Description of the main research directions investigated by the institute

The following description of the research carried out by the Institute is divided into the work of the corresponding research teams which are the subject of the evaluation. It should be pointed out, however, that these teams collaborate across their borders and even across individual departments or laboratories due to the interdisciplinary character of some projects. The main directions of research at ITAM are defined in the research and conception plan which covers the period up through the year 2024. A detailed description of each research direction is given in the individual evaluation report of the research team. Here we provide the evaluation committee with the most relevant information for the whole Institute.

The research is carried out by three main research teams that were created naturally from the previous research teams and groups and formally established in the last two years of the evaluation period (2018-2019). All topics solved by the division are fully in accordance with the research plan of the Institute and are in good synergy with the name of the division and its departments and laboratories.

Research activities are traditionally focused on the issues of applied physics, interdisciplinary topics of materials engineering, biomechanics, experimental methods in mechanics and a number of directions in oriented and applied research that are closely connected to architecture and construction. The diversification of the research focus along with high flexibility enables the Institute to respond quickly both to current trends in the research and to social needs. Examples of such activities include research on nanomaterials, smart materials, bio-materials and bio-structures, interdisciplinary problems of cultural heritage, high-pressure gas safety, durable highway construction, especially bridges, and communication structures—high mast television and radio transmitters.

At the beginning of the evaluation period (2015), the Institute was already fully making use of the unique laboratory infrastructure (called the Centre of Excellence Telč), which is now a part of the whole Institute that expanded the capacity of ITAM's laboratories with items such as:

- a climatic wind tunnel with an atmospheric boundary layer;
- a radiographic laboratory with X-ray micro-tomography and neutron tomography; and
- mobile laboratory and surveillance network databases with the results of long-term measurements of major engineering works and monuments.

In the last two years of this period, the laboratory of the ITAM parent premises in Prague was also equipped with unique devices.

The Theoretical and Applied Mechanics Team

The team's research covers a wide spectrum of problems in structural and continuum mechanics as well as structures. It addresses and develops methods of dynamics of stochastic mechanics and solves problems regarding local and global stability of nonlinear dynamic systems, bifurcation analysis, post-transition and critical phenomena in connection with the development of theory and structural reliability. Part of the research is related to the dynamics of non-adjoint systems and the development of solutions for partial differential equations describing the time evolution of the response probability function in multidimensional areas as well as solutions to non-holonomic systems in various formulations.

In the applications oriented research, the team is examining seismic processes using equipment from the Central Laboratory and tasks of structural aerodynamics and aeroelasticity with substantial use of the climatic wind tunnel. The research is also focused on continuum mechanics and the damage of the materials, polymer composites and the use of computational mechanics. Some of the activities are related to the investigation of structures under repeated loading, especially in the theory of reliability and service life of piping systems and in the fatigue of new generation steel bridges. The research also includes forensic analysis in civil engineering.

Brief descriptions of the selected principal research directions are listed below.

General mechanics, fracture mechanics and mechanics of materials

- In the period 2015–2019, fundamental research was carried out into the **Fracture toughness of steel** with the aim of developing a method, based on digital image correlation data, for determining the fracture toughness of low-C steels. The research was done in cooperation with the **Material Sciences Team**.
- Specific research has been carried out into the problem of **determining the effects of the curvature of a thin pipe wall on fracture toughness.** The motivation for such research was connected with the fact that CT specimens relating to pressurized pipelines are usually produced from flat sheets obtained from press-straightened pipe segments.
- **Pressure behaviour of a steel pipeline experiencing creep at normal temperatures.** Knowledge of the natural decrease in water pressure due to room temperature creep is very important for the detection of leakage in tightness tests on gas pipelines. A higher-pressure decrease rate than what is natural from room temperature creep means that the pipeline is not tight, so the leak must be found. These experimental studies and the analysis were done in cooperation with the Czech gas service company CEPS (pressurizing of the real DN500 pipe segments).
- **Research and testing of timber joints and their components**, including traditional woodworking technologies and approaches. Nearly every reconstruction of a decayed cultural heritage object involves some kind of reinforcement of the structure or replacement of decayed parts. The team focuses on the latter, especially on the replacement of parts of timber structures. The research outputs consist of several variations of the joint and the method of the repair, including a static design and a description of traditional woodworking techniques, which can be used for manufacturing.
- **Features to protect pipelines against dynamic threats—safety research.** The main work of our team concerned features to protect pipelines against dynamic threats (i.e., third-party attacks, bullets, blasts and shaped charge attacks). This part was included in the activity named “Security of citizens and critical infrastructure: Cost-effective materials for huge objects”. The research focused on the ability to absorb impact energy with the help of a combination of material properties and cover layers.
- **Finite deformations, time-discrete integration and incremental methods.** In connection with the origin of computational mechanics and the consequent progress of incremental methods, the problem of how to correctly time-linearize and time-integrate deformation processes within finite deformations came up again. The members of the team focused on advancing a geometrically-based approach to solid mechanics via a simple Lagrangian system on the configuration space of finite deformation tensors—symmetric positive-definite matrices. The main advantage of our approach is that it makes it possible to put time-incremental analysis on firm ground with the tools of differential geometry and Lie group theory.
- **Thermoplastic laminates and creep damage index.** Research into the mechanics of polymer composites focused on the correlation of a newly proposed local time-dependent indicator of the damage accumulation in a thermoplastic laminate matrix with the degradation of the mechanical properties of the material as a whole. The material tested here is a modern carbon fibre–reinforced plastic used in the aircraft industry. Isothermal fatigue transient tensile loading and three-point bending are used for full-scale tests. The results confirm that the micro-indentation technique applied to the laminate matrix can be a suitable method for assessing the influence of fatigue tensile loading on the basic and time-dependent properties of the laminate.

Dynamics and aerodynamics

- **Investigation of the random response of multi-degree-of-freedom systems using the Fokker-Planck equation.** The Fokker-Planck Equation (FPE) is one of the most powerful tools for investigating multi-degree-of-freedom (MDOF) dynamic systems under random excitation (linear/nonlinear). Its relevance among other methods follows from a direct solution of the response probability function (PDF) as the most universal descriptor of the system behaviour. An original finite element approach has been developed respecting its multidimensionality and non-self-adjoint character. An original simplex finite element has been developed along with a special algorithm of multidimensional mesh generation and adequate differential system assembling and has successfully been tested on Duffing, Van der Pol and other complicated TDOF systems.
- **Dynamic stability and post-critical processes of non-conservative and non-holonomic systems.** The analytic formulation of non-holonomic systems with higher order constraints and higher time derivatives in the energy functional with subsequent physical and engineering applications represents the backbone of contemporary rational and engineering dynamics. It concerns deterministic as well as stochastic formulations of the system response, system dynamic stability, post-critical processes, reliability and other problems.
- **Models of interaction between varying and moving loads and bridges for structural health monitoring.** The verification of structural health represents one of the main tasks performed during the lifetime of bridge structures. Emphasis was placed on the development of basic research theories and computational methods and implementing such theories and the predicted results in practical applications. The indirect method, respecting the stochastic forcing character, was used to investigate dynamic response.
- **Method for complex eigenvalue analysis of non-classically damped systems.** The expression of damping in differential equations, describing the movement of linear mechanical systems, always represents a certain compromise between its actual physical character and the simplicity of the overall mathematical solution. In practice, damping is usually considered to be proportional and in the form of so-called classical damping. The team, therefore, applies non-classical damping models, which allow more variable representation of the possible character of the damping mechanism.

The Material Science Team

The team worked on the topics of the experimental determination of the mechanical properties of biological tissues and artificial biocompatible structures used in regenerative medicine as well as the development of material models of tissues and their implementation in numerical simulations and the applications of engineering principles in the development of orthopaedic implants, compensation and tissue carriers. The researchers also developed diagnostic methods for monitoring and research into deformation and material behaviour under load as well as corrosion and aging due to environmental effects. The results are applied to material dating, design, conservation and restoration procedures, respectively, and also when designing new, historically-compatible materials. This is supplemented by the analysis of structural, technical and natural materials and the time-dependent processes and damage that affect them. For this purpose, primarily radiographic methods such as X-ray tomography have been developed. Finally, the development focused on applying imaging methods for automating data processing to the analysis of the degradation and transformation of materials, structures and models. Research into the microstructure and related chemical-physical and mechanical properties of various materials using conventional and advanced (or self-developed) methods has been established in the Institute in recent years and continued in the assessed period. Concerning material specialization, the Department of Biomechanics mainly deals with the experimental determination of the mechanical characteristics of biological materials and artificial biocompatible structures using various micro-mechanical loading

procedures and radiographic methods. The department provides facilities for not only experimental research but also the design, commissioning and testing of innovative testing equipment and state-of-the-art evaluation procedures. The Department of Materials Research focuses largely on building materials, both traditional and modern.

