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Reconstruction of a Baroque Open Beam Ceiling Based on Material Analysis

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Abstract. Reconstruction of a ceiling in the north-eastern wing of a former water fortress in Jeseník was carried out during the repair of its roof structure and replacement of the roof. The most damaged parts of the bearing ceiling beams were removed and partially replaced with new timber in the 70s of the 20th C. The way the work was carried out corresponded to the methods and approaches of the cultural heritage protection of that time. The replacement of damaged heads of ceiling beams with new timber that was fitted without connection to the original ceiling beams and only simply hanged on a metal girder can be considered highly provisional from the current perspective. That is why the repair of timber structures of the water fortress included also a reconstruction of the original ceiling system. Surveys focusing on the building archaeology and material assessing the condition of the incorporated timber were important for the final design of the repair and the concept of presentation of the Baroque ceilings.

Introduction

The large stone building surrounded by a water moat is one of the most significant historic monuments of the town Jeseník. The building archaeology survey [1] concisely describes the up-to-date knowledge about the history and construction development of the Jeseník fortress (Fig. 1). The detailed analysis of the roof structure and the ceiling, including dendrochronological dating [2], revealed that wood of fir was used for the construction. The roof structure and ceilings over three main wings of the historic fortress were made from trees felled between summer 1736 and the dormant period of 1737/38. This means that the addition of the topmost floor of the fortress, which gave it its current appearance, was most probably carried out just before 1741, when Jeseník was occupied by Prussian soldiers. As we know from historical archives, the fortress owner bishop Sinzendorf of Vratislav was captured and held prisoner in nearby Otmuchov at that time. Some smaller adaptation and gradual improvements of the fortress continued after that.

Fig. 1 A view of the fortress (the north-eastern wing is on the left)

Materials and Methods

All three wings of the former water fortress have very well preserved timber ceiling structures originating from the Baroque period. Their structure corresponds to the system of beam ceiling common in this area with lateral softwood decking. Our effort focused on the ceiling of the north-eastern wing, where damaged heads of beams were partially removed and replaced with new timber (Fig. 2, 3) in the 1970s. The ceiling beams were covered by boards and plastered false ceiling on reek subbase at that time and nobody considered exposing and presenting the originally visible parts of the open beam ceiling. The damaged parts of the ceiling were cut off and new timber elements were fitted on steel girders without being connected to the original ceiling beams.

The ceiling of the north-eastern wing covers an area of 9.5 m × 9.5 m in the ground plan. After the added boards and false ceiling were removed it was found out that the original ceiling was designed to be exposed. The structure consists of 14 supporting beams perpendicular to the longitudinal axis of the wing. These 205 × 265 mm in cross section beams were smoothly hewn on all four sides and their two bottom edges were decorated by chamfers. The decking planks were about 30 mm thick and 330 – 380 mm wide connected by shiplap and laid on ceiling beams in one layer. The surface of the supporting beams and the decking planks was coated with limewash and decorated by orange and blue spraying (Fig. 4, 5). The top layer of the ceiling structure was covered by filling on which a concrete screed was added later.

The original Baroque structure of the ceiling in the north-eastern wing has been preserved incomplete; yet it is a valuable proof of the high quality of craftsmanship in the first half of the 18th century. It is a representative example of carpentry that is unique and in its broader surroundings can hardly be found a comparable one.

Fig. 2 Parts of ceiling beams inserted during the reconstruction in the 1970s

Fig. 3 Steel girders holding the ceiling after the reconstruction in the 1970s

Fig. 4 Remnants of the original surface of ceiling beams after removal of the falls ceiling

Fig. 5 Detail of the colour decoration on limewash on the decking planks

Results

Building Archaeology Survey. A part of the design of repair were operational building archaeology surveys documenting the findings and determining construction history of the building.

One of the findings was the fact that the ceiling had originally been supported by a central girder, which was possible to document based on the mark left by the girder wood front on the transversal wall.

