

Experimental Approach to the Analysis of Historic Timber and Masonry Structures

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ABSTRACT: The paper presents a critical review of non-destructive as well as less invasive semi-destructive methods and approaches to investigations and diagnostics of historic masonry and timber structures. It presents the basic requirements for a comprehensive survey of historic timber structures and special methods developed for diagnosing their health. A comparison of different techniques suitable for testing wood characteristics comprises: resistance drilling, rod penetration, ultrasonics, X-ray, core drilling, videoscopy, together with standard tests on samples taken from real structures. There is a short comment on experimental analysis of joints, as tested on replicas or original parts of historic structures and used for calibrating theoretical models. Historic masonry characteristics are dealt with from the point of view of materials and from the point of view of structural integrity and homogeneity. Selected masonry diagnostics and defect location methods are presented, namely thermography, acoustic methods, dynamic identification and small sample testing. Special optical methods for measuring material characteristics and degradation phenomena are introduced and illustrated.

1 INTRODUCTION

Experimental approach to analysis of historic materials and structures is strongly influenced by a necessity to minimize interventions and to avoid damage of original material tissue or structural concept. Therefore, non-destructive and considerably invasive semi-destructive methods and techniques are preferred for investigation of historic materials and structural elements. Large historic structures and assemblies of elements or joints can be studied in situ using loading tests as well as in laboratory by study of models and replicas made from historic or even contemporary materials and using traditional or modern technologies. This paper does not aim to review all history and possibilities for experimental analysis of historic timber and masonry. It is rather focused on presentation of the author's experience in this field and on some recent development of specific techniques in other laboratories. Therefore, it mostly refers to works carried out and published by the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, the European Centre of Excellence ARCCHIP (Advanced Research Centre for Cultural Heritage Interdisciplinary Projects) within its national and international research projects.

Some approaches presented below have potential for wider applications than only for timber and masonry structures, which is shortly discussed and evaluated. Further, not only survey and investigations necessary for determining mechanical characteristics or structural health for design purposes or safety assessment are mentioned because any diagnostics and analysis of a historical material and structure must take into account also technological, art history and conservation aspects, especially the need to protect originality and authenticity.

2 HISTORIC TIMBER

2.1 Historic technology survey

The technological survey starts on the surface of historic timber elements (beams, joints and connectors). Various kinds of technological traces can be found here. The most important traces come from squaring and jointing carpentry operations. Iconography and experimental research into medieval carpentry technology investigating traces and use of traditional tools – different types of axes – helped to reconstruct the Central European technology for squaring logs into beams and for preparing carpentry joints. From the distinctive traces left by woodworking tools, we can distinguish between “low work”, i.e., work on the ground and the “high work”, and it is even possible to assess whether the medieval carpenter was left-handed or right-handed. This knowledge can be advantageously utilized for restoring valuable ancient roof frames from medieval times by replacing the deteriorated parts with new parts produced with the use of medieval axes and techniques, Drdácý et al. (2004).

Hewing round timber into square profiles involves three operations: scoring, hewing and flattening. The scoring facilitates the subsequent hewing. The carpenter divides the round edge into shorter parts by making notches perpendicular to the log axis. It helps substantially to split off the round edge during rough shaping (hewing) of the beam. The last thin layer of wood (0.5 cm to 2 cm) is then removed during flattening or planing with a broad axe. In the course of the work, and after each blow, an axe leaves traces that may be classified by typical elements as i) proper traces and ii) occasional traces. A detailed description can be found in Drdácý et al. (2004). Let us mention here that so-called proper traces form a “y” shaped pattern on the beam surface, which is composed of a “bladeprint” or splinter mark and a set of licks or scratches. The bladeprint is a straight or curved split on the surface of the hewn wood that is oriented according to the position of the carpenter. Surface marks referred to as licks or scratches on the surface are inconspicuous, slightly protruding arching parallel lines on the cut-out area, and they are left on the surface of the cut by imperceptible irregularities in the cutting edge of the instrument.

A simple technique was developed for analysing traces, based on the historic carpentry experience of master carpenter P. Růžička, i.e., working with traditional tools and comparing the results with historic timber structures and objects. The technique takes advantage of the spatial relation between the splinter mark, the lick and their orientation on the surface. When looking at the timber element we can use the self-explanatory diagrams presented in Figs. 1a and 1b. This helps to identify whether the work was done by a right-handed or left-handed carpenter hewing on the block or above the waist in vertical position, and also whether the carpenter worked on the piece in a horizontal position lying on “dogs” or on a stool. For practical survey procedures, a simple transparent sheet with the printed diagrams from the Fig. 1 is helpful and can be used for a very quick analysis of the origin of the discovered traces by overlapping it over the traces.

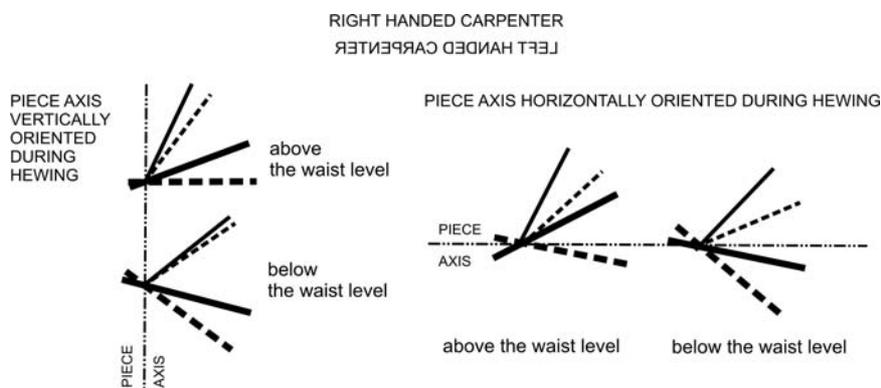


Figure 1a : Splinter marks (bold lines) and licks (thinner lines) help to identify the work mode

Figure 1b : Splinter marks (bold lines) and licks (thinner lines) help to identify the work mode

From archive documents we know that the surface of timber frames was treated with special coats, Drdácý et al. (2005), in order to prevent biological attack (mostly by oil) and also to de-

crease the combustibility of the wood (e.g., using alum). Such analyses are quite rarely carried out, but they are of great importance not only for history but also for durability assessment of timber subjected to different treatment technologies. Of course, it is very difficult to identify the chemical composition of the applied historic treatment agents for organic materials, e.g., oil-based coats. We have to keep in mind that some treatment materials are composed of several thousands of substances and it is difficult to determine them from the data that we can acquire now. For example, pine tar is likely to be composed of 8 000 to 15 000 substances, Mattinen, Linnanmäki (2006).