Brief descriptions of the selected principal research directions are listed below

Material research

- **Study of acid-base cements, including their reactions and properties.** The results of this work disclosed a scenario, at variance with previous models, in which during the progress of the cement reaction, porosity increases over time as a consequence of the main crystallization process. The proposed reaction model is consistent with the observed microstructural evolution and the development of mechanical performance and is thought to provide a framework to develop predictive models for properties by linking cement formulation and microstructure.
- **Fired-clay bricks.** Fired-clay brick is one of the most widely employed construction materials and perhaps one of the oldest. The research focused on the full characterisation of fired-clay materials as the evolution of mineralogical composition, microstructure and properties in the function of the firing temperature and the nature of the clay raw material.
- **Synthesis of calcium carbonate polymorphs.** The synthesis of $CaCO_3$ polymorphs was investigated in two main tasks: the synthesis of calcium carbonate polymorphs by mixing supersaturated aqueous salt solutions containing calcium ions and carbonate salts and synthesis through the transformation of calcium hydroxide particles with uptake of gaseous carbon dioxide.
- **Multiscale modelling of concrete strength.** Specific research has been carried out with the aim of establishing a link between the microstructure of cementitious composites and their mechanical properties. It focused on a fully analytical micromechanical model targeted at predicting concrete compressive strength based on stress concentration from macroscale down to the hydrate phase.
- **Fire-protecting alkaline aluminosilicate composite material.** The investigation aimed to characterise and quantify the microstructural and mineralogical changes occurring with temperature changes and to link them with the evolution of the mechanical and heat transfer properties of the composite material.
- **Salt degradation of building materials.** The widely spread phenomenon of material degradation by salts has been studied from different points of view: the first approach aimed to develop improved testing procedures for assessing the behaviour of inorganic building materials towards salt crystallization, which should overcome the limitations of existing standards; the second approach focused on developing a method for testing developed salt crystallization pressure on specific materials by a specific salt.
- **Study of mortars for monument conservation.** An ancient water-repellent admixture (linseed oil) for the production of lime and lime-pozzolanic mortars was studied to use in the repair of built heritage. The obtained results proved that the effectiveness of linseed oil was comparable to that of industrial water repellent agents. The study provided advanced insights into the role of linseed oil in the composition and microstructure of lime mortars or pastes.
- **Effects of nanosilica on properties of lime and lime-pozzolana binder.** The investigation of the effects of nanosilica on the performance of cement and concrete has shown several positive outcomes, but to date, limited attention has been paid to lime-based systems containing reactive nanoparticles that can significantly improve the performance of lime mortars for use in the repair of built heritage.
- **Investigation of porous structure and drying behaviour of samples composed either of lime mortar or of lime mortar applied to a brick substrate.** The novelty of the study relied on the use of a wide range of techniques to investigate the porous structure, in particular, NMR (Nuclear Magnetic Resonance), which was a powerful

method for non-destructively analysing the pores and the moisture transport in masonry systems simultaneously. The study highlighted the importance of studying the performance of mortars not only as single materials but also in combination with a porous substrate, as in real onsite conditions.

- **Study of historic mortars.** The team's researchers participated in a comprehensive study of the local soils and historic earthen building materials used in the Nako temple complex in the Western Himalayas. Onsite and laboratory investigations followed a holistic approach to characterise the materials and identify the historic manufacturing formulas. The research dealt with the physical properties as well as the craftsmanship of both the historic building materials and the local soil resources still used in the village.
- **Consolidation materials and procedures for mortars and stone.** Research into the consolidation of historical plasters, renders or stone, both traditional liquid consolidation materials and innovative nanomaterials. Consolidation treatment is a conservation method aimed at the consolidation, preservation or even salvation of historical mortars.

Biomechanics

- **Four-point bending test instrumentation for 4D computed tomography.** High-resolution time-lapse micro-focus X-ray computed tomography (4D micro-CT) is a method for investigating the deformation processes and fracture propagation characteristics of non-homogeneous materials during loading.
- **Assessment of local fracture toughness of quasi-brittle materials.** Research on local fracture toughness of quasi-brittle materials based on a combination of X-ray computed tomography measurements acquired during loading tests, advanced post-processing of the tomographic data including identification of the crack path and the calculation of the crack tip opening displacement from which fracture toughness is derived.
- **4D micro-CT analysis of natural and artificial tissues.** Reliable biomechanical characterisation of tissues (natural or artificial) with complex microstructure requires the employment of a highly-customised testing procedure. The developed method allows full-field displacement and strain calculation on the tissue microstructure. The method was also adapted for middle-term analysis of fatigue properties and microdamage propagation caused by cyclic loading.
- **Mechanical response of additive manufactured structures.** Studies focused on the influence of printing procedure parameters on the effective properties of the resulting structure and the relationship between geometry and the effective mechanical properties of periodic additively-manufactured structures. The tested structures included (i) bio-inspired structures and (ii) periodic structures exhibiting a negative Poisson's ratio. The studies on mechanical response were conducted on a multi-scale level.

The Applied Sciences for Cultural Heritage Team

Research into the interdisciplinary problems of cultural heritage, including historic materials, historic structures and historic settlements, has traditionally been carried out by the Institute throughout its entire existence of approximately 100 years, and this tradition continued in the assessed period. The team carries out large-scale research in the field of sustainability of cultural heritage. It develops materials (particularly composites with lime and silicate matrices) in view of their chemical-mineralogical composition and their mechanical and physical-technological utility properties. The results have been applied in the area of historic replication technology, the design of new, historically compatible materials, the knowledge of historical construction technologies and other archaeometry studies. The team also researches the problems of degradation mechanisms in porous historic building materials and modelling of their damage and strength. For the purposes of the preservation of historic buildings, the research focused on the exploration of the effects of nano-lime slurries and other nano-particles on mechanical and other characteristics of the materials to be reinforced as well as

the effects of additives on mortar and paint. Research was also conducted into historic timber and masonry structures, which are closely linked to the development of diagnostic methods and monitoring structures.

Brief descriptions of the selected principal research directions are listed below.

Diagnostics of historic materials and structures

- **Direct determination of the mechanical characteristics of degraded wood in-situ.** The newly developed methodology represents a breakthrough in the diagnostics of timber structures. It took advantage of a substantially upgraded technique for in-situ testing of timber in existing structures. The method is unique worldwide as it directly measures conventional compressive strength and the modulus of deformation using a mini jack with opening clamps inserted into a drilled hole of 12mm in diameter.
- **Acoustic methods for wood diagnostics.** The timber diagnostics research continued with a study of the application of acoustic methods to determine the mechanical characteristics of wood. The correlation analyses compared the parameters of specific equipment and the basic mechanical characteristics of wood.
- **Diagnostics and long-term monitoring of the structural behaviour of important historical monuments.** In the field of non-destructive diagnostics, a series of tasks for practice was researched on a contractual basis. Survey methodologies on the diagnostics of deteriorated built stock were investigated and tested in practice with international participation. The applied results in the area of diagnostics further include damage and failure analyses of various buildings and structures.
- **Radiometric investigations of various sites**. Optimisation of restoration procedures to achieve the best possible results with minimum impact on the monuments. The results also provided new insights into unexpected hidden details of the studied objects.
- **Reducing long-term weather effects.** Specific research into the problem of the effects of wind-driven rain on brick masonries. A comprehensive experimental programme was designed and materialized, including the development of a new method for measuring moisture content in the masonry.
- **Numerical modelling of thermal behaviour.** The response of architectural heritage to external conditions in the context of possible material degradation as well as the contribution to physical comfort.
- **Improved resilience of built heritage in relation to natural disasters.** Research into the resilience of cultural heritage was mostly a subject of international cooperation. Three major threats were investigated: earthquakes and wind, mostly in cooperation with the Team of Theoretical and Applied Mechanics, and flood and drought.
- **Strategies for the protection and conservation of cultural heritage**
  Investigations in this area included studies on safeguarding degraded historic materials, structural elements and neglected or unused objects. Material problems solved in cooperation with the Department of Material Research involved research into the consolidation of lime mortars and the consolidation and restoration of adobe or clay-based mortars. Major research in the area of sustainable restoration focused on the problems of historic ruins and was carried out as part of an international project. The outputs, which were provided entirely by the team, aim to define the rules and conditions for long-term maintenance of such monuments and their suitable use. They include guidelines for optimum application of NDT methods for assessment of the ruin conditions.
- **Conservation of historical timber.** Research into the field of the decay of wood and timber structures in relation to the traditional conservation approach. Deterioration stations have been established with wood specimens protected by means of various agents or traditional carpentry woodworking and subjected to various environments—from those buried in soil to those exposed to weathering.
- **Development of optical methods.** The 3D shape of small objects like cuneiform tablets can be acquired by digitalization devices built in-house, utilizing shadowless

illumination and computer-controlled translational and rotational movements while the reconstruction is carried out on Photoscan, which is now considered standard software. In the case of investigation and reconstruction of finely structured surfaces, the photometry stereo-based method is applied. In contrast to the “Structure from the motion photogrammetric method”, the relationship between the camera and the object is fixed, but the illumination of the scene changes. The surface topography can be derived from surface shading. To fully control the light in the scene, various specialised devices have been built over time at ITAM, some of which are even patented. The newest development concentrates on creating detailed hyperspectral maps of complex surfaces like paintings combining UV-VIS-NIR spectrometer with computer-controlled movement.

- **Technical recommendations for the design and testing of lime-based repair materials.**
  Specifications for the testing and evaluation of lime-based repair materials for historic structures and TC 243-SGM Specifications for non-structural grouting of historic architectural surfaces.
- **Study of lime technologies.** The research into this topic combines different interdisciplinary activities that focus on providing technical and scientific knowledge for the application of traditional lime-based mortars when repairing historic buildings.
- **Rediscovery of historic art and construction techniques.** The development of a new approach for understanding historic techniques with regards to sustainable and compatible conservation treatments. The objective is to provide a solution for the repair of specific artistic building elements (or their conservation) based on material authenticity.
- **High-performance testing of building materials** aimed at the development of techniques and/or devices providing high-quality material data at affordable costs, mostly applicable in the conservation/restoration field.
  - Innovated tests for the *assessment of a near-surface cohesion of renders* based on previously developed peeling tests of stone surface cohesion.
  - Additionally, laboratory and *field devices for measuring the rate of water penetration into materials* were developed and patented (2016).
  - A method for *testing the shear mechanical characteristics* of models of historic mortars has been developed using an in-house designed and manufactured electro-mechanical biaxial loading frame and a contactless DIC for deformation measurements.
  - **Development of X-ray radiography and computed micro-tomography.** The unique Twinned Orthogonal Adjustable Tomograph (TORATOM) patented on the European level has been equipped with newly created in-house software.
  - **Micro-tomography methodology.** A method was developed for the compensation of small movements of the X-ray source in high-resolution measurements.
  - **Study of time-dependent processes in materials.** New fast detectors shortened the time necessary for a complete tomography, thus enabling extensive measurements of materials under loading, such as sandstone or concrete materials, and developing time-dependent 3D models (so-called 4D tomography), useful for analysis of the mechanical properties of the materials and study of crack propagation.
  - **Special radiographic investigations.** In the field of X-ray radiography and computed micro-tomography, a series of tasks for practice was investigated on a contractual basis. Tomography was used to investigate metal archaeological artefacts and wooden objects.

Heritage Science

- **History of construction.** Comprehensive research into the history of carpentry structures, namely historic roof frameworks. It studied typology development, joint

details, erection techniques, carpenter or tool marks and traces, conservation and relationships to other European regions.