The survey results have also shown that the timber structures and wood as building material were affecting the appearance of the fortress to an extent than that was thought until recently. This concerns mainly the open beam ceilings and courtyard ambits of the wings. Dendrochronological dating of fir has clearly confirmed the temporal continuity of the preserved roof structure and of the ceilings.

Building Condition Survey. When the false ceiling was removed, it was found out that 7 out of 14 beams were partially replaced. The remaining beams were original in their entire length. Some beam heads were damaged by brown rot fungi (Fig. 6). The repairs carried out in the past thus not only failed to meet the requirements on high quality and durable repairs but also did not managed to remove or treat all decayed timber. Leaking of rainwater to the attic and the head of wall led to a gradual spread of wood-decaying fungus Gloeophyllum sepiarium. The aim of the building condition survey was establishing the extent and degree of damage of the individual ceiling beams.

The extent of damage was initially established visually, based on appearance, colour, surface deformation, typical marks, number of flight holes and other visually recognizable features. The obtained data were complemented by measuring of the moisture content in wood using contact moisture meter, and by measuring the elastic response of wood using an ultrasound device as well as resistance microdrilling and videoscope. These diagnostic tools in the mentioned combination are regarded to be very efficient aids for an accurate establishment of the extent of damage, as described in [3 - 6].

Based on the results of the condition survey the following repair measures for the ceiling were proposed. Removal and replacement of an entire beam was proposed for 2 beams. The first one, build in the wall head along its length, was totally destroyed. The other one had a transversal crack in its lower part (Fig. 7), which was the main reason for its complete removal. Extensions by prostheses were proposed for 12 beams – in two cases these were bilateral prostheses. The remaining 2 beams were left without any structural intervention.

The detailed assessment of the wood condition described above proved that the original material can be preserved to a great extent and thus the beauty and elegance of the original Baroque carpentry crafts can be admired also by the next generations.

Fig. 6 The beam heads damaged by brown rot fungus

Fig. 7 Detail of the transversal crack in the lower part of beam

Lime Coating Analysis. With the aim of exploring possibility to renew the limewash coating, a laboratory analysis of a sample taken from the ceiling decking planks was performed. The basic questions the material analysis was meant to answer were the following:

What is the material composition of the coating?

Can possible additives to the lime binder be identified?

Can we learn something about the technology of coating application?

The detailed material analysis used the following procedures: macroscopic description, optical microscopy on a polished thin sections, thermal analysis of the lime coating, SEM + EDS for element analysis of the binder and the pigments. To identify possible organic additives, the analytical methods were complemented with mass spectrometry on the MALDI-TOF principle. More information on the methods used for the analysis of historical materials can be found in e.g. [7, 8].

The macroscopic description of the samples reveals that there are several layers of lime coating which can be divided macroscopically into these stratigraphic layers:

V1 – background layer
V2 – layer with pigments (red and blue)
V3 – layer covering pigments (white)
V4 – layer covering pigments on the surface (grey)

The layers are of various degrees of damage. Layers V4 and V3 are missing in places. Layer V1 contains rather a larger amount of animal hair. Due to the size of the sample we cannot determine whether they were added intentionally or they are remnants from the brush used for the application of coating. The basic macroscopic division into layers is used also in the further analyses.

Optical microscopy allowed us to determine the thickness of the layers and to analyse them in more detail (Fig. 8, 9). The samples were used to make transversal cuts through the coating layers and prepare polished thin sections of the material on glued on microscopic slides. The background layer (V1) proved highly adhesive to the wood substrate. This layer was about 0.04 mm thick and it could be considered as one coating although in place it consisted of more layers (brush strokes). The layer with blue pigment consisted of isotropic sharp-angled particles with an average size of 0.02–0.04 mm. The layer with red pigment was thinner and the parts with the pigment formed a homogenous unit through which light did not pass. Above the pigment layer there is a visible coarser-grained zone (about 0.03 mm thick), which probably belongs to the layer V3. Layer V3 consists of more coating layers of the same character and composition. The top grey layer is formed from very gentle particles that could be removed by water – probably dirt. Except for the pigment layer, the other layers contained lime coating without additives. There are minor particles of limestone in places of the lime coating. It probably was the raw material used for the production of lime that was not perfectly burnt or processed. Such a relatively larger particle (about 0.1 mm in diameter) is shown in Fig. 8.

