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Possibilities and pitfalls of revitalizing the timber structure of an industrial building from the 19th century from the viewpoint of diagnosis

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Abstract. A typical feature of contemporary cities is the permanent shortage of land suitable for residential development inside the city. This leads to attempts in recent years to re-use the so-called Brownfields which have the appearance of the former industrial areas, the buildings of which are mostly far beyond the estimated lifetime. Apart from the standard procedure, i.e. demolition and new construction, it is possible to come across efforts, in recent years, to renovate and newly utilize the existing industrial buildings, some of which have a historical value and considerable design potential for an alternative use. The paper presents a case where an original five-story warehouse building from the mid-19th century should be prospectively used for residential purposes, while maintaining and utilizing, for aesthetic purposes, the timber ceiling structures. The paper describes the procedure of diagnosis of a timber structure and its results, suggesting potential risks of similar renovations where the object of interest has not been used and maintained for a long period of time.

1. Introduction

As part of the gradual revitalization of the former premises of textile production in Brno, designers consider utilizing one of the original buildings from the 19th century, probably a warehouse, for luxury housing. The building has five floors and its vertical supporting structures are made from quality massive brickwork, according to which the building was dated to around 1860. Architects and designers were attracted by its timber ceiling structures, supported inside with ornamental cast-iron pillars. The designer plans to use the timber ceilings, highly aesthetic at first sight, as a visual design element in the future interior. Within the scope of the planning, the Department of Building Testing, Faculty of Civil Engineering, BUT in Brno carried out a diagnosis of the building, and this paper focuses on the performed diagnosis of the mentioned timber structures and its results.

2. Scope of diagnosis and selected methods

On every floor, 1 or 2 testing sites were identified on beams or girders and 1 testing site on the beam heads. The diagnosis itself was performed by a proven combination of testing methods. They are:

- visual inspection,
- measurement of moisture content,
- resistance driving of the pin.

Figure 1. Timber ceiling structure supported with cast-iron pillars.

2.1. Visual inspection

The basis of a diagnosis of timber built into structures is a visual inspection. It is used to obtain information about the properties and condition of the material. The inspection of the condition of elements includes determining the type of timber used, timber defects, and detecting surface biotic and abiotic damage to timber [1].

The visual inspection reveals not only information about the condition of timber but also about technological procedures used, additional interventions into the structure and about an approximate age of the timber structure [1].

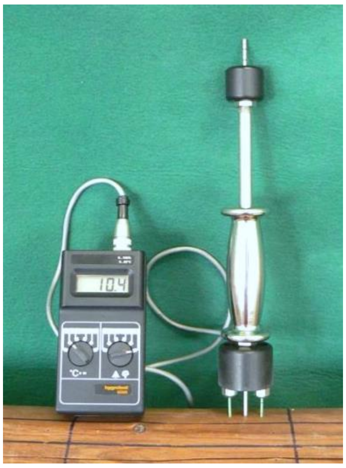

Figure 2. Device for measuring the moisture content of timber - Hygrotest 6500.

2.2. Measurement of moisture content

Timber is a hygroscopic material and has the ability to change its moisture content according to the humidity of its surrounding environment. The increased moisture content of timber influences both the risk of biotic degradation of timber caused by wood-decaying fungi and timber boring insects, and its physico-mechanical properties [1].

The CSN EN 335-1 [2] defines a potential occurrence of biological agents depending on the moisture content of solid wood. Generally, it is possible to say that if the moisture content of solid wood permanently exceeds 20%, timber is susceptible to be affected by wood-decaying fungi and timber boring insects [1].

The increased content of water can influence the survey results and at the same time, it can provide guidance e.g. in the identification of water leakage. The timber moisture content was measured by means of the Hygrotest 6500 device with an impact probe (figure 2). This method of measurement is regulated by CSN EN 13183-2 [3].

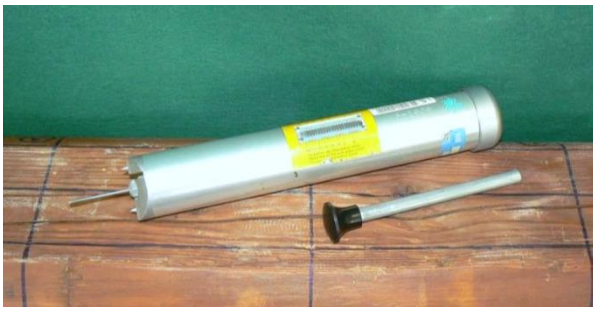

Figure 3. A device for measuring the depth of pin penetration - Pilodyn 6J.

2.3. Resistance driving of the pin

Resistance driving of the pin by means of the Pilodyn (Proceq) device is a method for quick estimate of the density of timber. Measurement with a Pilodyn device can be classified as semi-destructive testing because damage to the tested material is very low, almost negligible [4].

For the purposes of this research, a Pilodyn 6J model was used (figure 3), a simple mechanical device allowing to measure the depth of penetration of the pin with a diameter of 2.5 mm and a length of 40 mm driven into the timber with a constant driving force of 6 J. Using a dynamic impact of a calibrated shot, which is responsible for the penetration of the pin into the surface of the material, it is possible to measure the depth of pin penetration. The maximum depth of pin penetration is 40 mm.