- **Analysis of the foundation of historic cities.** Within a national project, a new hypothesis regarding medieval surveying and the foundation of historic cities has been studied by analysing over 40 Czech historic towns and some abroad that were founded by the Czech Kingdom (in Austria and Slovakia). The research aims to identify hidden cultural heritage value in protected urban complexes.
- **Regional history.** In the evaluated period, the major research linked to the city investigated the architectural and social activities of the Jesuit Order in Telč, where they operated a college, public and music schools, an apothecary and a meteorological station. New findings regarding the impact the Jesuit Order had on the shape of the urban environment will be presented in a forthcoming exhibition, an exhibition catalogue (in print) and an interactive map.

Research activity and characterisation of the main scientific results

Team of Theoretical and Applied Mechanics (TTAM)
The activities of the team, as the fundamental mainstay of the Institute, cover a very wide spectrum of problems in mechanics. Historically, the team has been a keystone of the Institute since it was established. Now it has crystallized into a modern research unit capable of solving actual problems that stem from societal needs on the basis of fundamental and applied research. The team is composed of the Department of Theoretical and Applied Mechanics, Department of Dynamics and Aerodynamics, Material Fatigue Laboratory (in Prague), Material Mechanics Laboratory (in Telč) and Climatic Wind Tunnel “Vincenc Strouhal” (in Telč).

General mechanics, fracture mechanics and mechanics of materials
Theoretical and experimental investigation into the relationships between CTOD and J integral. In the last evaluated period, fundamental research was carried out into the fracture toughness of steel with the aim of developing a method, based on the digital image correlation data, for determining the fracture toughness of low-C steels. This task was in accord with the planned activities of the team. The research was done in cooperation with the material sciences team, owing to which an optical measurement of displacements by DIC could be performed using the unique telecentric objective. This enabled a precise full-field in-plane stress-strain analysis to be performed and, finally, the J integral to be determined by its definition. The results proved that the J integral can be evaluated as a line integral directly from the fields that are obtained and that the optical nature of the method allows for simultaneous measurements of the CTOD parameter. When the DIC-based fracture toughness for ductile low-C steel was compared with that determined by the Standard ASTM E1820 – 01, very good agreement was found. This methodology can, therefore, be considered for use as a strong tool in the area of full-field measurements of crack-containing regions and also as a means of verifying engineering approaches. The significance of this methodology is heightened by the fact that it is perhaps the only option for measuring fracture parameters in situations where conventional methods cannot be employed.

Effects of curvature of a thin pipe wall on fracture toughness. Specific research has been carried out into the problem of the determination of J-integral-based fracture toughness parameters for curved CT specimens. The motivation for such research was connected with the fact that CT specimens relating to pressurized pipelines are usually produced from flat sheets obtained from press-straightened pipe segments. There is, however, scepticism regarding the validity of fracture toughness values gained from straightened specimens due to the occurrence of plastic strains that may be induced in the straightened semi-processed products during the press-straightening process. In collaboration with RCP Prague, a special force converter was developed that made it possible to load the curved CT specimens with a natural curvature in the circumferential direction, as it is in the real situation when a pipe is subjected to internal pressure. The examination of R curves for flat (straightened) and curved CT specimens showed that the fracture toughness of the pipe material determined on straightened CT specimens was practically the same as that obtained on curved CT specimens. This result justified the common practice of performing fracture toughness tests on CT specimens manufactured from straightened flat sheets.

Pressure behaviour of a steel pipeline experiencing creep at normal temperatures. Laboratory tests in room temperature creep were carried out on linepipe steel L360NB with the aim of working out the time dependencies of the water pressure in a pipe after stopping the water supply. Knowledge of the natural decrease in water pressure due to room temperature creep is very important for the detection of leakage in tightness tests of gas pipelines. A higher-pressure decrease rate than what is natural from room temperature creep means that the pipeline is not tight, so the leak must be found. The experimental results of the study enabled a family of curves that would decrease the water pressure with time, normalized by the

pressure at the yield stress, to be constructed for the steel for a time interval of 2–24 hours. The high application benefits of this output are the utilization of derived curves for the realization of so-called stress tests. This technological operation is carried out both when new gas pipelines are constructed and after old pipelines are repaired. The curves are part of a decision-making process for operating technicians on the tightness of the pipeline network prior to putting it into operation. A family of curves was implemented into the Czech standard for building high-pressure gas pipelines. These experimental studies and the analysis were done in cooperation with the Czech gas service company CEPS (pressurizing of the real DN500 pipe segments).

Research and testing of historical and new types of all-wooden joints and their components including the influence of traditional woodworking technology. The research and testing of timber joints and their components, including traditional woodworking technologies and approaches. Motivation: Nearly every reconstruction of a decayed cultural heritage object involves some kind of reinforcement of the structure or replacement of decayed parts. At ITAM, the timber research team focuses on the latter, especially on the replacement of parts of timber structures. For this purpose, all-wooden joints were designed and studied experimentally and analytically. All-wooden joints are equipped with wooden fasteners, whose behaviour and design values were studied in detail. They represent an aesthetic solution for joining the new beam part that will replace the decayed timber to the rest of the old element. The research outputs consist of several variations of the joint (corresponding with the way of loading of the structural element) and the method of repair, including a static design and a description of traditional woodworking techniques, which can be also used for manufacturing. The knowledge was disseminated through lectures; the joints are mainly used at cultural heritage sites. The data may be used for an expert recommendation to change the design standards for timber joints.

Features to protect pipelines against dynamic threats—safety research. TTAM is a member of the competence centre known as the Centre of Advanced Materials and Technologies for Protection and Safety Enhancement (no. TE02000162), which is supported by the Technology Agency of the Czech Republic. All planned deliverables and results were successfully completed during the period from 2014 to 2015. Our team mainly worked on features to protect pipelines against dynamic threats (i.e., third-party attacks, bullets, blasts and shaped charge attacks). This part was included in the activity named “Security of citizens and critical infrastructure: Cost effective materials for huge objects”. The research focused on the ability to absorb impact energy with the help of a combination of material properties and cover layers. Some sub-tasks were named: “Evaluation of fracture properties of pipeline steels including the ‘leak before break’ criterion”, “Evaluation of technological potentialities for protection of pipeline infrastructure”, “Pilot experiments on real pipe segments without internal pressure”, “Analysis of damage of pipe segments due to an explosion in relation to the fracture toughness of a pipe segment”, “A model for dynamic behaviour of pressurized pipe upon a shock wave” and “Key experiments on real pressurized pipes”. Two main results were achieved by the successful completion of the sub-tasks. The first was a modification of the main building standard for high-pressure gas pipelines (TPG 70204). Specifically, it was the implementation of the proposed low-cost protection against the dynamic effects of explosives, especially cumulative charges. This applies to gas pipelines that pass through strategically important locations. The certification of the protection method by a state agency was the second result.

Finite deformations, time-discrete integration and incremental methods. In connection with the origin of computational mechanics and the consequent progress of incremental methods, the problem of how to correctly time-linearize and time-integrate deformation processes within finite deformations came up again. This research advances a geometrically-based approach to solid mechanics via a simple Lagrangian system on the configuration space of finite deformation tensors—symmetric positive-definite matrices. This viewpoint stands in

sharp contrast with the common one, which handles the deformation trajectory in the bigger vector space of symmetric matrices. In addition to properly interpreting the stress power, the main advantage of our approach is that it makes it possible to put time-incremental analysis on firm ground with the tools of differential geometry and Lie group theory. In the evaluated period, it enabled us to identify the evolution equation of Lie-type for finite deformation to complete the time-discrete integration of deformation processes in its full length.

Thermoplastic laminates and creep damage index. Research into the mechanics of polymer composites focused on the correlation of a newly proposed local time-dependent indicator of the damage accumulation in a thermoplastic laminate matrix with the degradation of the mechanical properties of the material as a whole. The material tested here is a modern carbon fibre-reinforced plastic used in the aircraft industry (e.g., Boeing Dreamliner). Isothermal fatigue transient tensile loading and three-point bending are used for full-scale tests. The results of the fatigue pulsating tension loading of the laminate are presented together with the outcomes of the nondestructive measurements of the residual stiffness of the laminate. The local elastic and time-dependent properties of the laminate matrix, used as nondestructive indicators of the degradation of the matrix caused by repeatedly applied loads, are compared with the full-scale outcomes. The results confirm that the micro-indentation technique applied to the laminate matrix can be a suitable method for assessing the influence of fatigue tensile loading on the basic and time-dependent properties of the laminate.

Evaluation of the technical state of selected high-pressure gas pipelines in the area of Prague. As part of our industrial research, the team from ITAM has realized a number of experimental investigations into the mechanical and fracture mechanical properties of the steels that real high-pressure gas pipelines are made of. Six parts of the high-pressure gas nets were evaluated during the last five years. The aim was to assess the reliability of the gas pipelines on the basis of fracture mechanics principles, mainly for the company Pražská plynárenská (a Czech gas-distribution company). Critical crack dimensions were determined on the basis of the J-based fracture toughness for the real magnitudes of the operating gas pressure, and the life of the pipelines was evaluated with the help of the Paris law after their parameters were experimentally determined. The importance of the social and security impact of this application result can be emphasized. It is encouraging that our cooperation with gas companies is still ongoing. The significant outputs of this cooperation are decision-making processes regarding the reliability and safety of the operation of high-pressure gas pipelines in the transit and distribution gas networks.

Dynamics and aerodynamics

Investigation of the random response of multi-degree-of-freedom systems by means of the Fokker-Planck equation. The Fokker-Planck Equation (FPE) is one of the most powerful tools for investigating multi-degree-of-freedom (MDOF) dynamic systems under random excitation (linear/nonlinear). Its relevance among other methods follows from a direct solution of the response probability function (PDF) as the most universal descriptor of the system behaviour. Being based on Markov processes, it provides the possibilities of system response analysis, stochastic stability assessment, first excursion problem investigation, etc. Therefore, it is worthwhile to develop new methods of the FPE solution that are either semi-analytical or numerical.

Concerning numerical approaches, an original finite element (FE) approach has been developed respecting its multidimensionality and non-self-adjoint character. An original simplex finite element has been developed along with a special algorithm of multidimensional mesh generation and adequate differential system assembling. Computer implementation has been successfully tested on Duffing, van der Pol and other complicated TDOF systems. Relevant papers have won several domestic and international prizes.