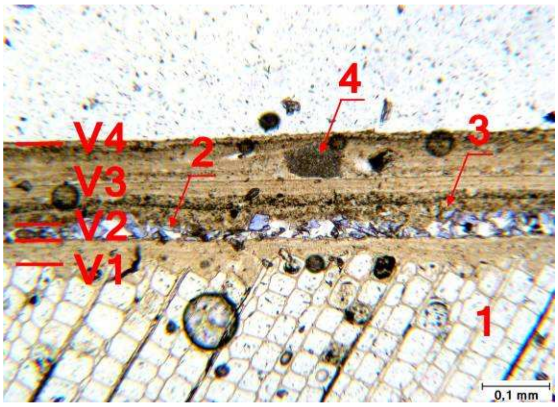

Fig. 8 Cross cut through the coating remnant, 0.24 mm thick. Basic division of the layers for analyses V1-V4. Legend: 1 – wood across the grain, 2 – pigment (crushed glass dyed by cobalt), 3 – a layer of binder over pigments, 4 – limestone particles. Plain polarised light.

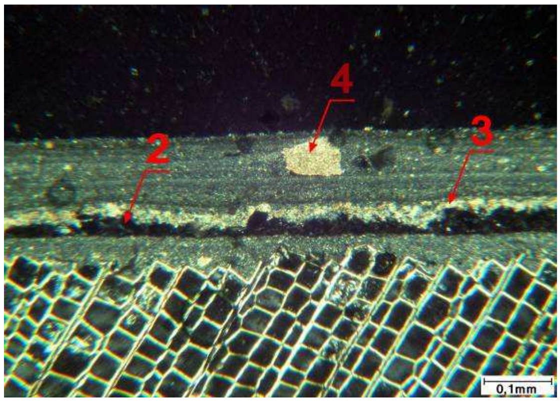

Fig. 9 The cut from fig. 8 in Crossed polarised light(CPL). Legend: 2 – isotropic glass material, appears dark. 3 – the layer over pigments has a different structure in comparison to the rest of the lime coating, 4 – limestone particle.

The thermal analysis of the coating was performed to confirm that the coating is lime and to specify the ratio of its main component, ie. calcium carbonate ($CaCO_3$) to other components. Based on the atomic weight of individual elements, we know that in case of 100g of pure calcium carbonate ($CaCO_3$) the weight loss during its thermal decomposition within 600–1000oC is 44g.

Table 1 Percentage of weight loss in two temperature ranges and the calculated content of calcium carbonate in the coating layers.

	200–600°C	600–1000°C	$CaCO_3$
background layer V1	4.3%	39.2%	89%
top layers V3+V4	3.6%	40.3%	92%

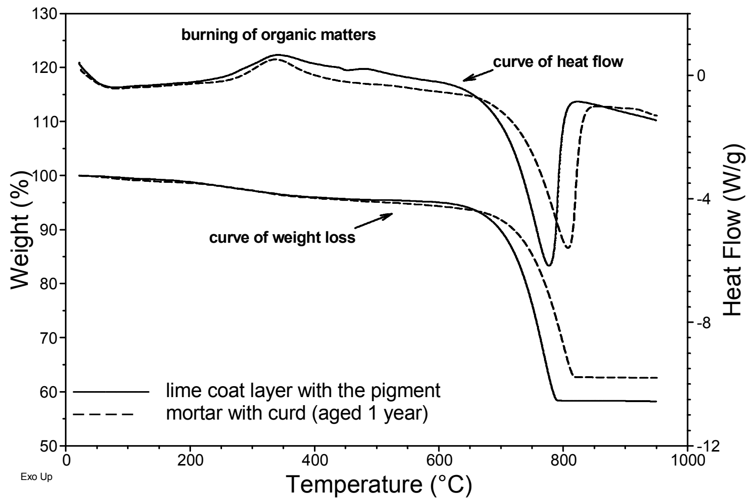

Fig. 10 Output of the thermal analysis of coating layers V3 and V4 with oxygen present. The curve of the heat flow shows an exothermic reaction within heat range of 200–600^{o}C. For comparison there are curves of weight loss and heat flow of a mortar binder sample created from lime with curd (2% of mass for binder).