When using Pilodyn, it is necessary to keep the direction of penetration strictly in the radial direction, due to a regular alternation of spring and summer parts of annual rings. When Pilodyn is used in the tangential direction, the pin can be potentially driven into one part of the annual ring only, and the measurement results can be significantly distorted. When measuring in the radial direction and with a deflection of less than 30°, the variability changes less than by 10% [5].

Density is one of the most important physical characteristics of timber, most mechanical properties of timber are positively correlated with density. To determine the density of structural timber on the basis of measuring the moisture content and penetration depth of the impact pin into timber, the following equation (1) can be used [6]:

$$\rho_{12} = 0.727987 - 0.027102 \cdot t_p \cdot [1 - 0{,}007 \cdot (w - 12)] \quad (1)$$

where ρ_{12} - is the timber density with a moisture content of 12% [g/cm^3];
t_p - penetration depth of the impact pin into timber with known moisture content [mm];
w - timber moisture content at the time of measurement [%].

From the density, it possible to determine the flexural strength using regression dependencies [7]. The results of non-destructive testing of timber are always only indicative. In case they should be made more precise, it would be necessary to perform conclusive tests. Conclusive tests are performed according to ČSN EN 384 “Structural timber - Determination of characteristic values of mechanical properties and density” and ČSN EN 408 “Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties” and are designed for a direct determination of some physico-mechanical properties.

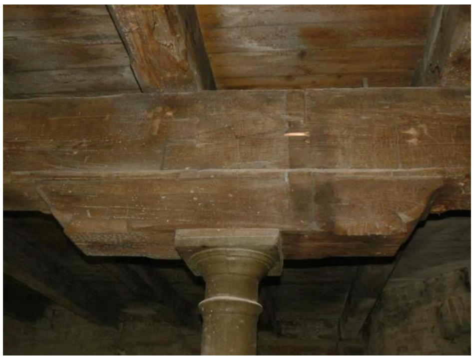

Figure 4. The girder is connected with splayed heading joints above some of the pillars.

3. Results and detected defects

On the basis of the visual inspection, we determined the structural concept of the beamed ceiling:
On the cast iron pillars, there are headpieces and girders. The headpiece is connected to the girder by a pair of steel bolts with washers. The headpiece from hard boradleaf timber (probably oak) is carved, the girder, probably from fir timber, is beveled. Above some pillars, the girder is continuous, above the others, it is connected with butt joints or splayed heading joints. The girder head sits in the air pocket in the facade masonry and lies probably on an oak base. Perpendicularly to the girders, there are joists (ceiling beams), which are partially embedded into the girders (cogging) at some places. The joists, probably from oak timber, are full-edged, some of them are beveled up to approximately 1/3. The joist head sits in the pocket in the central wall. Perpendicularly to the joists, planks are nailed down with butt joints, and they represent the ceiling and the floor at the same time [8].

Other conclusions of the visual inspection:

- In many places of the ceiling, the outer parts of headpieces with steel bolts had been removed in the past, and this impaired the functionality of the pillar – headpiece – girder whole (figures 5 and 6).
- There are large shrinkage cracks in the girders (figure 7).
- In many places of the ceiling, parts of beams were cut out, and in the floors, there are holes for the facilities (figure 8).
- At the location of the elevator shaft, parts of beams were removed without replacement (figure 9).
- Removal of parts of beams, and highly inappropriate prostheisng performed (figure 10).

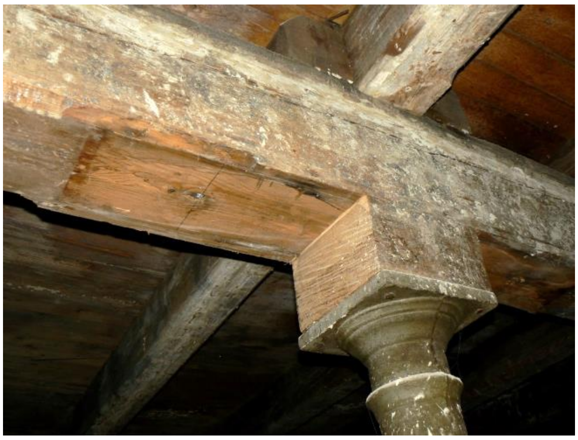

Figure 5. The outer parts of the saddle removed.

Figure 6. Non-functional steel bolt.

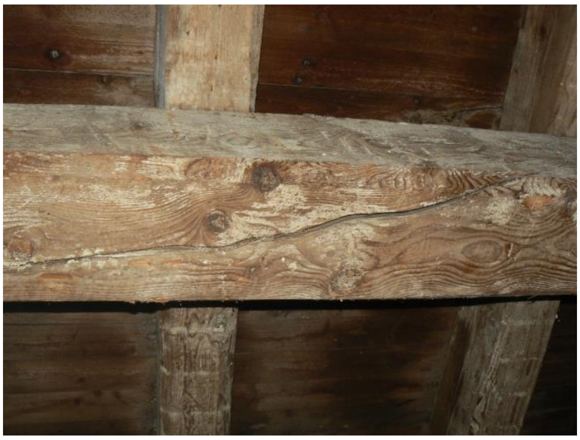

Figure 7. Shrinkage crack in the girder.