From the above mentioned examples, it follows that a surface survey is a very important source of historic information. Of course, several other traces are readable on historic timber, e.g., assembly marks, technological traces from transport log rafters, etc., and all of them should be carefully documented and conserved. Progress in the development of new equipment for diagnostics and analysis constantly increases our ability to interpret conserved traces. Therefore, in any intervention and remedial work we recommend that some structural surface be conserved in its intact and untouched state for future possible analyses.

2.2 Timber health survey

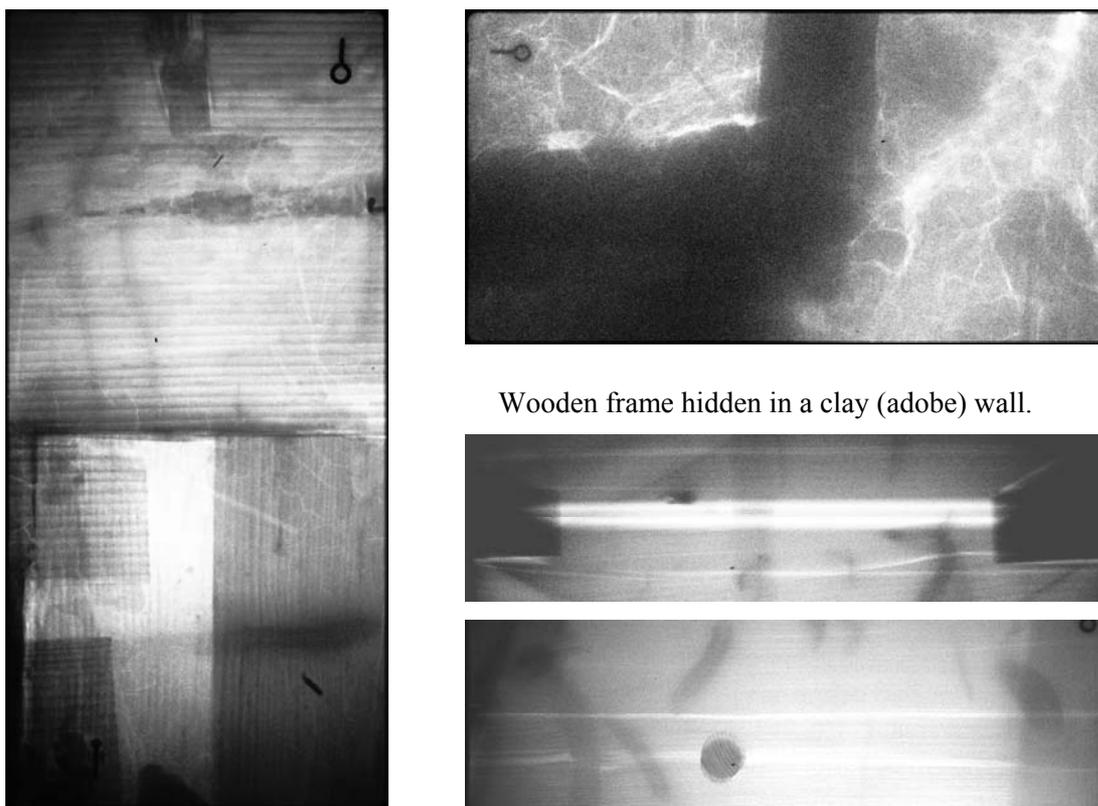
Non-destructive and considerably invasive semi-destructive testing methods are mostly suitable and reliable for a qualitative survey of historic wood and historic timber structures. Practically useful methods require good access to the tested structure, with the exception of resistance drilling and videoscopy, where we can examine also wooden structural elements built in masonry. Among health survey methods, X-ray visualization is usually the most appreciated.

2.2.1 X-ray diagnostics

Traditional X-ray technology using film and high-energy X-ray sources has been used to examine structures for over 60 years, Hacar, Waitzman (1944). X-rays emitted from traditional high-energy electromagnetic radiation sources are capable of penetrating most materials used for building construction. Depending on the material properties of the object being inspected, a photographic image is produced which reflects the density, thickness, energy absorption and chemical properties of the material. However, due to safety concerns and the high costs involved, it has been in only limited use in timber structure evaluation, Anthony et al. (2003). Unlike traditional film X-ray technology, the use of digital real-time X-ray technology for structure investigation is quite recent and has shown considerable promise for use on timber structures. Digital radiology offers significant advantages over traditional X-ray techniques for assessing structures: advances in the technology make it safer to operate and it has the ability to store images.

X-rays can be applied as real-time radiography to provide a two-dimensional image of an object of interest immediately on a screen, or as digital radiology with images stored for further processing. A modern complete radiology system consists of three units: the X-ray source, an imager and the control unit. Each of the radiology systems uses a pulsed X-ray source manufactured by Golden Engineering, Inc. with 150 kV maximum energy, 0.5 mA with 60 nanosecond bursts (approximately the same energy as a dental X-ray). The imager consists either of a 20 cm by 25 cm or a 20 cm by 43.5 cm X-ray sensitive imaging screen. The imager is typically mounted on a tripod or placed directly against the surface of the object of interest. Access to both sides of the object is required. The control unit is a portable computer with an image processor flat panel display, which enables real-time display of the radiographs in the field, Anthony (2006).

X-ray diagnostics can reveal not only decayed wood but also hidden structural defects, types and state of carpentry joints as well as types and imperfections of metal or wooden connectors. Some typical examples are presented in Fig. 2. The measurements are effective on other materials, e.g., clay walls, gypsum sculptures and even slender masonry walls (up to about 25 cm in thickness), see further examples in the paragraph on masonry.



Door frame corner joint and connection of a log wall to a door frame column – in reality all hidden under thick lime paints.

Wooden frame hidden in a clay (adobe) wall.

Layout and side view of a failed halved joint with hardwood conical shear dowels and a hardwood pin connecting the two jointed elements.

Figure 2 : Examples of X-ray visualization of historic timber structures and joints.

2.2.2 Ultrasonic methods

Ultrasound methods are further typically non-destructive methods for diagnostics of historic timber. For inspecting the state of the wood, high (ultrasonic) frequencies are necessary, while low frequency sound waves are mostly used for predicting the modulus of elasticity. (However, there are some examples of the use of high frequencies for estimating the modulus of elasticity, e.g. Feio et al. (2005), who applied Pundit Plus equipment, with a frequency of 150 kHz).