The development of semi-analytical solution methods has focused on the Galerkin-Petrov procedure, applied to a multidimensional operator of the FPE type in evolutionary form. The motivation for these studies came from the area of stochastic resonance (SR). This phenomenon is very important in physics and other disciplines including life and social sciences. In dynamics, it represents an efficient tool for investigating many systems with combined deterministic and random excitation. The problems of convergence and numerical stability have been investigated due to singular Dirac-type initial conditions and possible diffuse-type boundary conditions.

Dynamic stability and post-critical processes of non-conservative and non-holonomic systems. The analytic formulation of non-holonomic systems with higher order constraints and higher time derivatives in the energy functional with subsequent physical and engineering applications represents the backbone of contemporary rational and engineering dynamics. It concerns deterministic as well as stochastic formulations of the system response, system dynamic stability, post-critical processes, reliability (first excursion) and other problems.

Fundamental studies have been published concerning higher order non-holonomic constraints of the Appel-Chetayev type with respect to the general formulation of virtual displacements, velocities and higher parameters. The Gibbs-Appell principle has been introduced into this domain. This principle proved to be more efficient than conventional Lagrangian formalism. As an application of this tool, the non-holonomic system of a ball moving inside a cavity under external excitation has been investigated.

A number of non-conservative and gyroscopic systems have been investigated from the view-point of local and global bifurcation in order to delimit domains of aeroelastic stability in linear and nonlinear states. Post-critical processes have been thoroughly analysed, examining stability basins and transition effects. Quasi-periodic processes in the area of the lock-in regime have been thoroughly investigated in deterministic as well as in stochastic regimes. Bifurcation theory has been thoroughly studied in view of local (Hopf, Neimark, etc.) and global (Andronov-Vit and others) bifurcation types.

Models of interaction between varying and moving loads and bridges for structural health monitoring. The verification of structural health represents one of the main tasks performed during the lifetime of bridge structures. In cooperation with the Department of Civil Engineering of the National Taiwan University, the innovative indirect method for measuring such structures was proposed on theoretical and experimental bases. Emphasis was placed on the development of basic research theories and computational methods that integrate the advantages of each side and on implementing such theories and the predicted results in practical applications. The indirect method, respecting the stochastic forcing character, was used to investigate dynamic response. The development of theories and predictions of practical results obtained from the excitation of the moving load will be used for structural health monitoring. The unique equipment for detecting the dynamic properties of building structures, especially bridge structures, was successfully designed and tested. The proposed indirect method with the presented experimental results, based on a vehicle-bridge interaction, was proved to be an effective and useful tool for the long-term monitoring of bridge structures.

Method for complex eigenvalue analysis of non-classically damped systems. The expression of damping in differential equations, describing the movement of linear mechanical systems, always represents a certain compromise between its actual physical character and the simplicity of the overall mathematical solution. In practice, damping is usually considered to be viscous—that is, proportional to the velocity of motion—in the case of discrete systems in the form of so-called classical damping. In the vast majority of engineering problems, the results of the response of structures with classical damping models are sufficiently accurate and realistic. However, there are special cases of systems where this is no longer the case. It is necessary to mention the structures provided with special damping devices such as

footbridges or transmission towers. In such cases, it is suitable to choose a more complex damping model.

One variant is to apply so-called non-classical damping, which allows a more variable representation of the possible character of the damping mechanism. However, the decomposition of the solution of the response of the multi-degree-of-freedom system into individual independent equations requires a complex modal analysis of the double dimensional system. This numerical disadvantage is motivation to develop a more computationally effective method for determining complex modal properties. It was exclusively designed for special cases where the structures have equipped passive damping devices. Its algorithm is based on an approximate solution of a characteristic equation using a combination of perturbation and incremental approaches. The accuracy of the proposed method was successfully demonstrated on an example of a real structure and could be implemented into praxis.

Non-holonomic systems of higher order under deterministic and random excitation. The general theoretical background of the non-holonomic systems with a higher order of constraints and higher time derivatives in energy functionals is developed. The aim of this development is to investigate important attributes of non-holonomic systems, which appear in the dynamics of deformable systems interacting with a neighbourhood. The study is oriented towards theoretical investigation. Its core consists of the characterization of basic and generalized non-holonomic systems inspired by civil and mechanical engineering and also frequently by other disciplines (space dynamics, robotic, plasma physics, physical optics, etc.).

The definition of a dynamic system consists of the specifications of the system itself and the relevant constraints representing links with the surrounding environment. The governing differential system itself is deduced from a definition based on the Hamiltonian principle. A new form of the generalized Lagrange equation system is derived assuming higher time derivatives of displacement components in the kinetic energy definition as they emerge due to the interaction of mechanical and other physical fields.

Linear and nonlinear definitions of non-holonomic constraints including arbitrary time derivative order, which originate from the interaction of mechanical and other physical fields, are discussed. Consequently, the character of constraints can be very general. They include many variants with simple geometric coupling with fixed points and interaction with the movement trajectory via very complicated time-dependent constraints of deterministic or random types. Lagrangian multiplier techniques are employed, incorporating non-holonomic constraints of simple or higher order into the complete mathematical model. The Appell-Chetayev definition of virtual displacements is considered.

Stochastic resonance in dynamic systems. Stochastic resonance (SR) is a phenomenon that can be observed in many non-linear dynamic systems under combined excitation, mostly including deterministic periodic force and random noise. This phenomenon was first observed in the early 1940s when investigating Brownian motion. Later, several disciplines in optics, plasma physics, biomedicine and social sciences encountered effects of this type. Promising opportunities for employing SR in mechanics emerged only recently to model certain post-critical effects in non-linear dynamics and for developing new vibration damping devices.

The phenomenon itself manifests as a stable periodic hopping between two nearly constant limits on a Duffing-type oscillator, which is perturbed by random noises. The occurrence of this phenomenon depends on certain combinations of input parameters, which can be determined theoretically and verified experimentally. The basic version of SR can occur in every bi-stable system under a suitable combination of the additive Gaussian white noise and harmonic deterministic force.

Long-term experience shows that SR should be assumed either as a dangerous effect of a post-critical system response which should be suppressed (plasma physics, aeroelasticity, etc.) or it can represent an operating mode of the system itself (optics, special excitation devices, subthreshold signal detection, medical devices, etc.). It implies a very wide field of applications in physics, life sciences and social disciplines.

Aerodynamic characteristics of the Army Meteorological Drone. In 2018 and 2019, the climatic wind tunnel laboratory carried out, under a research contract to the Ministry of Defence, measurements of the aerodynamic characteristics of the Army Meteorological Drone as part of University of Defence research. Measurements were taken mainly of all components of force, torque and the parameters of the flowing air (temperature and speed), as well as measurements of Cx and area at all drone orientations and flow velocities. The resulting data and the integral characteristics processed will be used by researchers from the University of Defence to further develop the meteorological drone.

Research activity and characterisation of the main scientific results

Several different analytical techniques were adopted (X-ray diffraction, inelastic neutron scattering, small angle neutron scattering, x-ray tomography, nuclear magnetic resonance, calorimetry, Raman and infrared spectroscopy, scanning electron microscopy, instruments for testing of mechanical properties). Such research activity is required to develop specific expertise within the team. Expertise has also been obtained through training courses. In most cases, the experiments were performed at international facilities after the positive evaluation of proposals through a peer-review process that confirmed the quality of the research.

Study of acid-base cements, including their reactions and properties. The team has published 11 scientific papers in peer-reviewed journals. Magnesium phosphate cements are chemically-bonded ceramics attracting interest for applications in civil engineering, for nuclear waste encapsulation and as biomaterials. The group has, for the first time, proposed a comprehensive model of the reaction. This has been accomplished in several steps:

1. Investigate the relationships between microstructure and properties
2. Describe the reaction kinetics and the underlying mechanisms
3. Disclose the influence of the parameters of the mix formulation on the reaction mechanisms and, in turn, the microstructure and cement performance

The results of this work disclosed a scenario, at variance with previous models, in which during the progress of the cement reaction, porosity increases over time as a consequence of the main crystallization process. The latter occurs via amorphous precursors with the involvement of non-classical mechanisms of nucleation and growth as recently proposed for crystallization in carbonates and Ca-phosphates. The mutating chemical environment drives the transformations, which are, however, hindered by the reduction in molecular mobility as the reaction progresses. The proposed reaction model is consistent with the observed microstructural evolution and the development of mechanical performance and is thought to provide a framework to develop predictive models for properties by linking cement formulation and microstructure.

As one of the team members was always the first author in all publications, there is no doubt that the contribution of the team was largely predominant in the accomplishment of the research. Nonetheless, in most cases, the work included co-authors external to the team. They helped interpret the results from specific techniques adopted in the studies and/or helped set up experiments when performed at international facilities or external laboratories.

Fired-clay bricks. Fired-clay brick is one of the most widely employed construction materials and perhaps one of the oldest. The research focused on the full characterisation of fired-clay materials as the evolution of mineralogical composition, microstructure and properties in the function of the firing temperature and the nature of the clay raw material. The roles played by process variables, such as the extrusion step, were also investigated.
The aim of this work was, on one hand, to help improve process variables in brick manufacturing and, on the other, to provide a practical tool for the production of replacement bricks for historical buildings.

The main results can be summarized as follows:

- Textural features caused by the forming of an extrusion have been detected as anisotropy of the pore network. They are still present above 1000 °C and, unexpectedly, they are observed both in sections cut parallel and sections cut perpendicular to the direction of the extrusion. This can be explained by the double lamination induced by the screw extruder. This has important implications for mechanical performance and transport properties such as thermal conductivity or moisture penetration. The former is directly connected with building energy consumption, the latter with brick durability.

- The weight fractions of some mineral components, such as hematite, mullite and the amorphous fraction, have been found to be useful indicators of firing temperature. The values derived when applying these three methods were in good agreement with the nominal temperatures of the industrial cycles. Therefore, the derived calibration curves can be employed to produce bricks for restoration/replacement purposes.

