific staff and close contact and cooperation with the Italian and British centers continues in the long-term horizon.

Research Report of the team in the period 2010–2014

Institute	Institute of Theoretical and Applied Mechanics of the CAS, v. v. i.

Scientific team	Diagnostic methods and instrumentation

Analysis of deformation characteristics of the aluminum foams' periodic unit cells
Deformation response and material model of isolated cell-walls of a closed-cell aluminum foam were identified on the basis of micromechanical experiments and inverse finite element simulations taking stochastic nature of the studied material into account. Custom loading device developed at ITAM was used to perform a series of three-point bending experiments with the isolated rectangular cell-walls having approximately uniform cross-section to satisfy Euler-Bernoulli equation. Analytically derived material model was then extended by inverse numerical simulations of the bending experiments to obtain generalized solution valid also for specimens with nonuniform geometry and material properties.

Investigation of deformation behaviour of metal foam under dynamic loading Macroscopic samples of aluminum metal foam were investigate to evaluate the capability of porous structure to absorb deformation energy using a drop tower. Based on results of the material testing the segments of a protection helmet were designed (sandwich of metal foam and polystyrene) and tested with a headform impactor. Performed impact tests were simulated using FE method and results were compared with experimentally obtained values (acceleration, reaction force). Numerical material model suitable for description of the deformation behaviour of this porous structure during the impact testing was assessed based on comparison of experimental and numerical results. Identified material model were used for optimisation of parameters of designed segments (thickness of layers etc.). For that purpose facility of FTS CTU (drop tower) was used.

Effective material characteristics of metal foams Effective elastic properties of a closed-cell aluminum foam were determined analytically and numerically from homogenization theory at microscale and also using numerical discretization of the material's cellular microstructure. To obtain strain dependent compressive material characteristics for explicit numerical simulations of dynamic problems a series of experiments using custom-developed drop tower was performed to obtain stress-strain curves for different strain rates. The acquired data were then used for development of material model for LS-DYNA based on crushable foam theory suitable for numerical optimization of deformation behaviour of an innovative motorcycle helmet. The helmet was designed with respect to improved safety at higher impact velocities by utilizing multi-layer sandwich structure with core manufactured from the metal foam that was covered by extruded polystyrene liner.

Description of deformation behaviour of intact and defected rat vertebrae based on time-lapse tomography under loading To demonstrate of ability of the high resolution micro FE models the experimental study with rat vertebrae was performed. Samples of the rat vertebrae were incrementally compressed in a custom loading device and each load step was tomographed to obtain the detailed description of the deformation of the inner structure. The high resolution micro FE models was developed from the tomography of a zero deformation

step and the virtual compression test was performed. The results (displacement and strain fields calculated using FEM compared with experimentally obtained values using DVC technique) shown that the high resolution micro FE models are suitable for the assessment of the mechanical behaviour of entire bones as well as for investigation of the bone-implant interface.

Quasi-static compressive deformation characteristics of a closed-cell metal foam To evaluate mechanical characteristics of a closed-cell metal foam uni-axial compressive experiments were carried out using in-house developed loading device optimized on minimal attenuation of X-rays for the feasibility of radiographical imaging of specimens under loading. The device was designed geometrically and structurally with respect to dimensions of the representative volume element of the studied material that was determined by statistical image and signal processing methods. Using the device time-lapse X-ray microtomography under gradual loading was performed to obtain volumetric image data in every loading step and thus detailed response of the specimens' microstructure to applied load. High resolution strain fields were derived from the image data acquired in individual loading steps by digital volumetric correlation (DVC) of the deforming microstructure. The resulting displacement and strain fields were then used to calculate elastic characteristics of the specimens inversely using numerical simulations of the experiments based on detailed voxel finite element models of the undeformed specimens. Displacement of the top face of specimens calcualted by DVC was used in the FE simulations as a boundary condition to evaluate total reaction force inversely at the constrained nodes for assessment of the specimens' effective elastic characteristics. For that purpose facility of IEAP CTU (shielded box, positioning system and acquisition software Pixelman) was used.