Both methods are based on measurements of the velocity of propagation of an elastic wave through the volume of a wooden element. During the application, the time taken by the sound to travel through a piece of wood between transmitter and receiver is measured. Obviously, in situ measurement is possible only when transducers can be applied to the surface of the measured element from two opposite sides. (For health inspections, the so-called indirect variant of measuring on one surface only along the longitudinal axis is not sufficiently reliable).

The measured velocities are influenced by several factors, mainly moisture content, wood species, growth ring orientation, density, defects and imperfections or inclusions in the wood. Decay processes significantly prolong the travelling time perpendicular to the annual rings, which indicates deterioration or lower density, stiffness and strength, Ross, Hunt (2000).

Reasonable results of ultrasonic measurements of historic timber can also be acquired by a device called an Arborsonic Decay Detector (ADD), which uses ultrasound waves with a frequency of 77 kHz. In the author's experience, ultrasound measurements are valuable rather for a relative mapping of the quality of wood in the timber structure under investigation, which helps to discover places and elements affected by possible decay or by increased internal moisture. It

is difficult to achieve quantitative results without calibration by standard tests on extracted samples.

2.2.3 Resistance drilling

Devices taking advantage of measurements of resistance to drilling are quite frequently used for testing various building materials. In the case of timber structures, micro drilling with a very long and thin drill has proved to be a useful tool for describing the health profiles in massive wooden elements. The method was developed by Frank Rinn, Rinn et al. (1990). Rinn is also a producer of commercial devices for resistance drilling.

During drilling, the penetration path and also the energy necessary for cutting the hole are recorded and displayed graphically as a function of drilling depth and resistance against drilling. From such a graph it is easy to determine places with low or even zero resistance, indicating deteriorated zones and voids or cracks. The devices are sufficiently sensitive to measure differences between densities of annual rings, which are visible on the graph as peaks.

Attempts have been made to correlate the measured resistance to drilling with mechanical characteristics. However, the correlation is usually very low. Moreover, this method is highly influenced by moisture content, Fig. 3, which presents the results from measurement on a fir joist from the 15th Century before and after a severe fire. The moisture after extinguishing with a large amount of water increased from 24% to 88%, and the measured resistance dropped significantly, see Fig. 3, where a loss of joist height is also shown. The data was acquired using Resistograph 2450p with a drill 400 mm in length and with a cutting head 3.5 mm in diameter.

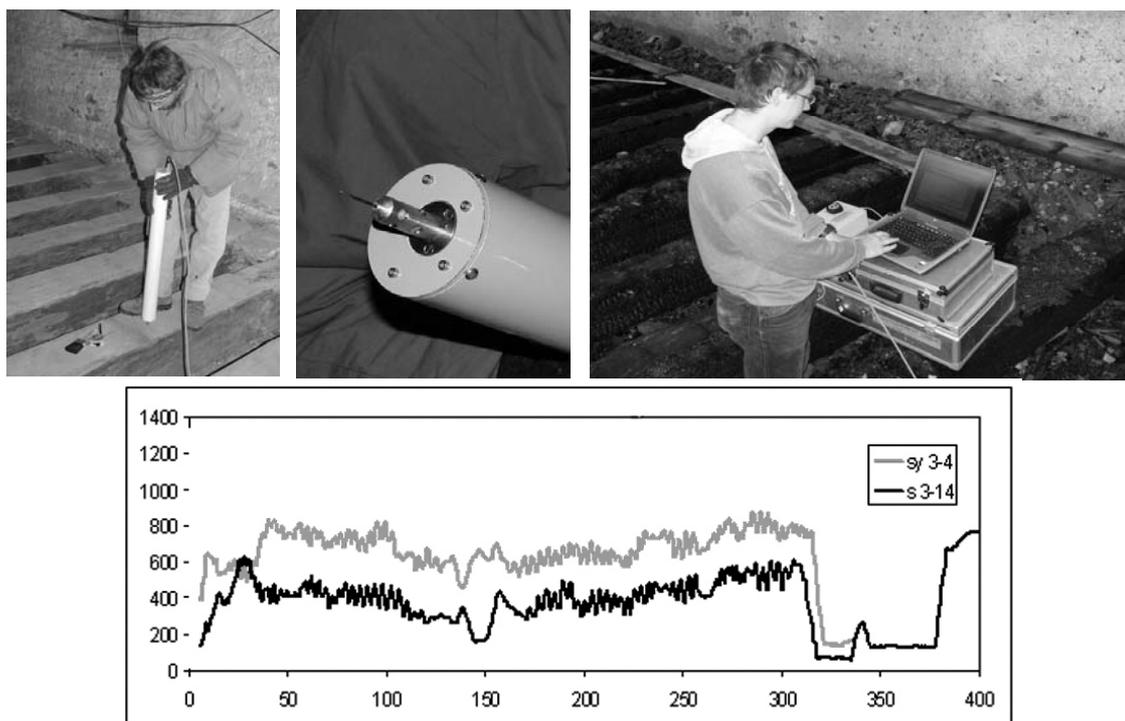


Figure 3 : Testing the resistance of wood to micro-drilling – operation of the Resistograph device (upper left), micro-drill head (upper centre), controlling unit (upper right), typical resistance graph of wet wood (lower curve) and 24% of moist wood (upper curve).

The area under the resistance graph divided by the length of drilling is usually used as a characteristic resistographic measure (RM) parameter, Feio et al. (2005). We recommend the use of a modified resistographic parameter (RP) calculated as the resistance graph area divided by the product of the length of drilling and the drill diameter, Frankl et al. (2006).

Although resistance drilling may be very helpful in discovering decayed timber, there are situations when this method completely fails. This happens mostly in the case of old and very hard timber, for example old pine wood, and in situations when drilling cannot be done perpen-

dicular to the annual rings due to lack of space, mostly drilling the joist heads near the collar beams, Fig. 4. In the above-described cases the drilling needle frequently bends and is deviated from the straight path in an uncontrolled way, and no resistographic investigation is possible. In such situations, another method proved to be very useful and reliable for inspecting structural health: videoscapy, in all its variants.

2.2.4 Videoscapy

Modern videoscapy technology does not require large openings for inserting a video camera, so it can be considered as a less invasive semi-destructive diagnostic method, similar to micro drilling. Holes about 10 mm in diameter are sufficient to accommodate the video on a flexible cable, which can reach much longer distances than any firm drill.