Thermal analysis and weight loss during the material decomposition show (Tab. 1) that the main component of the coating is calcium carbonate ($CaCO_3$), which makes about 90% of the lime coating. The weight loss *t* within the temperatures of 200–600°C corresponds to: (1) natural composition of the raw material – limestone used for lime production (i.e. the lime coating probably contains a small proportion of hydraulic components originating from the reactions of silicon and aluminium oxides during limestone burning), (2) occurrence of organic additives. The curve of the heat flow of the sample from the layers V2 and V3 (Fig. 10) shows an exothermic reaction indicating occurrence of organic additives (burning). However, we cannot identify the compounds corresponding to the weight loss within this heat range based on the thermal analysis only. The weight loss could be caused by other additives (animal hair, etc.) too.

The element analysis of the binder and parts of pigments was conducted using scanning electron microscope (SEM) equipped with EDS analyser. The polished thin sections were gilded and explored in detail in the high vacuum mode. Figs. 11 and 12 show profiles across the coating layers depicted using back-scattered electrons (BSE). The conspicuous white colour (Fig. 11) corresponds to the red pigment and identifies elements with a higher atomic number compared to the surrounding mass. We can also differentiate individual coating layers in the image. Fig. 12 shows the layer with pigments as well as the unburnt limestone particle (Fig. 9).

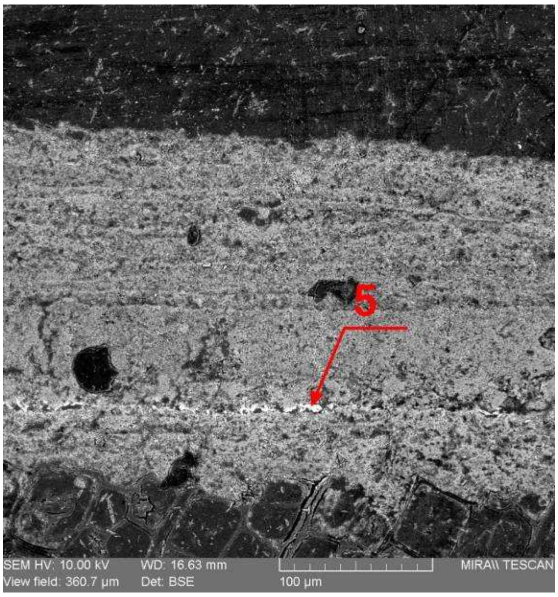

Fig. 11 Cross profile of coating layers SEM, BSE. Legend: 5 – conspicuous white colour is the red pigment with a higher atomic number compared to surrounding materials.

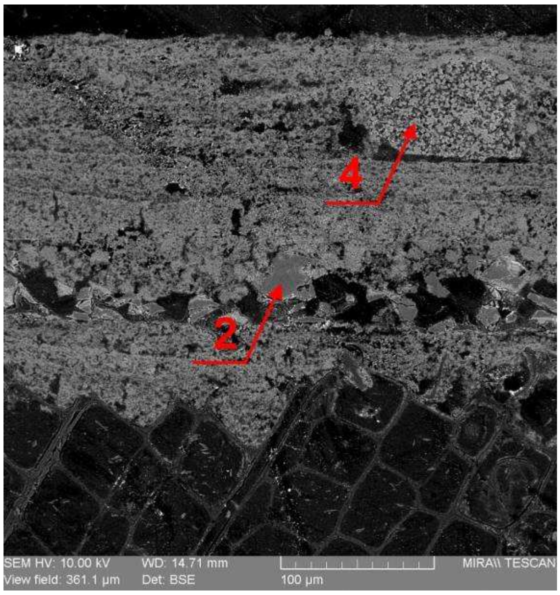

Fig. 12 Cross profile of coating layers SEM, BSE. Legend: 2 – sharp-angle glass particle – blue pigment, 4 – limestone / unburnt limestone particle.