Indirect identification of the material model for trabecular bone based on micromechanical testing On the basis of the performed micro three-point bending test of a single trabecula the numerical material model was indirect identified. For this purpose the FE model of the single trabecula was developed using „shape-from silhouette“ method and in house modelling software. Developed FE model was used for a virtual bending test and displacement of selected nodes was compared with displacement of markers tracked by Digital Image Correlation technique. Constants of the selected material model were varied to minimise of error between experimental and FE results using in house developed identification procedure. The set of material constants which the best satisfy the comparison criterion was taken as optimal for the material model of single trabecula.

Measurement of inner deformation of the trabecular bone structure using Digital Volume Correlation technique To verify the microstructural FE model and its ability to predict deformation behaviour it is necessary to measure the inner deformation in the loaded sample. Deformation of the inner structure of the trabecular bone caused by incremental uniaxial loading was captured using high resolution micro tomography. The reconstructed tomographic data was used for evaluation of 3D displacement field of the inner structure using Digital Volume correlation (DVC) technique implemented in Matlab and developed in our institute. The DVC technique uses a maximisation approach to find the correlation coefficient for the best fit between subimages (through all loading increments) defined around control points established in the reference image.

Measurement of the process zone evolution within Aluminum alloy sample Novel X-ray/optical imaging system was developed for online visualization of the damage evolution in specimen gradually loaded utilizing table top loading device. A large area flat panel detector

with rather long read out time is used for overall observation of slow damage processes. On the other hand, a semiconductor CdTe Timepix detector with small active area allows following the rapid damage processes occurred in the final phase of specimen failure. Optical imaging of the specimen surface was utilized for analysis of the specimen deformations.

Experimental evaluation of contour J integral and energy dissipated in the fracture process zone The direct calculation of the J integral, CTOD and separation energy based on experimental full field displacement measurement was successfully implemented and tested for specimen with completely yielded ligament. X ray radiography served for identification of the fracture process zone (FPZ) and newly developed crack. It was proven that the obtained dependence of the J integral on the loading displacement does not have any indication of the critical value Jc. The results show that the J integral is independent of the integration path although the integration paths tested crossed completely yielded ligament. It was documented, that simple calculation of the JCTOD integral from the CTOD gives similar results. However, obtained dependence JCTOD on loading displacement has such different shape than these calculated directly, that it cannot be reliable corrected using some conventionally used multiplication coefficient only.

Contrary with J integral evolution, the experimentally obtained dependence of the specific separation energy on the loading displacement has a sharp maximum, which corresponds to the intensive evolution of the separation area. Maximal value of the specific separation work (specific work of fracture) is significantly lower than J integral at the same loading state. Values of the specific work of external forces are in good correlation with measured J integral. We can conclude from this reason that evaluated specific plastic work is approximately equal to the fraction of the plastic work comprised in the calculated J integral as predicted by the theory of separation energy or essential work of fracture.

Advanced non-destructive testing (NDT) method developed combines neutron and X-ray imaging This combined method is targeted on characterization of specimens composed from materials with significantly different density Neutron Imaging and X-ray radiography are complementary methods from the point of view of the visibility and contrast of the material imaged. One potential application is the observation of the behavior of socalled Metal Composite materials, in which metallic and light material parts are combined. This material type is commonly used in the aerospace industry. Neutron Imaging is a suitable tool for the observation of the structure of the light materials in an environment of heavier elements like metals. X-ray radiography on other hand is an appropriate tool for the observation of geometry of metal components inside an environment of lighter materials.