Videoscapy provides information about the state of the structure, changes of material, and, when voids are present, even about the situation in the void. Thus infection can even be revealed in places remote from the inspection hole. Fig. 4 presents videoscapy measurements with two results identifying biologically decayed timber. In this case the hole was drilled along the surface of a timber joist adjacent to the masonry.



Figure 4 : Videoscapy test arrangement (left), wood decayed by fungi (upper right) and by long horn beetle (lower right)

The advantage of distance vision is clearly demonstrated in Fig. 5, which shows the remaining parts of a collar beam under ceiling joists. The holes made for videoscopic inspection can be used for protective and consolidation works, e.g. injection.



Figure 5 : Remaining parts of a collar beam inspected by videoscopy.

2.2.5 Rod penetration

The final method to be discussed uses a slender steel rod or pin of a given diameter, which is driven into the wood by a dynamic force usually generated by releasing a compressed spring. The depth of penetration correlates quite well with material density, Görlacher (1987), Feio et al. (2005).

As with the previous methods (ultrasound and resistance drilling) the measurements are strongly influenced by variations in material moisture. For example, in the case mentioned above the increase in the moisture of the historic fir from 24% to 88% caused a corresponding increase of penetration depth by 33% in measurements made using Pilodyn 6J with a needle 2.5 mm in diameter, Frankl et al. (2006).

2.3 Evaluation of mechanical characteristics

Some of the methods described above have been suggested for assessing the mechanical characteristics of historic wood, and there are literature references, e.g. in Kasal, Anthony (2004). Unfortunately, the rather low correlation of the data acquired by NDT methods with the mechanical properties of solid wood, together with quite large variations in these properties themselves, significantly reduces the practical use of the results for engineering design, and no reasonable generalizations can be made. In individual situations, and after careful calibration by means of standard tests on samples of the same material, useful relations might be derived.

One of the most elaborated methods – stress wave measurement – is successful in predicting the modulus of elasticity, and for a specific wood species (yellow pine) it even gives very satisfactory results for material strength estimates. This is valid for sound wood only, and any quantification of the mechanical characteristics of deteriorated wood by means of this method is very difficult and unreliable.

Similarly, quite fair results in well-defined cases are provided by some other methods mentioned above, namely rod penetration. However, this is a very superficial technique, and the acquired data may be distorted by frequent differences between the interior and surface layers of material, which are particularly affected by moisture and biological attack. Nevertheless, this method gives better correlations with mechanical properties than other already reported methods.

Semi-destructive methods working with small samples of real material extracted from the investigated structure are considered a promising way to make an advanced evaluation of historic timber. They take advantage of testing non-standard wood specimens in tension and compression loadings. Two methods have been suggested and are under ongoing development.

2.3.1 Small specimen tension tests

A semi-destructive method based on testing small non-standard samples taken from historic timber structures has been developed in co-operation with Bo Kasal, Kasal et al. (2003). The tension specimens are prepared from thin long strands cut out of a real structure along the wood fibres. Various methods can be used for extracting strands from the structure. They are influenced by accessibility, subsequent elaboration of testing specimens and wood species anatomy. On easily accessible structures the following technique seems to be the most efficient. A specimen of small cross section, which is significantly smaller than the area of the beam, is cut out along the wood fibre direction using a small-diameter thin kerf saw inclined 45° with respect to the surface of the beam, Fig.6 left. This means that two cuts are required to obtain a prismatic specimen with a triangular cross-section. The side width of the triangle can be adjusted from 3-8 mm depending on the depth of the cut. A typical test specimen is shown in Fig. 6, centre. Here the thin wood strand is provided with glued head blocks for easy fixing into special hinged testing machine grips, in order to minimize the bending disturbance in tension tests, Fig.6 right. The cross section of the specimens is slightly reduced in the mid-span before the test, in order to allow failure in the central part.

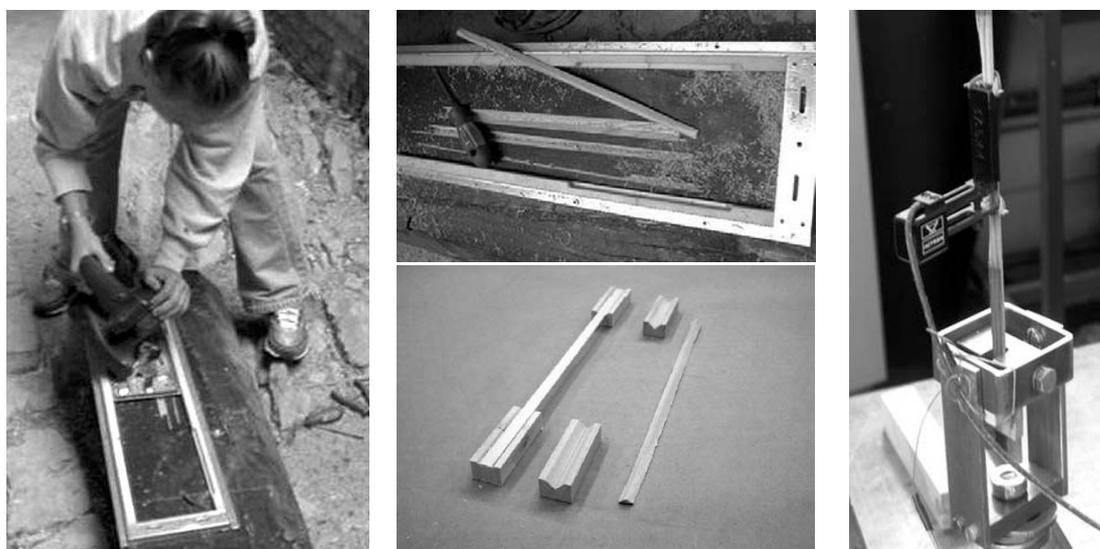


Figure 6 : Extraction of small tension coupons from a timber element using a kerf saw (left), cut triangular strands (upper centre) with head blocks (lower centre) and in hinged grips (right).

Small specimens have a cross-section area comparable to the ASTM standard specifications for tension tests of small clear wood specimens. Therefore, the tension strength values acquired through the described procedure are directly comparable with the standard tests. However, the method has drawbacks similar to all other techniques investigating surface layers. From the engineering point of view, it would be necessary to extract quite a large number of samples to achieve a sufficiently reliable evaluation and strength estimate. The estimate of strength is further reduced when visual grading of the tested timber element is taken into account. Under the constraints of minimum invasion it seems more acceptable to combine several NDT and semi-destructive methods: the former for homogeneity (density) and health evaluation, the latter for determining the guiding design or the engineering values of the mechanical properties that can support a reasonable assessment of the state and safety of a historic structure. Of course, other “classical” characteristics are helpful and must or should be determined, e.g. moisture content, specific density, annual rings density, dendrological data, biological attack.