The EDS analyses of individual coating layers and pigments confirmed the element composition of the lime coating found by the thermal analysis, i.e. the coating is about 90% of carbonated air lime. The red pigment is lead oxide. The blue pigment is a glass material containing cobalt (Tab. 2).

Table 2 Proportional division of oxides of the main elements.

	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	CoO	CuO	As_2O_3	PbO
Lime coating (V1)	1.3	1.2	0.6	3.8	0.3	92.7				
Red pigment (5)	1.8	1.6	1.2	1.8	0.8	24.2				68.5
Limestone – raw material (4)				5.2		94.8				
Bluish particles (2)	0.6		1.2	53.6	10.0		13.1	2.7	9.1	

To identify the organic additives, the analytical methods were aided by mass spectrometry on the *MALDI-TOF* principle. The analysis was performed by Ing. Mgr. Štěpánka Kučková, Ph.D. in compliance with methodology [9]. The obtained spectrum was compared with the database of protein binders. Layer V3 containing a part of the pigments was identified to contain milk proteins. The presence of organic additives detected by the thermal analysis can be partially explained by milk proteins. A well-known traditional binder containing milk proteins is for example casein.

To sum up, the analyses determined that the analysed material is lime with a high content of calcium carbonate. The lime used for coating can be classified as air lime. The coating layers can be divided into the background lime layer, a layer with pigments and lime layers covering the pigment layer. Lead oxides (red colour) and crushed glass dyed by cobalt (blue colour) were used for dying. The layer with pigments contains milk proteins – probably casein was used as a binder as a binder of the pigments which are apparently sprayed on the ceiling. The background layer was pure lime and was applied directly to the wood surface. Analytical methods answered mainly the first two questions concerning the material composition. As regards the technology used for the application, we cannot give a clear answer as the samples were relatively small.

Discussion

The design of the reconstruction was undertaken by the employees of the Institute of Theoretical and Applied Mechanics of the ASCR, who specialize in properties of materials incorporated in historical buildings. Research into this field needs to gain and verify data in the field, therefore, the evaluation of the condition and the building archaeological context of the open beam ceiling in the Jeseník fortress was a valuable model case.

The design of the reconstruction included specific recommendations for structural and chemical treatments and finally also professional consulting and continuous inspection of the process of the repair works. A selection of timber suitable for the overall reconstruction as well as details demand experience and a careful and highly professional work. Our priority was to maintain the largest possible amount of the original material. Only two beams were replaced as a whole. The partially damaged elements were fitted with extensions of the same profile and the same surface treatment fixed by all-wood adjustment joints. As the original layout without the false ceiling was to be renewed, it was necessary to choose a joint that would not disrupt the aesthetic impression of this future exhibition space in the north-eastern wing of the fortress. Therefore, we chose a joint with an oblique tenon and mortise (Fig. 13).

Fig. 13 Detail of all-wood joint after joining

Fig. 14 Detail of hand-made mortise

The newly inserted timber was hewn by hand using adzes. The adjustment joints had to be made using hand tools (saw, chisels, ...) (Fig. 14). The reconstructed system of open beams in the ceiling, now without the steel girders, which had been removed, needed a central girder. The support for ceiling beams was provided based on the finding that also in the past the ceiling was supported in this way. The question was whether the girder can be left without a post. The structural stability calculations demanded a post to be inserted. The resulting shape and dimensions (Fig. 15) were selected based on regional analogies, such as the ceiling in the St. Cross Church nave in *Javorník*.

When fitting the new parts of beams in the wall heads, also a constructional protection of the timber in the sense of an aired space around beam heads was provided (Fig. 16). Contact with walling leads to timber degradation by higher moisture and the following attack of biotic pests. Freshly harvested timber poses a considerably higher risk of wood-decaying insect attack than timber originally incorporated – for this reason a preventive chemical treatment without inorganic salt content was proposed. These salts in consequence of crystallization pressures but also chemical reactions cause changes in the structure of wood polymers [10]. However, even the best treatment and reconstruction of a timber construction will not be efficient in the long term without regular checks and maintenance.