The described work is summarized in four scientific papers published in peer-reviewed journals. The contribution of the team is reflected in the fact that a team member is always listed as the first and corresponding author. The presence of co-authors not from the team is the result of collaboration at an international level and/or experiments conducted at international facilities. Their contribution was essentially technical support in the execution of experiments and data analysis. This topic was the subject of an invited lecture at the Congress of the European Ceramic Society in 2019.

Synthesis of calcium carbonate polymorphs
The synthesis of $CaCO_3$ polymorphs was investigated in two main tasks: the synthesis of calcium carbonate polymorphs by mixing supersaturated aqueous salt solutions containing calcium ions and carbonate salts and synthesis through the transformation of calcium hydroxide particles with uptake of gaseous carbon dioxide (a so-called carbonation reaction). Several different types of supersaturated solutions were tested, and carbonation reactions of various lime-based materials containing calcium hydroxide particles like lime putty or nanolime were tested. Reaction rates were investigated, and the products were analysed. The knowledge obtained on these two systems was recently used to study combined systems composed of synthetic calcium carbonate polymorphs and nanolime suspensions that were tested as novel consolidation agents for the preservation of stone cultural heritage objects. The investigation of these scientific topics was also supported by the Czech Science Foundation in two projects—one postdoctoral and one standard. Currently, 7 impact papers listed in Web of Science with a total of 60 citations, 1 utility model, several papers in conference proceedings and oral lectures at international conferences have been published/presented on these topics since 2015. Results were also obtained through international collaboration, and 5 experiments at European neutron and synchrotron facilities won awards after the submitted proposals were reviewed.

Multiscale modelling of concrete strength. While concrete is generally viewed as a homogeneous material, it has a heterogeneous microstructure with distinct material phases spanning several orders of magnitude. Specific research has been carried out with the aim of establishing a link between the microstructure of cementitious composites and their mechanical properties. The research focused on a fully analytical micromechanical model targeted at predicting concrete compressive strength based on stress concentration from macroscale down to the hydrate phase. Understanding the stress distribution within the microstructure opens the door to material optimization during design, possibly reducing the amount of cement necessary, which can have a beneficial effect by lowering CO_2 emissions associated with cement production. The results achieved in collaboration with TU Vienna researchers were published in a scientific paper in a leading peer-reviewed journal.

Fire-protecting alkaline aluminosilicate composite material. An intumescent alkaline aluminosilicate composite material was developed for fire-protection of structural elements. What is innovative about the proposed material is the combination of binder and granules of the same chemical composition, which swells under the effect of heat. Its specific composition, leading to the formation of zeolite-type minerals during the hardening process, ensures that only water is released as the temperature increases, without causing any health risks, contrary to the organic fire-protecting coatings often used in practice. The investigation aimed to characterise and quantify the microstructural and mineralogical changes occurring with temperature changes and to link them with the evolution of the mechanical and heat transfer properties of the composite material. The complete information obtained about the behaviour

of the material allows the mix design to be modified accordingly and allows the adaptation of its properties to specific applications. The findings of the study were published in an impact journal. The work was the result of international collaboration (Kyiv National University of Construction and Architecture).

Salt degradation of building materials. The theme of salt degradation of building materials (mainly stone) is on the scope of the two team members involved in the RILEM Technical Committee 271 ASC, and it also represents the topic of one dissertation thesis solved by the team. The widely spread phenomenon of material degradation by salts has been studied from different points of view: the first approach aimed to develop improved testing procedures for assessing the behaviour of inorganic building materials towards salt crystallization, which should overcome the limitations of existing standards; the second approach focused on developing a method for testing developed salt crystallization pressure on specific materials by a specific salt. Research into improved testing procedures for the RILEM technical committee was mostly performed in collaboration with international members of the TC 271 ASC Committee.

The results on this topic were presented in two scientific papers published in impact journals in the evaluated period. The first paper critically reviewed the literature on salt crystallization tests, identified the advantages and limitations of the several testing protocols and provided new ideas for the development of improved salt crystallization procedures. The second paper presented approaches to a novel non-standard salt crystallization testing method that would better characterise the behaviour of salts in porous systems. The method presented used both single-component and multi-component salt solutions and more realistically simulated the real conditions of salt degradation than other methods. The team will continue to work on this research topic in the next period.

Study of mortars for monument conservation. Mortar is an essential material in construction. Lime mortar has been used for centuries, and there is historic evidence that it is durable and compatible with traditional materials. However, several research studies aiming to reproduce historic mortar recipes show the failure of the materials, especially when exposed to severe weathering agents involving water ingresses, like freeze-thaw cycles and salt crystallization. The team, therefore, investigated the effects of various lime mortar additives on mortar performance. An ancient water-repellent admixture (linseed oil) for the production of lime and lime-pozzolanic mortars was studied to use in the repair of built heritage. The obtained results proved that the effectiveness of linseed oil was comparable to that of industrial water repellent agents. The study provided advanced insights into the role of linseed oil in the composition and microstructure of lime mortars or pastes. The results have important implications for applications in mortar or coating (paint) production and are, therefore, likely to be of interest to scientists researching either the field of restoration of historic structures or the formulation of new construction materials. Besides two scientific papers in impact journals, a certified methodology and a utility model on how to prepare and apply the mortars with oil were also developed and published for use in conservation practice. All outputs were provided entirely by the team.

Another part of the study focused on the effects of nanosilica on the properties of lime and lime-pozzolana binder. The investigation of the effects of nanosilica on the performance of cement and concrete has shown several positive outcomes, but to date, limited attention has been paid to lime-based systems containing reactive nanoparticles that can significantly improve the performance of lime mortars for use in the repair of built heritage. The research on nanosilica admixture mainly involved the micro-textural and micromechanical properties of the modified binding systems. This work significantly contributed to the knowledge of the use of nanotechnology in lime-based systems.

The last branch of the study of repair lime mortar properties investigated the porous structure and drying behaviour of samples composed either of lime mortar or of lime mortar applied to a brick substrate. The novelty of the study relied on the use of a wide range of techniques to investigate the porous structure, in particular, NMR (Nuclear Magnetic Resonance), which was

a powerful method for non-destructively analysing the pores and the moisture transport in masonry systems simultaneously. The study highlighted the importance of studying the performance of mortars not only as single materials but also in combination with a porous substrate, as in real onsite conditions. The results were published in a scientific paper in an impact journal; the first and corresponding author is a member of the team. he presence of co-authors not from the team, is the result of collaboration on an international level and/or experiments conducted at external facilities.

Study of historic mortars. A historic lime-based mortar with crushed brick particles, known as cocciopesto, was studied using optical microscopy, SEM-EDX and the nano-indentation method. The sample from the late Byzantine church built approximately in the 9th century in the Üsküdar district, located in Istanbul, Turkey, was used for the analysis. The results provided a coupled micromechanical and chemical study on the interfacial transition zone (ITZ) between fragments of crushed bricks and the surrounding matrix, providing knowledge of the chemical-mechanical properties of this specific type of ancient mortar. The resulting paper (created in cooperation with the Czech Technical University in Prague) is one of the most read and cited papers in the field of historic mortars.
Unburnt clay (adobe and earth mortars) is another historic material that is widespread on building structures in Asia and South America. The team's researchers participated in a comprehensive study of the local soils and historic earthen building materials used in the Nako temple complex in the Western Himalayas. Onsite and laboratory investigations followed a holistic approach to characterise the materials and identify the historic manufacturing formulas. The research dealt with the physical properties as well as the craftsmanship of both the historic building materials (adobe, joint mortars, plasters and renders) and the local soil resources still used in the village. The results presented in the article facilitated a better understanding of material culture and advanced the study of damage and decay processes found in the temple buildings. Also, a proper conservation and preservation strategy was presented. The results of the research contributed to the knowledge of authentic village-building tradition in the Western Himalayas, which has been continuously disappearing and substituted by modern materials and technologies. The study was done in collaboration with Prof. M. Drdácký, a member of the Division of Applied Sciences for Cultural Heritage (DASCH) team, and with researchers from the Academy of Applied Arts in Vienna. The first and corresponding author of the scientific paper published in an impact journal is a member of the team.

Study of consolidation materials and procedures for mortars and stone. In the field of the consolidation of historical plasters, renders or stone, both traditional liquid consolidation materials and innovative nanomaterials were studied. First, members of the team published a detailed critical overview of currently available inorganic conservation materials, focusing on their effectivity or compatibility limits and preceding a discussion on the use of calcium hydroxide nanoparticles for architecture and art conservation (the chapter of the scientific book about nanolime material for monument conservation was written in cooperation with one external co-author). Then, a member of the team created, as the first editor and co-author, a scientific book containing conservation studies on Leitha limestone treated with nanolime materials (in cooperation with the University of Pardubice and University of Applied Arts in Vienna). Four scientific papers were published in impact journals on the topic of consolidation of mortars or stone. The output on this topic also included conference papers, other chapters in books, one habilitation thesis, certified methodologies describing the effects and recommended treatment procedures utilising the investigated consolidants, including various types of mortar and stone. Consolidation treatment is a conservation method aimed at the consolidation, preservation or even salvation of historical mortars, which are valuable from the cultural heritage point of view, and therefore, the published results were very important for conservation practice.
Regarding updated methods, the in-depth deposition of the consolidating nanoparticles was monitored by means of differential X-ray transmission radiography without requiring the use of labelling substances. As the method provided evidence about the effectiveness of the

proposed consolidation treatment, restorers and conservationists obtained highly-appreciated information on how to optimise the consolidation treatment.
Some outputs were provided entirely by the team; the aforementioned books resulted from collaboration with external co-authors.

Four-point bending test instrumentation for 4D computed tomography. High-resolution time-lapse micro-focus X-ray computed tomography (4D micro-CT) is a method for investigating the deformation processes and fracture propagation characteristics of non-homogeneous materials during loading. For this purpose, a unique experimental device (Czech national patent 307897) capable of four-point bending (4PB) tests during X-ray imaging has been developed. In contrast with standard bending setups, the proposed device is designed for vertical orientation of the investigated specimen, whose axis of rotation is identical to the rotational axis of the CT devices. The device is composed of three main components: a pair of motorized loading units with integrated movable outer supports of the four-point bending arrangement, a pair of stationary inner supports of the four-point bending arrangement, and a cylindrical load-bearing frame housing the loaded specimen together with the loading units and all the supports.
Proof of concept and pilot experiments were successfully performed in the TORATOM CT scanner. Based on the results acquired, fracture-process zone and macroscopic crack propagation in a quasi-brittle material can be observed in 3D using an in-situ loading procedure and high-resolution 4D micro-CT.