Analysis of mechanical properties of trabecular bone at the tissue level To describe mechanical properties of the compact phase of the spongy bone which serve in material models in further numerical simulations of complex bone structures, a testing methodology was developed and employed for testing base structural elements of the bone. A custom modular loading device was developed which provides a possibility to test micro-scale specimens (smaller then 2mm in length) in different loading modes (tension and three-point bending) and in conjunction with X-ray microradiography. The specimens of single trabecula were extracted from several anatomically different locations and were tested in tensile and bending mode. During the loading radiographs of the loading scene were captured continuously. Real-time control of the testing setup enabled a sufficiently low loading rate, which was crucial in order to capture radiographs with a favourable signal-to-noise ratio. The

specimens' surface was equipped with gold plated micro-spheres (diameter 5 to 15 microns), which served in the radiographs as tracking features. The deformation behaviour was described based on displacement tracking of these features using digital image correlation method. This technique enables to track the displacement on the specimen surface with sub-pixel accuracy. Additionally, in the radiographs strain evolution was tracked and relationship between strain and change in attenuation for X-rays was analysed. For that purpose facility of IEAP CTU (tomography setup and acquisition software Pixelman) was used.

Digitization of small objects by means of Photometric stereo technique The technique is based on the so-called photometric stereo method utilising the relationship between apparent brightness of a point on the object's surface and its orientation towards direction of illuminating light. The method yields the field of surface slopes first, which can be further transformed into surface topography. Although used less frequently than methods based on stereoscopic principles, this technique can be advantageous for digital recordings of the objects for several reasons. For example, it is easy to acquire surface texture and the surface topography in order to preserve the complete information about the object. Another advantage, implied by underlying physical principle, concerns the precision of the method being independent on the distance to the studied object. Furthermore, the measurement resolution of the method can be easily tuned to roughness and variation of the object's surface.

Study of implants for spinal surgery The study of mechanical behavior (especially fatigue) of implants for spinal surgery was performed. This study includes an analysis of the materials such as titanium or titanium alloys 6AL4V ELI /Grade 23. The mechanical properties and biocompability of implant can be improved by surface treatment. In this work, specimens with two types of surface treatment and implants without surface treatment were used. The first surface treatment was based on deposition TiO2. The second deposition was based on TiN surface. Were implemented various calculations and simulations damage implants. Special attention was paid, fatigue life estamitation of pedicle-screw. For theoretical analysis of fatigue process was used new method proposed by Navarro, and applied on special case of hollow screw.

Research Report of the team in the period 2010–2014

Institute	Institute of Theoretical and Applied Mechanics of the CAS, v. v. i.

Scientific team	Building materials, historical structures and conservation science

Consolidation, strengthening and nano-materials

Evaluation of the consolidation effect of lime water and other consolidants on lime based porous substrates The efficiency of various strengthening substances was assessed by especially designed tests and procedures. No consolidating effect of distilled water on the compressive strength of the tested mortar specimens with a low lime binder content (1:9) was observed. The mechanical characteristics of the tested mortar specimens were also not improved by a treatment of a lime water with added metakaolin. The lime water treatment was proven to be effective only after a sufficiently large number of applications (160 saturations). Barium water treatment significantly increased mainly the tensile strength of the tested mortar specimens. In addition, also other substances used in conservation to restore the cohesion and reinforcement of natural stone and plaster were evaluated. These were especially substances based on silicic acid ester and nanoparticle suspensions of calcium hydroxide in ethanol or isopropyl alcohol. The suspension of lime particles in alcohols allows application of a much higher concentration of active ingredients than is possible in the case of an aqueous solution, moreover, in many cases the use of non-aqueous suspension is also advantage. In terms of time and the strengthening effect the experiment proved that the combined use of dilute silicic acid esters followed by a multiple application of a nano-lime suspension in ethanol could be a very effective approach. Testing of mechanical properties of historic building materials before and after treatment is the basic method enabling experimental determination of the consolidation effect of strengthening substances penetrated in age-damaged surfaces of historic buildings.