2.3.2 Core drilling compression tests

In order to identify compression characteristics, an old core drilling method has been studied and improved. Core drilling involves extracting a small-diameter core from the material and testing the core in compression in special grips. The material characteristics (strength properties)

of wood along the fibres are the most important, since they directly control parameters such as bending, tensile and compressive strength along the fibres. Therefore, accurate orientation of the load with respect to the fibres is critical in estimating the material strength. For this purpose, a concave compression head is used to induce parallel-to-grain force, Fig. 7 (right). The core is then loaded in the direction perpendicular to the longitudinal core axis, and this generates a relatively complex stress-state which moreover significantly changes during the course of the test. Deformation of the core is measured by means of two LVDTs. Although the slope of the load-deformation curve correlates with the modulus of elasticity of the material, and the yield point corresponds to the compressive strength of the material, we cannot calculate the modulus of elasticity from this test directly due to the non-uniform strain and stress distribution. However, the slope of the force-deformation curves maps directly into the modulus of elasticity. Maintaining the correct orientation of the fibres with respect to the applied load is difficult, and a slight error in orientation will result in reduced apparent strength and modulus of elasticity. However, any error in specimen orientation will always result in conservative estimates of material strength. The conservative estimate will result not only from an error in specimen orientation but also from an increase in the variability of the test data, which will result in a conservative estimate of the lower 5th percentile. A special drill and a battery operated drilling machine are presented in Fig. 7 (left).



Figure 7 : Drilling machine for extracting a wooden core (left), detail of a drilled core (centre), and testing grips with an inserted oriented core (right).

Core drilling has been used for extracting small samples for testing building materials in different forms, from short column compression tests and a splitting test to the presented compression along the longitudinal axis of non-brittle materials. In the latter case, the stress state in the tested specimen is quite complex and variable in the course of loading. Because of the fundamental importance of the stress state for interpreting the test results, detailed studies have been carried out, Minster et al. (2006), Micka et al. (2006).

It has been proved that the above-described non-standard semi-destructive compression test on small cylindrical cores can be exploited to determine Young's modulus in the direction of the fibres by means of a combined approach of FEM numerical modelling using the ANSYS System and experimental analysis based on moiré interferometry. With the ANSYS model and the Monte Carlo method, the overall compression at an acting vertical force of 1 kN was computed for 1000 random values of modulus of elasticity along the fibres and also across the fibres, and the sensitivity was evaluated. Naturally, the modulus of elasticity E_L has a decisive influence on the overall deformation for loading along the fibres L , while the other parameters have an influence of less than 2.5%. From the calculated dependencies, the equations describing a probable modulus of elasticity as a function of the overall compressive deformation have been derived, (the modulus units are MPa, and the deformation corresponding to the vertical load of 1 kN is, in mm):

$$E_L = 5,287195 \cdot 10^4 - 6,7011265 \cdot 10^6 \cdot u_L + 2,5845044 \cdot 10^8 \cdot u_L^2$$

$$E_T = 7,8342295 \cdot 10^2 - 9,3867098 \cdot 10^3 \cdot u_T + 3,7115080 \cdot 10^4 \cdot u_T^2$$

The equations can be used to estimate probable modulus of elasticity values in the two main axes of symmetry for Czech spruce wood in dependence on knowledge of the elastic response of the sample to a change of vertical load of $\Delta P = 1\text{ kN}$ along the load direction. The optimum Young's modulus value can be read from the graph in Fig.8 (right) for a given ratio of E_T / E_L . The procedure and results have been validated experimentally. It should be mentioned that the experimentally attained elastic overall deformation cannot be measured from the overall deformation of the loading grips, and for practical application the elastic response can be achieved by unloading the specimen in the course of the test in the stage when plastic deformation on the contact between the grips and the wood has developed sufficiently and the central part is elastically and evenly loaded, Fig.8 (left). In the core drilling method, cores 5 mm in diameter and 30 mm in length are typically used.

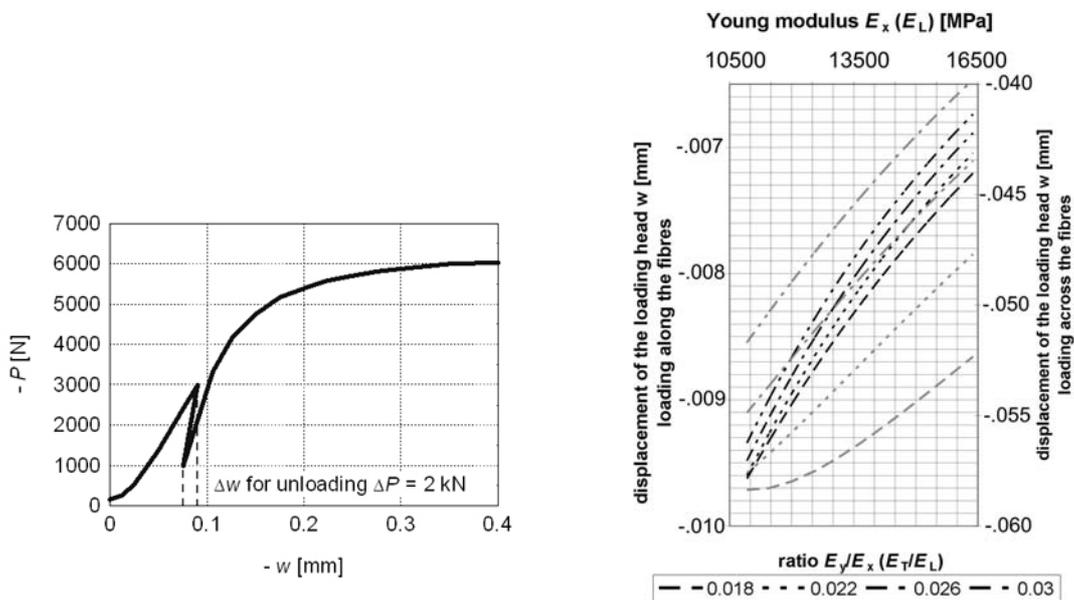


Figure 8 : Load-deformation diagram with the partial unloading for estimate of elastic deformation (left) and graph for estimate of optimum modulus of elasticity along fibres for given ratios of E_T / E_L (right).