Assessment of local fracture toughness of quasi-brittle materials. Closely connected with the previous topic and based on acquired data, a novel method for testing the local fracture toughness of quasi-brittle materials was developed. This technique is based on a combination of X-ray computed tomography measurements acquired during loading tests, advanced post-processing of the tomographic data including identification of the crack path and the calculation of the crack tip opening from which fracture toughness is derived. The basic advantages of such an approach are: the fracture toughness is calculated independently on the specimen geometry, boundary conditions and crack length and shape; therefore, it can be used for non-standard specimens and loading tests, while the usual requirements are not fulfilled; fracture toughness can be calculated for an arbitrary number of positions at the crack front and for several loading levels—we can obtain a large number of results using just one sample, whereas the standard approach would require that a number of specimens be tested individually, while these specimens are typically different in their structure and geometry.
To develop the method, a number of subtasks had to be solved: a technique for correcting the unavoidable thermal deformation of the X-ray tube that decreases the quality of the tomographic reconstruction was implemented; a new loading machine for the four-point bending tests was developed in-house; the precise 3D digital image correlation technique needed for precise alignment of reconstructed volumes to one another with subvoxel resolution was programmed; software for identification of the crack path within a heterogeneous structure was developed; a precise 2D digital image correlation technique for calculating the displacement fields with deeply subpixel resolution was programmed; the crack tip was reliably identified as the distance between crack faces was smaller than the tomographic data resolution; and both compression and tension elastic modules were measured. The first results were presented at the European Conference on Fracture Mechanics. The main paper will be published in 2020.

4D micro-CT analysis of natural and artificial tissues.
Reliable biomechanical characterisation of tissues (natural or artificial) with complex microstructure requires the employment of a highly-customised testing procedure. For this purpose, methodology and technical equipment was developed that allows X-ray micro-CT inspection (on-the-fly tomography) of continual loading procedures. Time-lapse imaging with stepwise loading cannot be applied in this case because of material relaxation. Our method integrates the usage of i) single-photon counting detectors (suitable for low-attenuation

materials) for fast but detailed imaging, ii) the highly-precise positioning necessary for loading rates down to 0.1μm/s and force measurements and iii) controlled ambient conditions simulating physiological body fluid circulation. The concept was successfully proofed, and a unique dataset of deformation bone scaffolds, cancellous bone and cortical bone was acquired. For the evaluation of these data, digital volume correlation was used. It allows full-field displacement and strain calculation on the tissue microstructure. The method was also adapted for middle-term analysis of fatigue properties and microdamage propagation caused by cyclic loading.

Mechanical response of additive manufactured structures. In the field of additive manufacturing and its utilisation for engineering practice (including biomedical engineering), several studies were performed focused on the influence of printing procedure parameters on the effective properties of the resulting structure and the relationship between geometry and the effective mechanical properties of periodic additively-manufactured structures. The tested structures included (i) bio-inspired structures (tissue models obtained by 3D computed tomography) and (ii) periodic structures exhibiting a negative Poisson's ratio (auxetics). In the testing of bio-inspired structures, attention was given to the comparison of several base materials including poly-lactic acid or UV-curable materials and to the influence of the level of filling or printing direction on effective mechanical response in different loading directions. In the testing of artificial periodic structures, optical strain measurements were utilised to obtain a full-field strain map of the loaded structure and to analyse the mechanical behaviour of the lattice in accordance with the numerical simulations. The studies on mechanical response were conducted on a multi-scale level, as the investigations covered both macroscopic tests using standard or in-house developed experimental setups and local, micro-level testing performed by indentation measurements.

Control system for laboratory devices. The control system for laboratory devices used for in-situ 4D CT has been vastly improved and optimised. New functionality of the control software has been developed, such as closed-loop experimental procedures and open-loop experimental procedures. The control software has also been equipped with new capabilities such as remote control and a scripting interface. The remote control enables control of the laboratory devices over a network while data-acquisition and all the necessary security features are handled on the local side of the control system, which runs a real-time Linux system. This approach gives the control system a lot of flexibility as the devices can be controlled remotely using various portable devices. Currently, the control software is compatible with multiple platforms such as Linux, Windows, etc. The scripting interface of the control software provides a programmable interface that is used for fully-automated testing that involves complex and time-consuming procedures. This functionality also makes it possible for the control system of the in-situ devices to be integrated into or made to cooperate with other control systems and laboratory setups. In terms of control software performance, massive parallelisation has been a huge leap forward. The current version of the control system can utilize up to 8 CPU cores, which has resulted in about 10x higher data-acquisition performance than the previous version.

Research activity and characterisation of the main scientific results

Team of Applied Sciences for Cultural Heritage (TASCH)

Research into the interdisciplinary problems of cultural heritage, including historic materials, historic structures and historic settlements, has traditionally been carried out by the Institute throughout its entire existence of approximately 100 years, and this tradition continued in the assessed period. The team is composed of the Department of Monument Diagnostics and Conservation, Department of Heritage Science, Department of Lime Technologies, Laboratory of Diagnostics I (in Prague), Laboratory of Diagnostics II (in Telč—mobile laboratory) and Laboratory of X-Ray Radioscopy.

Diagnostics of historic materials and structures

Direct determination of the mechanical characteristics of degraded wood in-situ. The newly developed methodology represents a breakthrough in the diagnostics of timber structures. It took advantage of a substantially upgraded technique for in-situ testing of timber in existing structures. The method is unique worldwide as it directly measures conventional compressive strength and the modulus of deformation using a mini jack with opening clamps inserted into a drilled hole of 12mm in diameter. (The device has been developed and patented entirely by ITAM). This unprecedented method makes it possible to assess the mechanical properties of a timber element directly in the field at an arbitrary depth in the structural element and under real moisture conditions, which was not possible in the past. The research and outputs further focused on optimising the combination of the abovementioned method with other applicable in-situ techniques, namely pin-pushing and resistance micro-drilling, and on correlating it with standard material tests. The results have been used in both basic research projects and applied research or practice research tasks. The method attracted international collaboration, which has also been reflected in the joint publication activities. It is the basis for ongoing bilateral cooperation with Padua University on a study comparing local NDT results with data obtained from loading tests of structural elements. Practical applications included the assessment of the condition and measurements of the mechanical properties of the timber ceiling structure in the Müller House, Komenského náměstí no. 1, Opava; the assessment of the condition of the truss in the Church of the Holy Spirit in Telč; the endoscopic survey of the ceiling beams on the ground floor of the northwest part of Karlštejn Castle; the detection of the extent of timber damage and traceological analysis of the craftsman's work in Čistá u Litomyšle no. 97; the construction and technical assessment of the state of timber, trace analysis and surveying of a timbered barn in Skalička 3; and the evaluation of the wooden construction of the movable roof of the Paraplicko garden pavilion at Cesky Krumlov Castle.

Acoustic methods for wood diagnostics. The timber diagnostics research continued with a study of the application of acoustic methods to determine the mechanical characteristics of wood. The correlation analyses compared the parameters of specific equipment and the basic mechanical characteristics of wood. It shows that the correlation depends on the equipment used, the mechanical characteristics variable and the species of wood in a way that is not sufficient for practical application unless other complementary methods are also applied.

Diagnostics and long-term monitoring of the structural behaviour of important historical monuments. In the field of non-destructive diagnostics, a series of tasks for practice was researched on a contractual basis. Survey methodologies on the diagnostics of deteriorated built stock were investigated and tested in practice with international participation. Passive and active thermography investigations carried out on the rendered historic masonry structures of important Czech monuments brought about important historic findings (e.g., Telč Chateau, Kunštát Chateau) as well as identification of structural defects (e.g., Eisgarn in Austria as part of an international research project). The work also required the development of specific software tools for the analysis of thermography records (e.g., for the visualisation of masonry stones and for merging individual pictures into wider and balanced images). Similarly, the

application of the ground penetration radar for structural surveys (e.g., Telč Chateau, the US Embassy residence in Prague) was in high demand. In the Telč Chateau, which is listed as a National Cultural Monument and also protected as a World Heritage Site, the thermography helped identify gothic arches and remains of vault ribs hidden under a layer of renaissance rendering without its removal. The ground penetration radar was used to discover buried ancient walls under the modern pavement of the chateau yard. In the Kunštát Chateau, which is an important monument with recently-discovered medieval frescoes, a complex NDT survey focused on identifying walled-up ancient openings, the structure of the masonry and material characteristics of the mortars used. Thermography, videoscopy, GPR and small sample testing methodology were applied. In the US Embassy, GPR was used to discover the position of reinforcement bars and steel beams in a concrete slab for the purpose of restoration works.

In the period from 2015 to 2019, long-term monitoring of the behaviour of important historic buildings continued (National Museum in Prague, Royal Summer Palace at Stromovka in Prague). The network of monitored structures was extended to include the Fürstenberg Palace in Prague (Polish Embassy) and the Church of All Saints in Sedlec–Kutná Hora (on the UNESCO World Heritage List). The measured data were regularly evaluated, the rate of damage development was assessed and appropriate measures were recommended if necessary.

The applied results in diagnostics further include damage and failure analyses of various buildings and structures. TASCH analysed a glass ceiling in the main building of the Academy of Sciences that was having problems with cracking and breaking and recommended a new arrangement of the supports of the glass sheets.

The Department of Diagnostics carried out radiometric investigations of various sites (mostly historic stucco statues and decoration) as contracted applied research. The results helped conservationists optimise restoration procedures to achieve the best possible results with minimum impact on the monuments. The results also provided new insights into unexpected hidden details of the studied objects.

Some of the applied results were achieved in cooperation with other teams—for example, an assessment of the monetary value of a gothic wooden church in Guty that was lost due to arson (50%) and complex condition diagnostics of the provost´s areal in the Prague Royal Castle for the purpose of its restoration and refurbishment (50%).