Design of a new nanotechnology for strengthening of degraded mortars and stones In order to contribute to preservation of build heritage, murals and artworks made of stone the effectiveness of substances based on nano-lime, used for strengthening deteriorated lime mortars and natural and/or artificial stone, mainly limestone, was experimentally verified. For the selected representative materials of historic buildings a new technology using calcium hydroxide nanoparticles suspended in alcohol was successfully designed. This research carried out within a joint European STONECORE Project was selected among award finalists of best research projects at the EuroNanoForum 2013.

Earth pressures of incoherent rocks

Development of an experimental equipment and methodology for research of a lateral pressure of granular multiphase materials The newly developed device serves for research of a lateral pressure of granular multiphase materials, e.g. soil, powder etc. on medium size specimens from 1.5 to 3.0 / 1.0 / 1.2 m. The device has a movable front wall and a firm but displaceable (different sample length) rear wall. The side walls are made of transparent safety glass which allows to monitor displacements of the specimen during its deformation. Progress

of lateral pressures is measured by a fixed bi-component load cells. Movement of the front wall is measured at the top and the bottom by displacement potentiometers. The movement of the front wall and the monitored data are controlled and recorded by a computer. Trial testing and verification of operation was carried out as a part of the development. Testing method was evaluated and a new testing methodology was proposed.

Calibration Eurocode 7-1 (Geotechnical design) Two long-term experiments E5 / 0.2 (April, 8th – October, 13th 2010) - 5 phases of movement, max. displacement at the bottom u = 226.89 mm, speed of 0.005 mm / min, E6 / 0.2 (March, 25th -December 13th 2011) - 5 phases of movement, max. displacement at the bottom u = 212.32 mm, speed of 0.005 mm / min - showed a different behaviour of a granular body than assumed by a current theory. A follow up numerical analysis of the experimental data confirmed the different behaviour of an ideal granular body than that of the considered by the current theory and its application in practice (Eurocode 7-1, Annex C). When such behaviour is fully demonstrated the development of an advanced theory with subsequent modifications of Eurocode 7 - 1 is going to be proposed.

Degradation of wood

Determination of the degradation of wooden structural elements The research resulted in the damage characterisation of joists caused by action of wooddestroying fungi. The degree of damage and changes in strength of wooden joists was determined in order to characterise the damage typology. The obtained material properties were divided into six categories according to the proportional decrease of properties in relation to sound and healthy wood. The obtained categories were transferred back to the network segments depicting the original profile element and thus provided a model description of the shape and course of the degradation of the element by fungi, designated as "degradation profile of an element". Spatial descriptions of the degradation profiles serve as a basis for assessment of remaining load bearing capacity and determination of durability of structures in relation to the type of biological damage.

Determination of the influence of chemical degradation caused by the reaction of certain chemical compounds contained in fire protection coatings on mechanical properties of wood Flame retardants containing corrosive substances were previously reapplied to a series of wooden structures in the Czech Republic mainly during the 20th century. Subsequently, it was found that these retarders cause degradation of surface layers of wood. This process of chemical corrosion is in practice referred to as "surface pulping of wood." The research results comprise of standard and special experimental methods used for determination of mechanical properties (compressive strength, tensile, flexural, hardness and impact strength) of the damaged surface layer of wooden structural elements. The experimental results showed a loss of adhesion and a decrease of mechanical properties of wood in its surface layers.

Changes in physical properties of wood (swelling and water absorption) caused by the action of pure cultures of wood-decaying fungi in laboratory conditions The research focused on completing the existing information about the changes of physical properties of wood caused by the action of wood-destroying fungi. Significant changes of selected properties (in tens of percent) were found after a relatively short exposure time to wood-destroying fungi (3-6 weeks). Considerable changes of physical properties of wood were caused by species of fungi with brown rot (cellulose decaying fungi) somewhat less pronounced changes (in the same time period) were caused by the wood-destroying fungi with white honeycomb rot (lignin decaying fungi).