Fig. 15 Design of post with a spread bearer to support the girder

Fig. 16 Detail of the aired space around beam heads

For the final surface treatment of the new timber elements, pure lime coating from air lime was recommended. Based on the analyses, we can say that pure lime coating was successfully used here in the past. Its adherence to wood is very good. Unfortunately, the material analysis only provides partial information on the used materials and application technologies. Generally, we can recommend a lime coating made from matured lime putty, which can be activated mechanically or the lime putty can be prepared by slaking with excess of water and used after maturing. Its quality is described by the shape and size of groups of plates of calcium hydroxide $Ca(OH)_2$. When lime putty matures, it disintegrates to smaller particles. The smaller particles and the larger surface area, the higher quality is the lime putty [11]. The research into traditional materials and technologies has not yet yielded a precise manual concerning the optimum time of maturation and evaluation of the lime putty quality [12]. The quality of the lime putty is thus often evaluated based on restorers' practical experience.

The application of the lime coating needs to be tested first using test specimens. The quality of the coating also depends on the way of application and the surface [13] as well as the following care. It is recommendable to pre-wet the surface before application. A pure lime binder gains strength by carbonation, i.e. the reaction of calcium hydroxide with carbon dioxide present in the air. For an optimum reaction a specific coating moisture and temperature within 10–25°C are necessary. Fresh coating should be wetted by water mist, typically 4 – 6 hours after application. Wetting should be repeated in dependence on the surrounding conditions. The speed of carbonation depends on the thickness of coating and surrounding conditions. The protective mode after application should last several days.

Pure lime coating can be also recommended for the treatment of the current coating. The renewal procedures need to comply with the overall preservation concept and cultural heritage protection views. Technically, the grey surface layer could be removed as well as the released parts of older coatings so that the new coating adheres well to the surface. Lime coating binds well to older lime coatings, it is not necessary to rub off the older coating down to timber.

Surface treatment of new timber, or the renewal of the original lime coating, needs to be in agreement with the overall conception of the reconstruction. As far as usage of traditional materials and technologies is concerned, the renewal of lime coating for timber constructions in the interior can be recommended.

Conclusion

The described example of preparation and implementation of a reconstruction of a part of a significant historical monument – in our case Baroque ceilings – shows that it is important to combine results of surveys and analyses of building archaeology and construction with material analyses in order to propose a suitable concept of reconstruction and presentation that would be adequate to the preserved state and the artistic and historical significance of a monument.

Summary

Reconstruction of a ceiling in the north-eastern wing of a former water fortress in Jeseník was carried out during the repair of its roof structure and replacement of the roof. Surveys focusing on the building archaeology and material assessing the condition of the incorporated timber were important for the final design of the repair and the concept of presentation of the Baroque ceilings. The ceiling of the north-eastern wing covers an area of 9.5 m × 9.5 m in the ground plan. After the added boards and false ceiling were removed it was found out that the original ceiling was designed to be exposed. The structure consists of 14 supporting beams perpendicular to the longitudinal axis of the wing. These 205 × 265 mm in cross section beams were smoothly hewn on all four sides and their two bottom edges were decorated by chamfers. The decking planks were about 30 mm thick and 330 – 380 mm wide connected by shiplap and laid on ceiling beams in one layer. The surface of the supporting beams and the decking planks was coated with limewash and decorated by orange and blue spraying. The detailed material analysis used the following procedures: macroscopic description, optical microscopy on a polished thin sections, thermal analysis of the lime coating, SEM + EDS for element analysis of the binder and the pigments. To identify possible organic additives, the analytical methods were complemented with mass spectrometry on the *MALDI-TOF* principle. To sum up, the analyses determined that the analysed material is lime with a high content of calcium carbonate. The lime used for coating can be classified as air lime. The coating layers can be divided into the background lime layer, a layer with pigments and lime layers covering the pigment layer. Lead oxides (red colour) and crushed glass dyed by cobalt (blue colour) were used for dying. The layer with pigments contains milk proteins – probably casein was used as a binder as a binder of the pigments which are apparently sprayed on the ceiling. The background layer was pure lime and was applied directly to the wood surface.