2.4 Comments on structural testing under specific conditions

Research into the behaviour of real historic structures under repeated loading is a challenge in relation to natural hazards. Similarly to the example above, a suitable combination of experimental and numerical modelling gives the most satisfactory results, e.g., Drdácý et al. (2000). In such studies, historic structures or structural assemblies from demolitions or partial failures are valuable testing objects, and all administrative steps that allow the demolition of a historic object should contain a first option of use for research. Original historic material can be utilized for making replicas or models, although it is mostly hard to work with, and historically known tools and procedures cannot usually be applied.

3 HISTORIC MASONRY

3.1 Introduction

Experience of applying NDT for diagnostics of architectural heritage has shown that reliable data can only be obtained by combining various NDT techniques with some local investigations (drilling, flat-jack, etc.) for calibration and verification. Therefore, together with advances in

NDT techniques, there is a need for additional in-situ testing and laboratory testing on small samples, as has been shown above. Comparing the results of NDT with laboratory tests and with real mechanical measurements on specimens helps to evaluate the accuracy of NDT for different types of masonry and damage. It also enables us to assess data for the possible application of design standards in safety evaluation of historical masonry objects.

From among the vast variety of NDT methods for masonry investigations, we will concentrate on non-invasive techniques suitable for diagnostics of surface layers. This illustrates the possible applications of different methods for a single problem, depending on requirements and costs.

As far as diagnostics of mechanical material properties is concerned, let us continue with examples of testing non-standard samples. This has been initiated by the problem of testing historic bedding mortars or renders, where the typical thickness of the extracted sample is around 10 mm, and there is a general need for small micro-samples in order to protect historic masonry, where minimum intervention is always required.

3.2 Diagnostics of subsurface defects

Three different methods have recently been analysed or developed at ITAM for a non-invasive survey of subsurface defects of masonry. The first semi-automated approach to acoustic tracing (AAT) was developed in the EC FP5 ONSITEFORMASONRY project. The method is a development of a classical method applied in restoration practice for investigating rendering defects, based on manual percussion and marking the places that produce a different acoustic response. The method takes advantage of various dynamic and therefore also acoustic characteristics of detached parts, in comparison with parts that are perfectly adhered. The signal can be analysed simply by an operator or by means of electronic signal analysis. The position of the changes is usually marked with chalk directly on the surface, and then can be recorded optically (by means of photography or video). There is a faster variant that takes advantage of “natural” percussion, which is generated by surface irregularities and rebounds of a hard sphere dragged along the surface. This phenomenon is accompanied by a distinct acoustic signal that enables subsurface voids to be detected. The method is also known as the “acoustic tracing method”. During application of the AAT method, the investigated surface is excited by a slight knocking of a hard rubber sphere, e.g. the ball from a computer mouse. The location of the sphere is recorded on a video camera, together with the acoustic response associated with the knocking. The recorded data is consequently evaluated by means of special software tools, and a map of the defects is created. The measured acoustic signal can be evaluated by various approaches. In any case, the frequency spectrum at individual points is determined first, then the frequency spectra that are found are marked by means of pseudo-colouring, and are used for creating maps of possible defects, Fig. 8. The position of the knocking sphere is localised by means of image analysis and recognition of a contrastive “ball-shaped” body on the evenly grey surface. The pixel coordinates of the centre of the ball are determined and then used to create a map of possible defects. The method is especially suitable for hard and polished surfaces, where the methods described below usually give inferior results, Drdáký, Lesák (2006).

The second method uses thermal radiation measurement to indicate plaster detachment. Here the detection of loosened parts is based on the idea of measuring their differential cooling or heating compared to the heavy and integral parts with higher thermal inertia and different conductivity. Several tests on different walls with artificial subsurface defects proved that thermography is very efficient for plaster detachment diagnostics and void diagnostics. Even small defects are well visible after a short time of cooling of a preheated system.

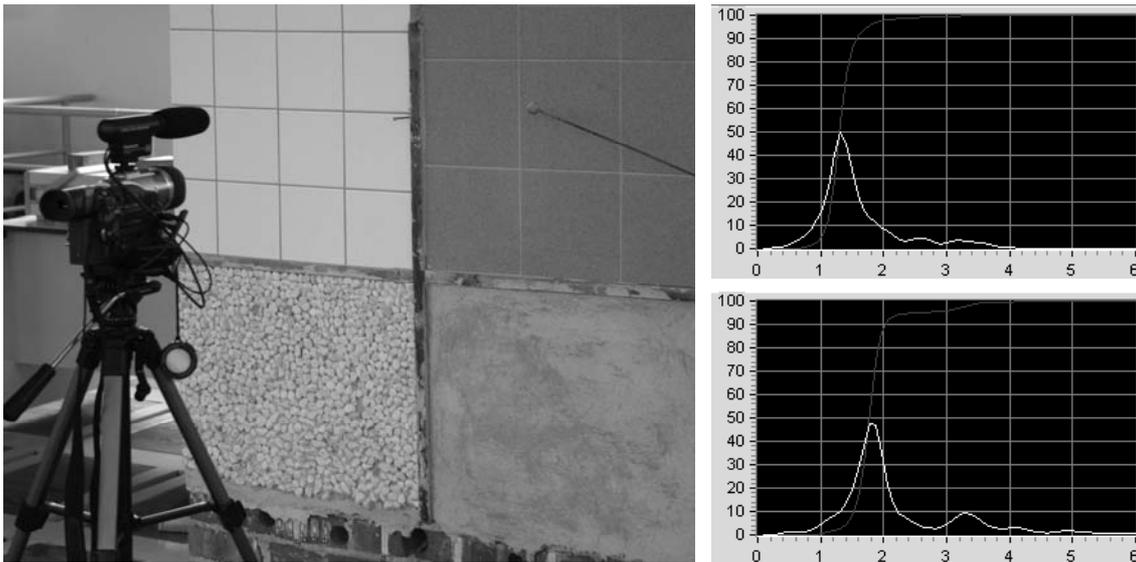


Figure 9 : Test arrangement for semi-automatic acoustic tracing with a video camera and a knocking ball (left), a typical large defect spectrum (upper right) and small defect spectrum distribution (lower right) – horizontal axis projects frequencies in kHz.