Wood-damaging fungi in truss structures of Baroque churches The study presents a comparative study of biological damage to wooden structural elements of truss structures in small and medium-sized Baroque churches in the Czech Republic. The result is the ascertainment of the genus composition of wood-damaging fungi active at typical high-risk locations of typologically similar truss structures.

Diagnostics of historic materials and structures

Long-term monitoring of structural behaviour of important historical monuments In the period 2010-2014 continued a long-term monitoring of important historic buildings (Château Telč, New Town Hall in Prague, National Museum in Prague), which was launched in 1994. In 2010, the network of monitored structures was extended to the Royal Summer Palace at Stromovka (Prague).

Non-standard testing of mechanical characteristics of historic mortars A set of non-standard techniques have been developed or modified for testing mechanical characteristics of mortars on small specimens extracted from existing structures. Size effect and correction of experimental data were evaluated, namely low slenderness in the case of compression tests and cross-section height in the case of bending tests.

Characterisation of historic materials Several case studies and historic material characterisations were carried out during the monitored period. To name at least some: The Roman mortars used in the construction of the Ponte di Augusto (Narni, Italy) were assessed (bending and compressive strength, SEM– EDS, TGA and DTG analysis, porosity) with an aim to understand their particular function in the bridge structure. Historic mortars of the Charles Bridge in Prague were characterised in order to evaluate their quality and in relation to an estimated effectivity of new conservation approaches. Analysis of historic glass tesserae from Sv. Vitus Cathedral, Prague Castle was carried out to determine their provenance and details of their production technology.

Development of devices for testing mechanical properties of wood (2 patents) Two devices were designed, developed, tested and patented: (i) a diagnostic device for field and laboratory measurement of conventional strength and modulus of deformation during pushing jaws into sides of a drilled hole, and (ii) a device for measuring mechanical resistance of wood against pushing in a needle or pulling out a screw. The first device may be also used in situations where it is not possible or appropriate to use a resistance drilling but it is necessary to determine the mechanical properties of wood throughout the diameter of the element. The second device is used for determination of mechanical properties of built in wood in order to assess reliability of timber structures or for their design modifications, strengthening, load capacity, etc.

Confirmation of correlation between the conventional strength derived from the newly designed devices and the mechanical properties of wood determined by experiments according to standards and numerical simulations A significant result was achieved in the field of wood diagnostics as the correlation relationship between the conventional strength derived from the newly-designed instrument and the mechanical properties of wood determined according to standards. The verification of the applicability of the new instrument was based on experiments and numerical simulations. The tested semi-destructive methods produced relatively low damage of wood and they can be used to assess all types of wooden structures.

Innovation of the existing methods used for assessing performance of construction materials A methodology comprising of several non-destructive testing methods for use to diagnose historic materials was proposed. It includes test for assessment of a surface cohesion of stone and renders and determination of the rate of water penetration into material. A modified standard methodology for testing strength of mortars was used for the diagnosis of historic mortars on an Italian ancient bridge. The measured characteristics can be also used to study building history and technology, or to assess the effectiveness of conservation methods.

Description of traditional lime technologies (hot mix) in order to support the use of lime in repairs of historic buildings Research carried out on traditional lime binders and technologies contributed to the description of the differences between historic and modern lime mortars. The study provided the basic data for the assessment of newly designed mortars for repairs from the compatibility point of view. The mechanical properties (compressive strength and flexural strength) and physical properties (open porosity, bulk density, capillary absorption) were determined on hardened mortar specimens. Hot mixed mortars had comparable properties with the mortars prepared from hydrated lime or lime putty. Due to the micro-cracks in the binding matrix the hot mixed mortars showed higher porosity and capillarity.

Research and development of new materials

Compatible dilation limits of masonry joint mortars The effects of joints on the behaviour of masonry and on the damage processes have been investigated in various studies. The typically observed damage to some water-sensitive stone in ashlar masonry has usually been explained as a consequence of increased moisture and possible frost damage in the vicinity of impermeable mortar joints. A new numerical model describes the compatibility limits in relation to coefficients of thermal expansion and moduli of elasticity of two adjacent materials.