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References

[1] L. Augustinková, D. Kouřilová, Z. Orlita, Building Surveying and Historical Archives Search Report on Water Fortress in Jesenik, Jesenik No. 120, (Standardní stavebně historický průzkum vodní tvrze v Jeseníku, Jeseník čp. 120). Unpublished report (2010)

[2] J. Bláha, M. Kloiber, T. Kolář, E. Pulkrtová, Report from operational surveying documentation, Jesenik No. 120 – Water Fortress – roof structure, (Nálezová zpráva operativní průzkumové dokumentace, Jeseník čp. 120 – vodní tvrz – krovy). Unpublished report (2010)

[3] M. Drdácký, M. Kloiber, M. Kotlínová, Low invasive diagnostics of historic timber. In: In-situ evaluation & non-destructive testing of historic wood and masonry structures, RILEM Workshop, 10-14 July 2006, ITAM AV CR, v.v.i., Prague, (2006) pp. 24-40

[4] M. Drdácký M. Kloiber, Non-destructive survey of historic timber. In: In-situ evaluation & non-destructive testing of historic wood and masonry structures, RILEM Workshop, 10-14 July 2006, ITAM AV CR, v.v.i., Prague, (2006) pp. 8-23.

[5] V. Sebera, M. Kotlínová, J. Tippner, M. Kloiber, Numerical Simulation of Elastic Wave Propagation in Wood with Defined Tree Rings, Wood Research 55(3) (2010) pp.1-10

[6] V. Heřmánková, M. Kloiber, J. Tippner, O. Anton, Diagnostic methods for assessment of timber, (Diagnostické metody pro hodnocení konstrukčního dřeva), Proceedings of conference Zkoušení a jakost ve stavebnictví (Testing and Quality in Construction) *2011*, Faculty of Civil Engineering, Technical university of Brno, (2011) pp. 79-96

[7] I. Kopecká, V. Nejedlý, Assessment of Historic Materials: analytical methods for restoration and cultural heritage protection, (Průzkum historických materiálů: analytické metody pro restaurování a památkovou péči), Grada publishing, (2005) p. 101

[8] J. Válek, Z. Slížková, A. Zeman, J. Frolík, J. Bruthans, P. Chotěbor, P. Měchura, Assessment of historic mortars and renders – determination of characteristic properties with regard to their repair, (Průzkum historických malt a omítek – určování charakteristických vlastností s ohledem na opravu), Proceedings of Conference Conservators and Restorators, Technical Museum in Brno (2008) pp. 98-103.

[9] S. Kučková, M. Crhová, L. Vaňková, A. Hnízda, R. Hynek, M. Kodíček, Towards proteomic analysis of milk proteins in historical building materials, Int. Journal of Mass Spectrometry, 284 (2009) pp. 42-46.

[10] I. Kučerová, M. Novotná, K. Dvořáková, A. Michalcová, Influence of protection substances based on inorganic salts on wood, (Vliv ochranných přípravků na bázi anorganických solí na dřevo), Proceedings of 32. Conference on *Sanace a rekonstrukce staveb (Rehabilitation and Reconstruction of Buildings) 2010*, WTA-CZ, (2010) pp. 20-32

[11] K. Elert, C. Rodriguez-Navarro, E. Pardo, E. Hansen, O. Cazalla, Lime mortars for the conservation of historic buildings, Studies in Conservation 47 (2002) pp. 62-75.

[12] J. Válek, Differences between Historic and Modern Lime Binders Used for Preparation of Mortars and Renders, (Odlišnosti historických a moderních vápenných pojiv použitých pro přípravu malt a omítek, Proceedings of Vápenický seminář 2011 (Lime Seminar), VÚSTAH (2011)

[13] P. Kumpoštová, Water Fortress – regional museum of Jesenik region, (Vodní tvrz – vlastivědné muzeum Jesenicka), MSc Thesis, Mendel Univesrity in Brno (2011).