Natural daily sun heating and the usual drop of air temperature in the evening are sufficient to develop the necessary temperature gradient for infrared visibility of subsurface defects, Fig. 10 (left). Practical measurements can be effectively done after a few minutes (about 3-5) of cooling, Drdácý, Lesák (2006). Thermography is generally the most suitable contact-less method for detecting subsurface defects, namely plaster detachments. The measurement is very simple. Of course, the necessary equipment is quite expensive but it is widely applicable for NDT analysis. Interpretation of the results requires some experience and detailed documentation of the measured surface quality, at the best by means of usual photography. The method is significantly disturbed by moisture content, and this phenomenon should be further researched because it can bring about both negative and positive effects.

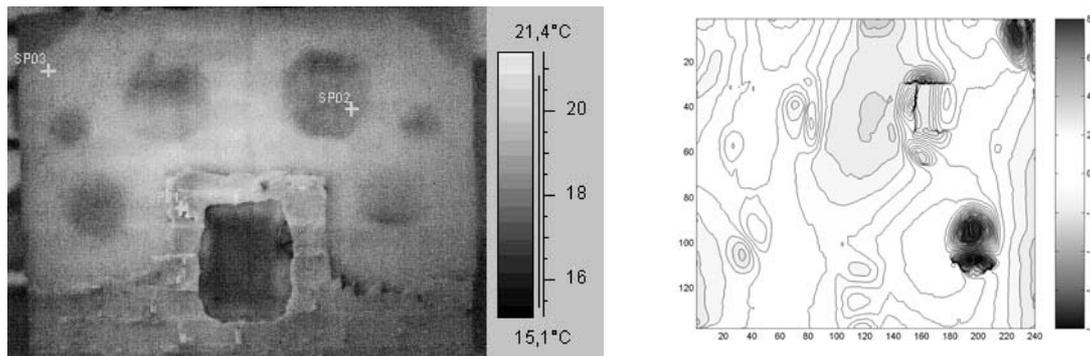


Figure 10 : Temperature distribution on the plaster surface (well visible different material layers, joints between bricks etc.) – (left), vibration modes of plaster defects on the identical test wall at the excitation frequency of 990 Hz (right).

The second presented method takes advantage of the fact that during dynamic excitation the attached plaster follows the velocities and frequencies of the vibrations of the wall in contrast to the detached parts, which vibrate at different frequencies and velocities that can be measured optically. The third method takes advantage of the fact that the best measurement results are provided by laser Doppler interferometry. Such a laser camera can monitor the surface from large distances – without special surface preparation of the order of metres. Scanning allows for

all field measurements and also allocates the velocities on positions on the surface with a resolution to about 1 mm for practical distances. The measured surface can be excited to vibrate by means of principally different methods – by means of acoustic excitation of the detached parts, or mechanically through vibration of the whole system. The first variant has been studied for several years at the University of Ancona (Italy), with very positive results (e.g. Castellini et al. 1999, Tomasini et al. 2000). The second approach has been studied at ITAM, Michoinová et al. (2000), and recent examples have been published in the USA (Vignola et al. 2005). In the ITAM tests, the vibration was introduced into the test specimen from an electromagnetic exciter and transmitted through a thin rod connected to the wall. The vibration frequencies varied continuously from 40 to 1500 Hz, and the natural frequencies were determined. Under these frequencies, the velocities were scanned across the full rendered area. The intensity of excitation generating a maximum velocity of about $5 \text{ mm}\cdot\text{s}^{-1}$ was used. Fig. 10 (right) presents selected results. It was well possible to detect small defects at high frequencies corresponding to the maximum amplitude of the vibration velocity. The spatial resolution of the measurements was 5 mm. Detection of plaster detachment by means of surface velocity measurements using laser Doppler interferometry and mechanical excitation of the wall is quite a time consuming and expensive procedure. The measurement time is dependent on the quality of the signal, the frequency of movement, and the spatial resolution. The higher the frequency, the shorter the measurement time; the weaker the signal, the longer the measurement time, because we need more cycle repetitions to achieve reliable results. Fortunately, small defects exhibit higher natural frequencies and the reasonable measurement frequencies are near 1 kHz. It is advisable to repeat the measurement with a phase shift of 90° , which may help to discover more defects. It seems that acoustic excitation is easier than mechanical excitation, which is suitable rather for small objects, lightweight wooden walls and false “vaults”, walled up timber frames and free standing masonry walls. There may be prejudices against vibration excitation as a possible cause for damage of historic rendering. However, we did not experience any damage or defect propagation during our tests.

3.3 *Small sample testing*

Testing historic mortars remains a subject of discussion, as it is obvious that conventional standard mortar tests yield more or less nonsensical results, which are practically useless for an assessment of the actual safety of or, conversely, the threat to a given historical structure. With negligible exceptions, mortar in historic structures does not occur in the thickness required for the manufacture of standard test specimens and is not subjected in these structures either to flexure or to compression in the way similar to test conditions. For this reason, there has been a growing demand to change the methodology of the tests of mortars taken from historic masonry. Attempts have been made to apply experience from soil and rock mechanics to this field (e.g., Van Balen), i.e., to test mortars in the conditions of tri-axial stress which, naturally, is much more exacting and requires appropriate instrumentation. For practical engineering purposes, simpler approaches are useful.

The sampling of historic materials – mortars and masonry elements – for mechanical tests requires an experienced professional capable of taking into account all circumstances influencing the test results. These include: the sampling place in the structure with regard to the rate of material degradation, its moisture content, possible previous interventions and possible technological effects. In the case of integral structures, the best suitable sampling method is core drilling, which makes it possible to prepare a sample of a masonry element that can be tested on site straightaway. A core drilled across the joint can also provide a sufficient quantity of material for preparing a sample for a compression test or even for a flexural test, if the sample is extended by “prostheses“. The drilled hole may be used for further NDT examinations, such as videoscopy, or for the measurements of masonry stresses. In partly degraded buildings it is possible to obtain even major test specimens during demolition or from parts of destroyed masonry, as in the case of timber structures. The mechanical properties are also influenced by the depth from which the sample has been obtained.