Assessment of the effect of a small amount of linseed oil, an hydrophobic additive (added in 1.5 wt. % in respect to the weight of binder) on lime and lime with metakaolin mortar. The physic-mechanical properties and durability of the hardened mortars towards sodium chloride crystallization cycles was determined with the aim of using it for conservation of historic building structures. Significant durability improvement of both lime and limemetakaolin mortars enriched with linseed oil was achieved: remarkable capillarity reduction and consequently higher resistance to NaCl cycles. Linseed oil had a different effect on the two studied mortars: mechanical strength was slightly reduced for lime+oil (LO) and slightly raised for lime-metakaolin+oil (LMO). The study proved that 1.5 wt. % of linseed oil is a good proportion to achieve satisfactory performance on tested mortars. Based on the laboratory tests on lime mortars with addition of metakaolin and linseed oil and an assessment of the effects of these additive on durability of lime mortars was designed a basic recipe for a mortar production with an enhanced durability in relation to freezing and water soluble salts content.

Setting performance requirements for design of a repair mortar for historic masonry The Technical Committee TC 203RHM RILEM, issued recommendations regarding practices in the design of mortars for the repair of historic masonry and internal / external plasters. The members of the team are also co-authors of these publications and active members of the RILEM TC groups. The published requirements for new mortars are based on research works and experiences with diagnostics of historic materials degradation. They also include

knowledge on the different thermal expansion, deformation and moisture transport in porous systems and other material properties that were also experimentally studied by he team at ITAM.

Preparation of magnesium phosphate cement by recycling the product of thermal transformation of asbestos containing wastes Asbestos containing wastes have been employed for the first time in the formulation of magnesium phosphate cements. Two samples were mixed with magnesium carbonate and calcined at 1100 and 1300 °C. Under these conditions, complete destruction of asbestos minerals is known to occur. The product, containing MgO, after reaction with water-soluble potassium di-hydrogen phosphate, led to the formation of hydrated phases at room temperature. Crystalline and amorphous reaction products were detected, with the latter being likely the meta-stable precursor of the former. Measured strengths were found to be in line with data from the literature, suggesting that this material may be used as cement. The process here described represents a viable recycling opportunity for this class of hazardous wastes. Simultaneous destruction of asbestos minerals and formation of reactive MgO during thermal treatment, bring benefits in terms of energy requirements and preservation of natural resources in cement manufacturing.

Comprehensive study on mechanical properties of lime-based pastes with additions of metakaolin and brick dust In order to understand the behaviours of lime-based mortars, and to identify the influence of pozzolans, it is important to investigate the microstructure and properties of lime-based pastes without any aggregates. In our work, nine different sets of pastes with additions of metakaolin and brick dust were studied. The chemical composition and microstructure were investigated by means of TGA, SEM–BSE microscopy and EDX analysis. The mechanical strength and fracture properties were determined by a destructive tests, while the evolution of the Young's modulus was monitored using the resonance method. The study revealed that the metakaolin exhibits much stronger pozzolanic activity than the brick dust, and that the mechanical properties of the pastes are not necessarily enhanced by increasing the amounts of pozzolans. These information contribute to a better understanding of lime-based mortars and are essential for their proper design.

Research and valorisation of traditional materials

Determination of optimal calcination temperatures for production of natural hydraulic binder known as Staroměstské lime Natural hydraulic lime (NHL) binders are nowadays not produced in the Czech Republic however they had been historically well spread and used. Well known was the Staroměstké lime. The experimental re-evaluation of the traditional lime binders provided a new technical knowledge for their use for repair of monuments and also it was an inspiration for a development of new alternative binders. The optimal calcination temperature of DvorceProkop limestone for production of NHL (Staroměstské lime) was determined to be ranging from 1000 to 1100 °C.