Strategies for mitigating global threats in the built environment

Reducing long-term weather effects. Specific research has been carried out on the problem of the effects of wind-driven rain on brick masonries. A comprehensive experimental programme was designed and materialized, including the development of a new method for measuring moisture content in the masonry. Burnt brick masonry piers were tested in the “Vincenc Strouhal” climatic wind tunnel under various combinations of rain intensities and wind speeds. The results were achieved in cooperation with the Team of Theoretical and Applied Mechanics, which contributed by controlling the climatic wind tunnel during the rain calibration. This research activity will continue in the next period. The second important topic was related to the numerical modelling of thermal behaviour and the response of architectural heritage to external conditions in the context of possible material degradation as well as the contribution to physical comfort.

Improved resilience of built heritage in relation to natural disasters. Research into the resilience of cultural heritage was mostly a subject of international cooperation. Three major threats were investigated: earthquakes and wind, mostly in cooperation with the Team of Theoretical and Applied Mechanics, and flood and drought. The research into flood disasters was extended from problems regarding built stock to problems regarding the protection of residential areas as well as the protection of moveable heritage. Specific results directly applicable in practice have been published for resilience improvement in case of an earthquake

(dissipative timber joints, dissipative masonry/timber floor connections, enhanced out-of-plane stability of masonry walls in collaboration with the Centre for Experimental Mechanics) and flood events. This research orientation has started to involve and develop the possibilities of remote sensing—for example, the COPERNICUS programme and ontology-based damage models and analysis. Part of this research contributed to an international contract with the EU on Safeguarding Cultural Heritage from Natural and Man-Made Disasters: A comparative analysis of risk management in the EU. The outputs of this research are available on the project websites and intended for risk management bodies or individuals.

Strategies for the protection and conservation of cultural heritage

Restoration and sustainable use of cultural heritage. Investigations in this area included studies on safeguarding degraded historic materials, structural elements and neglected or unused objects. Material problems solved in cooperation with the Department of Materials Research involved research into the consolidation of lime mortars and the consolidation and restoration of adobe or clay-based mortars. In this research, all experimental methodologies and mechanical testing were provided by the TASCH.

In cooperation with the Department of Applied Mechanics and Structures, computational models of full-scale lap scarf timber joints were investigated and experimentally tested. Such dowel-type joints are important for replacing decayed parts of historic timber joists.

Major research in sustainable restoration focused on the problems of historic ruins and was carried out as part of an international project. The outputs, which were provided entirely by TASCH, aim to define the rules and conditions for long-term maintenance of such monuments and their suitable use. They include guidelines for optimum application of NDT methods for assessment of the ruin conditions.

Conservation of historical timber. The decay of wood and timber structures has been studied in detail in relation to the traditional conservation approach. Deterioration stations have been established with wood specimens protected by means of various agents or just traditional carpentry woodworking and subjected to various environments—from those buried in soil to those exposed to weathering. Protective paints have also been developed, tested and, finally, suggested for practical applications. In this research, as applied results, two “functional samples” have been developed—namely oil-based paints for the reconstruction of the “Libušín” house in Pustevny and for the restoration of the façade of the “Jurkovič house” hotel in the Luhačovice Spa.

Sustainable safeguarding of moveable heritage. The safe storage, exhibition and display of moveable heritage together with the environmental requirements on so-called “green museums” have been the subject of a long-term research project supported by the Czech Ministry of Culture. The goal of the project is to protect museum collections by obtaining detailed knowledge of the museum’s environmental dynamics through long-term monitoring via a specialized network of sensors, enabling maximal indoor climate stability with minimal means. The main aim of the networks was to integrate various detectors in one platform and make the data available long-term in a readable format that is easy to process on-the-fly as well as ad hoc. A complex hierarchy of sensors, control units and communication units has been developed to meet every possible scenario concerning the required processing power (research topics range from extremely low power consumption to energy harvesting), available or lacking energy supply and site connectivity to the internet (topics span from radio transmission to long-range networks). Data mining exploitation of the accumulated sensors’ data enables the adjustment of ranges of safe or acceptable margins of environmental parameters for the storage of various types of objects. Data are also used to parametrize so-called dose-response functions for material degradation prediction.

Optical methods developed for documenting the shape and the state of preservation of heritage objects and materials. The 3D shape of small objects like cuneiform tablets can be acquired by digitalization devices built in-house, utilizing shadowless illumination and computer-controlled translational and rotational movements while the reconstruction is carried

out on Photoscan, which is now considered standard software. In the case of investigation and reconstruction of finely structured surfaces, the photometry stereo-based method is applied. In contrast to the “Structure from the motion photogrammetric method”, the relationship between the camera and the object is fixed, but the illumination of the scene changes. The surface topography can be derived from surface shading. To fully control the light in the scene, various specialised devices have been built over time at ITAM, some of which are even patented (e.g., an integral device for developing digital 3D models using the photometric stereo method together with the Department of Materials Research). A recently-developed fully-transportable dome illumination enables the acquisition of data directly from a museum collection. The newest development concentrates on creating detailed hyperspectral maps of complex surfaces like paintings combining UV-VIS-NIR spectrometer with computer-controlled movement.

Technical recommendations for the design and testing of lime-based repair materials.

Members of the team actively participate in the RILEM Technical Committee’s TC 277-LHS Specifications for the testing and evaluation of lime-based repair materials for historic structures and TC 243-SGM Specifications for non-structural grouting of historic architectural surfaces. The state-of-the-art reports and recommendations issued by TCs are highly recognised by researchers working in the field and by building conservation practitioners. Part of the research undertaken for this committee work has been led by ITAM members and focused on the specific testing procedures of stone repair materials. New testing methods of injection grouts were developed, examined and verified in an inter-laboratory comparative assessment (round robin test). Another important contribution is the work revising the current standards and aiming to provide improved tests and evaluation procedures for mortars traditionally used in historic buildings based on low-strength binders.

Study of lime technologies

Lime technologies of historic buildings. The special focus on lime production and processing technologies is driven by the widespread use of this type of binder in historic buildings and its multivariable application in mortars as bedding, floor coating, etc. The research into this topic combines different interdisciplinary activities that focus on providing technical and scientific knowledge for the application of traditional lime-based mortars when repairing historic buildings. These activities resulted in the following outputs: a GIS-based map of historic limestone quarries and lime workshops, certified methodologies regarding the processing of lime and production of mortars replicating the historic techniques for the Czech Ministry of Culture and an evaluation of various types of historic lime kilns and their operation regimes in Central Europe. Experimental research provided data on production-specific properties of lime, optimal production conditions and the composition of natural hydraulic limes produced from historically well-known sources that had ceased their operation. The outputs from this research theme also comprised applied results for practice such as prototype mixes based on analytical studies of historic originals. The research also contributes to the topics that are most important now regarding the search for alternative binders, lowering carbon dioxide emissions and CO_2 abatement.

Rediscovery of historic art and construction techniques. Understanding the materials and techniques used by artists is part of conservation science, which covers a wide interdisciplinary field that has been rapidly growing over the last decades in Europe. The members of the team have been developing a new approach to understanding historic techniques with regards to sustainable and compatible conservation treatments. This novel approach is based on detailed material analysis combined with experimental determination of application techniques and evaluation of the resulting material properties. The objective is to provide a solution for the repair of specific artistic building elements (or their conservation) based on material authenticity. Four studies into historic flooring constructions and masonry mortars of the Roman period, Renaissance sgraffito decorated renders and Baroque gypsum-lime plasterworks have been successfully concluded thus far. Although the studies are locally

specific, there is a strong link with the neighbouring countries (transfer of techniques) and, more importantly, the general understanding of the original materials and techniques has the potential to provide solutions for advancements in cultural heritage preservation worldwide.

Methods of characterisation of historic mortars. The characterisation of historic mortars is carried out within collaborative projects with archaeologists and art restorers as well as general building practice. The expertise of the researchers in the fields of analysis and historic materials (lime, gypsum, natural stone, burnt ceramics) plays a crucial role. The provenance of the marbles used in an early gothic Cistercian monastery was determined based on the petrography, elemental and mineralogical composition, cathode-luminescence and stable isotopes $\delta^{13}C$ and $\delta^{18}O$. The origins of raw materials for lime production were determined for the earliest building phases of the Prague Castle. Advanced binder analyses have also contributed to the selection of samples for carbon dating. Advanced expertise in historic materials is appreciated in construction practice, where degradation caused by moisture and salts is a common problem. Laboratory research and experiments into hygroscopic moisture content contributed to the description of nitrate salt behaviour in buildings.

Development of experimental techniques and devices

Considerate high-performance testing of building materials aimed at the development of techniques and/or devices providing high-quality material data at affordable costs, mostly applicable in the conservation/restoration field.

It included innovated tests for the *assessment of a near-surface cohesion of renders* based on previously developed peeling tests of stone surface cohesion. All the results and supporting materials are distributed freely in the open science way. The method is reliable, low cost, ready for practical use and acknowledges significant response from practice.

Furthermore, laboratory and *field devices for measuring the rate of water penetration into materials* were developed and patented (2016). The devices use micro-tube water outlets and automatically store data from several measurement series. The tube does not need to be fixed to the surface and thus enables measurements of complex and curved shapes, for example, on sculptures.

A method for *testing the shear mechanical characteristics* of models of historic mortars has been developed using an in-house designed and manufactured electro-mechanical biaxial loading frame and a contactless DIC for deformation measurements. The shear parameters are measured on thin-walled tube specimens, and numerical simulations were developed in cooperation with the Department of Materials Research and used a FE multiscale material model. (50%)

A study on *comparative tests of biaxial bending of thin discs and uniaxial bending of rectangular plates* was carried out. A special fixing and loading rig for circular discs was built. Both techniques were studied using quartz sandstone test specimens and yielded results adequately describing the changes in the stone after consolidation treatment, and their choice in practice is determined by aspects other than mechanical testing modes—namely, sample extraction techniques, core drilling or saw cutting—and the planning of other types of tests—for example, dilation behaviour under various moisture and temperature conditions.