The methodology for tests of small specimens is influenced by several factors. In the first place, by the fact that the real size of the mortar sample taken from the historical masonry

structure is usually less than 2 cm in thickness. The manufacture of the specimen for a compression test (cutting a cube) significantly influences the properties of the sample, as it necessarily disturbs the surface strata and reduces the strength. Moreover, the manufacture of a small cube is very labour and time consuming and in most cases it cannot be done without supplementing the compressed surfaces with gypsum. For this reason, specimens in the shape of irregular mortar “cakes” from the masonry joint have been preferred in recent times for compression tests, and the thickness is usually levelled with gypsum or some other material to a constant dimension (Fig. 11). However, it is difficult to measure the modulus of elasticity of such samples, even if we use an “optical strain gauge”. This is another reason why the methodology for flexural testing of real mortar is being developed. However, in this case, too, we must cut the samples, and this involves the same problems of surface disturbance. Nevertheless, at least two sample faces can remain without interference and, consequently, with intact properties. These faces, however, are always the contact surfaces of the mortar and masonry elements and, consequently, the surfaces are technologically influenced differently from the basic material. There has been little study of this effect, which may either improve or deteriorate the mortar characteristics. In any event, the sample size remains too small for flexural tests. Therefore we have devised and are using sample extension with another material in the form of so-called “prostheses”. The method was developed at ITAM and has been used, among other applications, in the analysis of various types of historical mortars, e.g. Drdácý, Michoinová (2003), Drdácý et al. (2006). In the course of “prosthesization”, the sample of the material taken from the structure is supplemented symmetrically on both ends to the required length with two “prostheses”, ensuring that Navier’s assumption of linear stress distribution along the cross section in flexure is satisfied. This assumption forms the basis for the technical elasticity and strength of materials, and has been used in the derivation of mathematical models required for test evaluation. Moreover, if a short sample were to be used, the measured deformation would be significantly influenced by the contribution of the shearing force. A suitable material for mortar prosthesization has been found in wood, which is sufficiently strong, light, inexpensive, well workable and can be glued (Fig. 11). The tested material is situated in the centre of the test specimen.

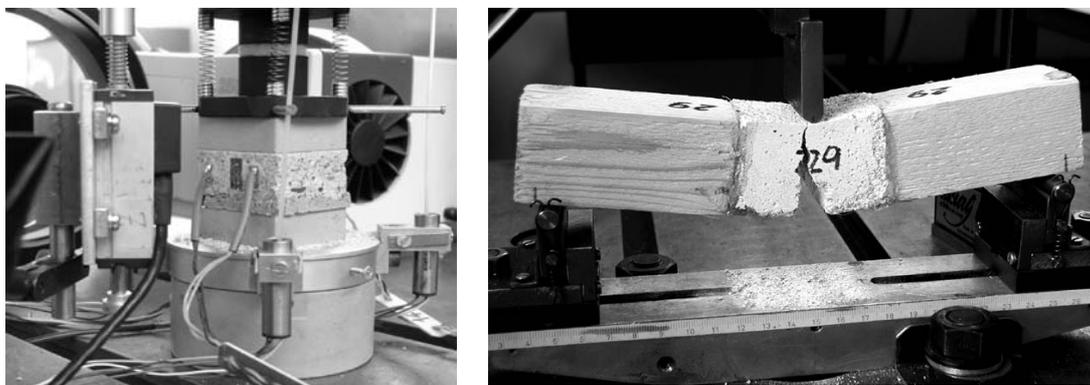


Figure 11 : Compression test with deformability measurements (left) and a three-point bending test of a lengthened mortar sample (right).

According to the results of the tests comparing the flexural strength of pure mortar beams with the strength ascertained on prosthesized identical material, the influence of prosthesization is negligible. The ratio of the strength of the prosthesized sample to that of the “standard” i.e. all-mortar specimens loaded in four-point flexure attained values from 0.98 to 1.02 (Drdácý & Michoinová 2003), if the specimen broke in its central part (undisturbed mortar). Three-point bending tests appear more favourable than four-point flexure, as they place less emphasis on the area of the glued joint. In our experiments we dealt with the problem of disturbance of cut ends by bandaging the glued joint between the mortar and the wooden prosthesis (Fig. 11).

3.4 Comments on NDT for masonry

Only a few innovative methods for historic masonry diagnostics are presented in this paper. However, there are laboratories with very high and competent experience in this field, e.g., POLIMI in Milan (Binda) and BAM (Maierhofer) in Berlin, who coordinated a special European project on diagnostics of historic masonry (ONSITEFORMASONRY), which initiated a new RILEM TC on Strategies for the Assessment of Masonry Structures.

The classic methods that have been studied and applied include ultrasonics, radar, radiography, optical methods including thermography, stress waves, microwaves, acoustic emission, flat jack, monitoring of cracks, and a wide variety of in situ material tests and laboratory methods. It is beyond the scope of this paper to cover all of them, but at least the potential of optical methods should be mentioned here.

Advances in computational tools are dramatically enhancing the power of optical methods and enabling large images to be analysed and processed. Let us present two such techniques: i) Coded Photometry Stereo, which provides microtopographic maps of surfaces and ii) computer tomography or microtomography. Both methods have a very wide scope of applications, and two examples are shown in Fig. 12.

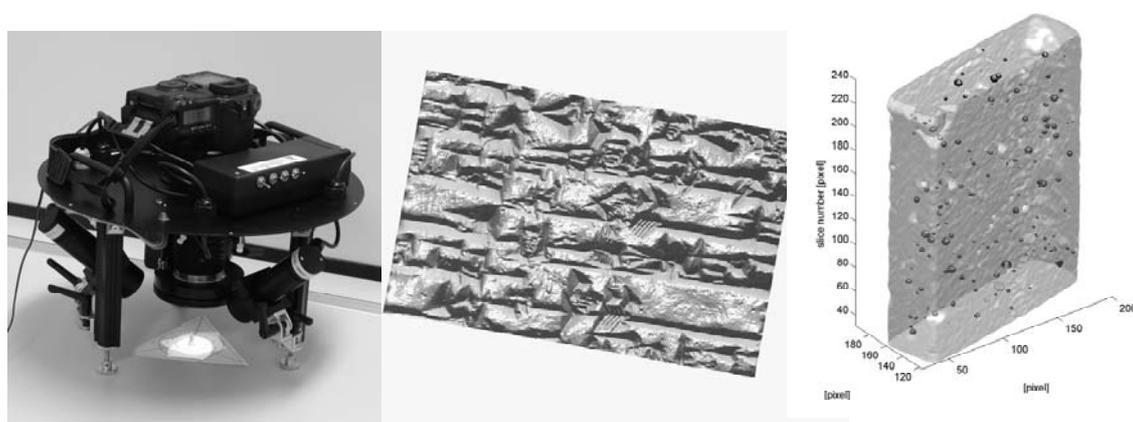


Figure 12 : Laboratory version of the Coded Photometry Stereo device (left), CPS image of a cuneiform tablet (centre) and bulk visualization of a concrete block (2×13×7 mm) – (right).

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