Design and development of a traditional lime kiln for a small scale production of lime A newly designed prototype of a lime kiln allows a small scale production of lime in a way that corresponds to the historic one in intermittently operated kilns. The kiln was design to study the traditional production processes and it was equipped with a monitoring devices for a description of temperature distribution, draft an emissions of O2 a CO2 during the burning and calcination process. The kiln was used for research and development of "copies" traditional lime binders, that are no longer produced, and which could find their use in conservation of build heritage.

Development of a method for examination of historic technological traces and it application to determine criteria for selection of replacements stone for repair of historic ashlar masonry For the investigation of the surface layer of facing masonry a trial model walls were prepared at a scale of 1: 1. Stone was obtained from 12 different quarries (sandstone, limestone and calcareous marly limeston) and individual masonry blocks were cut and carved by ten different techniques that are known to be used in the past. The trial walls are used for an evaluation of devices recording differences in the surface structure and its changes during long-term climatic exposure. According to the guidelines using the newly gained knowledge a repair of a part of stone masonry of mediaeval castle Kost (District Jičín) was carried out.

Strategies for protection and conservation of cultural heritage

Selection a design of tools and methods for the European Cultural Heritage Identity Card The selection a design of suitable tools and methods was one of the main contributions to the 7th FP EC project that developed a new system for identification of cultural heritage assets - Cultural Heritage Identity Card. The proposed system of the EU-CHIC project supports the long term maintenance, preventive conservation and rehabilitation of cultural heritage assets and other important historic sites. It contributes to the development and implementation of the tools proposed for the assessment of efficiency of repairs and also for the evaluation and monitoring of irreversible changes of unmovable cultural heritage due to repetitive human interventions and environmental effects.

Comprehensive flood protection of monuments A collection of works covering the damage analysis caused by floods on monuments enabled a processing of proposals for measures to reduce or completely mitigate damages on cultural heritage during floods. Scientific findings for assessing the historic materials and structures affected by floods or excessive water ingress include examples of a behaviour of typical monuments during and after flooding. The results are important for a flood risks mapping and also contain recommendations and guidelines for the use of non-destructive methods for monitoring the behaviour of historical materials after a flood (drying, desalination, biological control). Building stone is a porous material that degrades under the action of moisture and also due to the secondary crystallisation pressures of water-soluble salts present in the masonry. Several non-destructive methods was used for determination of moisture in an experimental evaluation of three different full scale masonry walls during their drying phase after complete saturation. This resulted to a description of the process of drying of historic masonry and validation of applicability of various non-destructive methods for determination of moisture in masonry.

Analysis of changes of properties and potential risks in the internal environment of buildings affected by flooding An analysis of key factors influencing the quality of the indoor environment during flooding was carried out. A penetration of flood water into a building, along with other symptoms, causes deterioration of parameters of the internal environment - heat and moisture, odor, microbial, aerosol and toxic. The surveys and analysis of flooded structures engaged in finding species of moulds occurring in buildings immediately after flooding with a view to their possible influence of health complications of persons staying or working in affected buildings. The research study documents that a flood means for the indoor environment and buildings a significant amount of risk factors, each requiring a specific approach remediation.

Interdisciplinary research

The structure and material composition of ossified aortic valves identified using a set of scientific methods Aortal valve mineralization very frequently causes a genesis of aortic stenosis, which is the most often surgically treated heart disease. Hydroxyapatite deposits have been identified as one of the causes leading to the loss of elasticity of the aortic valves. It is known that phosphates/calcium is accumulated in valve tissues during mineralization, but the mechanism of this process remains unclear. The work is focused mainly on the study of protein composition of mineralized aortic valves by nano-liquid chromatography electrospray ionization in a quadrupole orthogonal acceleration time-offlight mass spectrometry. New methodological approach based on direct enzymatic digestion of proteins contained in hydroxyapatite deposits was developed for the study of pathological processes connected with osteogenesis.