In cooperation with the Department of Materials Research, an innovated and patented *fully controlled loading device for four-point bending of short beams* was developed and intended for 4D x-ray tomography, where it has been used for fracture mechanics research. The conservation of an almost identical volume of material during the x-ray scanning and the very fine loading control are its main advantages, which facilitates the detailed study of fracture zones and crack development mechanisms in quasi-brittle materials. (20%)

In relation to weathering deterioration effects, specific research has focused on the problems of salt crystallization effects. A special *device for measuring salt crystallization pressures* has been designed and built in cooperation with the Department of Materials Research. (50%)

Development of X-ray radiography and computed micro-tomography

TORATOM device performance development and enhancement. The unique Twinned Orthogonal Adjustable Tomograph (TORATOM) patented on the European level has been equipped with newly created in-house software. The software was developed to control the device in advanced modes, allowing a quick alignment of the device before experiments, including alignment for dual source / dual energy measurement mode and effective data acquisition from various detectors. Furthermore, the process of scanning large flat objects was algorithmized and automated. Research was also done on precise identification of the device geometry using advanced measurement phantoms in cooperation with researchers from Padova, Italy, and Leuven, Belgium.

Micro-tomography methodology. A method was developed for the compensation of small movements of the X-ray source in high-resolution measurements, and again, this method was implemented as a software tool. Using precise positioning, novel data-acquisition procedures with repetitive acquisition of reference images and appropriate data processing, details below 5 micro-meters could be reliably distinguished. The work produced shared results with the Department of Materials Research in the field of bone research, foam and artificial bone scaffolding testing.

Coupling of TORATOM and X-ray fluorescence (XRF) data on historic artefacts. A novel X-ray fluorescence camera was used to map the surface composition of historic sculptures and wooden statues. A setup was developed for automated XRF scanning procedures, useful for composition mapping on flat objects such as paintings, utilizing a hand-held XRF device together with the TORATOM positioning system.

Study of time-dependent processes in materials. New fast detectors shortened the time necessary for a complete tomography, thus enabling extensive measurements of materials under loading, such as sandstone or concrete materials, and developing time-dependent 3D models (so-called 4D tomography), useful for analysis of the mechanical properties of the materials and study of crack propagation.

Special radiographic investigations. In the field of X-ray radiography and computed micro-tomography, a series of tasks for practice was investigated on a contractual basis. Tomography was used to investigate metal archaeological artefacts such as metal bracelets, iron age swords and bronze age objects, allowing the discovery of hidden structures and engravings. Massive image processing was used to read writing on ritual lead amulets (defixiones) from ancient and medieval times. The porosity of mortars and cement-based materials was studied on tomographic 3D models. Tomography of wooden objects, such as statues, helps identify former restoration interventions and annual rings in wood can help in dating. An important application is the use of the dual energy approach to visualise characters on historical manuscripts. In biology-related research, TORATOM is often used to visualise the inner structure of scaffolds and bones. In the field of construction materials, the dual energy mode of TORATOM was employed in the investigation of composite materials.

The laboratory carried out around thirty tasks for practice. Here are summaries of the most interesting ones.

Tomographical investigation of lead amulets (defixiones). Defixiones are folded lead sheets with engraved texts, and they have been found in Europe since ancient times. Lead is generally very difficult to X-ray due to its high X-ray absorption that causes a lot of scattering, lowering the contrast in the resulting image. However, after massive postprocessing, it was possible to visualise the writing, even on a folded defixion. The investigation was done in collaboration with the Museum of TGM in Rakovník (Czech Republic), the Fraunhofer Institute (Germany), the Masaryk University in Brno (Czech Republic), the Hungarian National Museum and the Museum of Szombathely (Hungary).

Scanning of historical paintings with high resolution. The roentgenography of paintings is of great importance as it can visualise hidden structures such as underpaintings, former

restoration events and damages. TORATOM in Telč, thanks to its 13 movable axes, can be used in scanning mode to scan large paintings tile by tile at a resolution in units of micrometres per pixel. An automated algorithm of the scanning was developed and implemented in Python for precise device positioning. Several paintings up to 120 x 90 cm in size were investigated, finding underpaintings on several of them. The work was done in cooperation with the Restoration Faculty of the University of Pardubice in Litomyšl.

Tomography of an Únětican dagger from the Early Bronze Age. An extraordinarily well-preserved Early Bronze Age dagger was found in 2015 near Roztoky u Prahy, Bohemia. It was part of a larger depot containing mostly bronze artefacts but also some golden jewellery. The dagger was placed inside the sheath, and the whole object was slightly corroded. The purpose of the tomographical research was to visualise the engravings on the blade inside the sheath. The tomographical model allowed the identification of these engravings and also visualised other decorative and technical features such as the connection of the blade to the handle. The work was done for the Středočeské muzeum v Roztokách u Prahy.

Investigation of decoration on Iron Age swords. Iron Age artefacts, which in the Czech context originate from the Celts, suffer from heavy corrosion. Nevertheless, the iron core beneath the corrosion is often well preserved. Decorative engravings made on sheaths and swords are sometimes still present on the corroded objects, but they are completely masked by the corroded layer. It is very often impossible to mechanically remove the corroded layer to get to the engravings with respect to the state of the corrosion of the artefact. This is when X-ray computed tomography comes into play as it can visualise the engravings thanks to the difference between the absorption coefficient of the metal and its oxides (corrosion products). In this way, various Celtic swords from the collections of the National Museum in Prague were investigated and new, unexpected features were discovered.

Furthermore, the following new software has been developed.

ToraST (Toratom Software Tool) is a continually developed user interface for interacting with the TORATOM device. At present, it encompasses an image viewer suitable for the image formats that are native to the TORATOM´s detectors, a batch-processing plugin used for automated image corrections and a tomography plugin that is able to operate the available scintillation detectors (Perking Elmer XRD1622 and Dexela 1512NDT). The tomography plugin features a tool that geometrically aligns the device. The batch-processing plugin makes it possible to do any mathematical operation on the images, where up to two additional images can be used for one operation on the projection image. A unique feature of the batch-correction plugin is the flat field correction interface, where all the projections are loaded together with the open beam and dark field correction image. After that, the correction is started, taking the projection file in each step and doing the recalculation using the open beam and dark field image. The result is then saved to the drive in the specified format.

ToraPar. The desktop application ToraPar was developed in Python, including the graphical user interface, which simplifies the planning of tomographical measurements. The input parameters are the size of the detector and its pixel pitch, the aperture of the X-ray beam and the diameter of the circumscribed cylinder of the investigated object. The software allows tuning of the geometrical parameters—that is, source-object and source-detector distance—in order to get the required voxel size and detector coverage. It alerts the user if the chosen geometry leads to problems such as limited field of view or the object projection exceeding the width of the detector, etc. It also suggests the optimum number of scanning steps. One part of this software tool is dedicated to optimum acceleration voltage planning.

ToraSpot is a desktop software tool with a graphical user interface used for semiautomated correction of X-ray spot movement in projection images. During lengthy measurements, the position of the point, or spot, from which the X-ray beam originates can vary in the order of up to tens of micrometres because of temperature dilatation effects and defocussing of the electron beam. This fact leads to variations in the scanning geometry and distorted projection images, in particular when high magnification is required. One of the distortion effects is the

shift in the projection images. Although this shift is not the only distortion caused by the movement of the spot, it is the one that can relatively easily be detected and compensated for. The acquisition software for the TORATOM device was developed earlier in a way that allows it to spread the entire set of projection angles into several sets, where a reference image at the zero angle is taken at the beginning and at the end of each set. The ToraSpot software tool analyses these reference images, identifies the shifts in the horizontal as well as vertical direction and calculates the corresponding sub-pixel shifts of the individual projections. The user can subsequently launch the recalculation (transformation) of all the projection images. In this way, the effective spatial resolution of the resulting tomographical model can be improved.

XRD plugin and Dexela plugin. As the software tools developed for the TORATOM device are based on Python language, it was necessary to implement an interface between the C++-based dll libraries of the detectors and Python. This was done for the XRD1622 flat panel detectors and Dexela 1512NDT detector. The interface contains most of the functions that are part of the dll and thus enables the control of the detectors using standard functions from the documented application user interface (API).

One functional sample "*Long objects holder"* has been developed. In measurement practice, there are often long objects to be investigated such as historical swords or statues. To be able to fix them onto the rotational platform, a fixation kit was manufactured out of wood, as metal would affect the tomography because of attenuation and scattering. The setup consists of four wooden rods, which can be screwed into the rotational platform plate, and a wooden plate that is used as the upper fixation support. The upper fixation plate is movable along the rods, and it can be fixed in any position by means of wooden collet-like anchors. The object is placed onto the rotational platform and it is fixed from above with the upper support. In this way, objects up to 90 centimetres in length can be reliably fixed.

Heritage Science

History of construction. Comprehensive research into the history of carpentry structures, namely historic roof frameworks in the Czech Republic, was the subject of a national research project supported by the Czech Ministry of Culture. It studied typology development, joint details, erection techniques, carpenter or tool marks and traces, conservation and relationships to other European regions. The results are available in an interactive map and a book (in print).

Analysis of the foundation of historic cities. Within a national project, a new hypothesis regarding medieval surveying and the foundation of historic cities has been studied by analysing over 40 Czech historic towns and some abroad that were founded by the Czech Kingdom (in Austria and Slovakia). The research, supported by the Czech Ministry of Culture, aims to identify hidden cultural heritage value in protected urban complexes as important elements for city identity, protection and future development along with an improvement in knowledge about the work of medieval land surveyors and city locators.

Two functional samples have been developed reconstructing a possible *multi-angular groma* for surveying town layouts.

Regional history. ITAM is firmly anchored in the Vysočina Region and especially in the World Heritage City of Telč, which has a rich architectural history. In the evaluated period, the major research linked to the city investigated the architectural and social activities of the Jesuit Order in Telč, where they operated a college, public and music schools, an apothecary and a meteorological station. The Jesuits also significantly influenced the development of the cultural landscape. This project, supported by the Czech Ministry of Culture, has a cross-border dimension. Other smaller tasks involved, for example, works on the history of stone quarries or the use and provenance of marble in the region. The Jesuit archival records known as the "annual reports" have also been studied extensively as part of the research focused on identifying and further studying cultural heritage left by the Jesuits in the Telč region. New

findings regarding the impact the Jesuit Order had on the shape of the urban environment will be presented in a forthcoming exhibition, an exhibition catalogue (in print) and an interactive map.