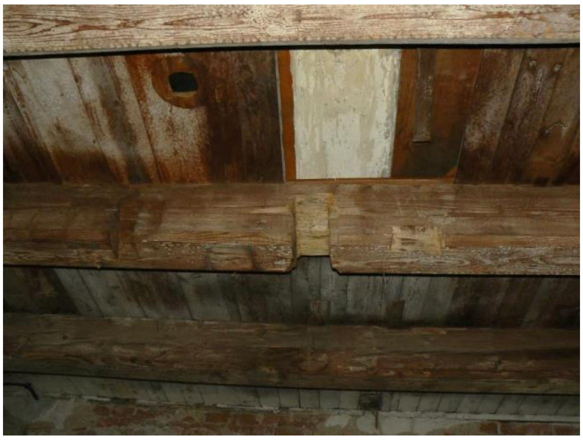

Figure 8. Weakening of the supporting beam.

Figure 9. Removal of beams without replacement.

Figure 10. Incorrectly performed prosthesing.

- Biotic damage to timber in the ceiling structures

Most of the elements in the ceiling structure had no visible biotic damage (they do not have traces of decay or affection by timber boring insects). The exceptions are, however, heads of three girders which are visibly damaged by decay and timber boring insects to a varying extent (figures 11 and 12). The actual damage can have a far greater extent because this damage typically spreads through the centre of the element first and only then gets to the surface of the structure.

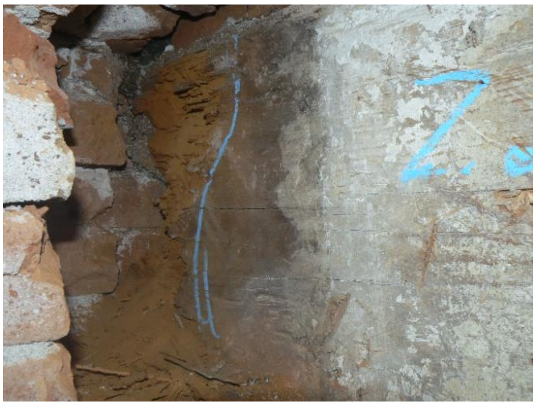

Figure 11. Biotic damage to the girder.

Figure 12. Biotic damage to the girder.

The moisture content determined by Hygrotest 6500 and the density determined by Pilodyn were recorded for each test point in the table 1 and subsequently, an overall assessment was performed.

Table 1. Example of the record.

Measurement - beam			1	2	3	Average
Moisture content	ω	%	12.9	13.0	13.2	13.0
Pilodyn	t_p	mm	14.0	14.0	14.0	14.0
Estimate of timber density with 12% moisture content						
ρ_{12} =	351	kg/m^3				
Estimate of average flexural strength of timber with 12% moisture content						
f_m =	32.5	MPa				

4. Evaluation of the survey and recommendations

4.1. Moisture content of timber in the ceiling structures
The values of measured moisture content ranged from 9.3% to 16.2%. This means that all the elements of the ceiling structure have a value of moisture corresponding to the standard for timber built in the structure. This is also the reason why the detected biotic damage does not spread further.

4.2. Strength of timber in the ceiling structures
The estimate of average flexural strength of timber with 12% moisture content ranged from 18.8 MPa to 47.8 MPa.

4.3. Biotic damage to timber in the girder heads
Biotic damage to timber detected in the girder heads is a fundamental problem. Considering the fact that it was one third of the probes on the girder heads, it cannot be excluded that the same damage occurs in other (non-tested) elements. That is why we recommend to gradually expose all the heads and if biotic damage is found, to exchange them.

4.4. Removed headpieces above pillars
In a number of places, the outer parts of headpieces between pillars and girders, including steel bolts, were removed in the past. If ceiling structures are maintained, we recommend their adequate functional replacement.

4.5. Missing parts of girders and beams
In many places of the ceilings, end sections of girders (elevator shaft) and end sections or other sections of beams were removed in the past, and they were either not replaced or replaced in an inappropriate manner. We recommend adequate replacement of the missing parts of the elements.

5. Conclusion
The results of the pre-construction condition survey of the timber structures of ceilings in the building suggested considerable risks and potential complications of an attempt to newly utilize old industrial buildings which had not been maintained for a long period of time. What the architects considered at first sight to be a beautiful, monumental timber structure combined with cast-iron pillars with magnificent design, became rather a nightmare after a detailed diagnosis. The survey revealed places with significant decay (beam heads) and damaged supporting elements above pillars, which, due to the removal of parts of headpieces, also lost part of their stability. At the same time, ceilings are affected by a typical problem of the industrial objects used for a long time, where, due to multiple changes to

the function of the building and the facilities installed therein, various secondary openings in the structure were created, non-professional replacement of parts of elements was performed, etc. All this brings a new insight into a potential restoration, where simple maintenance of the existing timber structure without changes is not quite realistic.

Acknowledgement
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