THE "MAAGDENTOREN" OF ZICHEM (BELGIUM): DAMAGE ASSESSMENT OF FERRUGINOUS SANDSTONE BY X-RAY TOMOGRAPHY

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ABSTRACT

The ferruginous sandstone of the gothic "Maagdentoren" is suffering from a specific biological deterioration process triggered by perforating activities of mason bees. The damage due to these perforations causes extensive loss of material, so that a durable conservation of such degraded stone blocs becomes questionable.
In order to evaluate the conservation possibilities of stone blocs damaged by perforating mason bees, an investigation of the internal structure by means of X-ray tomography was carried out. This investigation revealed that the cumulative effect of the digging work by multiple generations of mason bees may result in networks of perforations. Bioturbated sandstones were found to be most suitable for attack by mason bees because of morphological and geometrical compatibility between the original layered burrowings by marine organisms and those by the mason bees. As a conclusion the conservation is not recommended of sandstone blocs for which the load bearing capacity is endangered by the branched and layered perforations.

INTRODUCTION

The Hageland is an area to the north-east of Brussels in Belgium, characterised by a particular landscape of rolling hills in steeply-sloped longitudinal rows. They are underlain by marine, medium-coarse, poorly sorted glauconitic sands of the Diest formation, of Miocene age and protected from erosion by alteration of part of the glauconite and limonitic cementation in the oxidation zone following the hill morphology [1-3]. The lithification thus is a late diagenetic process related to pedogenesis, probably still ongoing but slowly under the present climate. The resulting 'Diestian' ferruginous sandstone is of heterogeneous composition and variable quality. Quartz dominates apart from around 30% of glauconite. Clays are present as films around the sand grains and some infillings, preventing effective goethite cementation. The total porosity attains 25% while the density 2050 kg/m^3. The average compressive strength of quality stones is 12 N/mm^2 with a sound velocity of 2420 m/s. However, alteration processes occurring between or even within apparently similar stones may lead to lowering of the quality to 8 N/mm^2 and a sound velocity of 1370 m/s [4].
The rusty brown Diestian ferruginous sandstone is a local building material, but very typical for the Hageland and linking its architectural heritage to the landscape [5-7] (Figure 1).

Diestian sandstones were most renowned for constructing gothic buildings, although quarrying for vernacular use and for restoration works continued till the early 20th century. Upon extracting the still soft quarry-stone material, more attention was paid to their format and regularity than to the ultimate durability of the material. As a consequence, exposure to natural weathering processes often causes important damage. Although it is generally assumed that reserves must be vast, today no potential quarry locations with high quality Diestian sandstone are known. Hence, restoration of several iconic monuments built with this ferruginous sandstone for which the degradation pattern implies replacement is a difficult topic.

The Maagdentoren (freely translated as "Virgin Tower") is a dungeon erected in 1387 in the alluvial plain of the river Demer at the outskirts of the former city of Zichem. The round tower with a height of 26 m and wall thickness of 4 m at ground level was built in ferruginous sandstone apparently coming from a single source. Renovation works did not affect the dressed sandstone masonry which till recently has nearly kept its original dimension. Although considered as heritage of exceptional value for the Flemish region [8, 9], the tower suffered from neglect and partially collapsed in 2006 (Fig. 2). Following urgent consolidation works [10], a conservation and restoration strategy had to be determined [11]. The ferruginous sandstone masonry of the Maagdentoren suffers from severe deterioration phenomena for which adequate restoration methods have to be established. Generally, the ferruginous sandstone is characterised by the presence of a superficial black crust serving as natural protection of the stone. This limonite rich skin tends to fall off, leaving behind a weak surface to natural exposure [12].

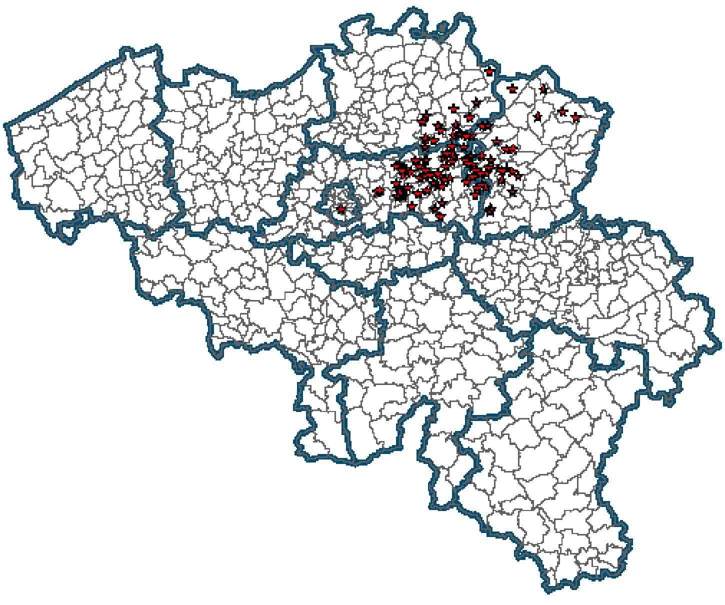

Figure 1: Representation of ferruginous sandstone of the formation of Diest as building stone in Belgian monuments, concentrated in the Hageland, a landscape corresponding to the geological outcrop of the Diest sand and characterised by hills underlain by Diestian sandstone.

Figure 2: Maagdentoren at Zichem, an abandoned medieval four stage dungeon erected in the 14th century, after its partial collapse in 2006 due to loading by roof breakdown, important soil deposit and long-lasting water infiltration. The structure has since been consolidated in its present form and protected against further infiltration. The present study deals with the standing walls not affected by the collapse.

Moreover, both ferruginous sandstone and mortar are suffering from a specific biologic deterioration process caused by the burrowing of mason bees identified as *Osmia cornuta* [13] (Figure 3). Since a few decennia perforations by mason bees have become pervasive and are probably linked to the changing environment since the surrounding area gained the status of protected natural landscape. Female mason bees, active in early spring, use especially the weaker parts of the ferruginous sandstone and the mortar to lay their eggs. Every year, a new nest is made by these solitary bees. Although perforations are observed all around the tower, especially the south-east side is heavily affected. Locally damage by multiple perforations results in crumbling and erosion of the stony material for which a durable conservation becomes uncertain.

Figure 3: Detail of ferruginous sandstone masonry severely damaged by the perforations of mason bees.

Proper conservation strategies can not be defined from a visual inspection of the degree of damage caused by the mason bees. Stone blocs presenting few perforations at the surface may be completely crumbled inside due to a branched structure of the perforations. In order to evaluate the conservation/restoration possibilities of stones damaged by mason bees and to interpret the load bearing capacity, knowledge of the internal structure is necessary. Important questions to be answered are the depth range of visible perforations and their three dimensional structure inside the stone.

A visualisation of the internal structure can be obtained by means of X-ray tomography (CT-scan). X-ray tomography is a "non destructive" three dimensional imaging technique [14, 15]. A well known application is the medical computer tomography (CT) for visualisation of the internal structure of the body. Nowadays, there is a growing interest for X-ray tomography in scientific and industrial fields. The strong technical evolution of X-ray sources and detectors enables a resolution of 1 µm, depending on the size of the object (approximately 1:1000th of the maximum diameter of the object). An object of 10 mm diameter can hence be scanned with a resolution of 10 µm.

A radiographic image of an object is a « shadow image », based on the intensity of absorption of X-rays radiated through the material. Through rotation of the object, radiographic images at different orientations are taken. These images are combined into a 3D volumetric reconstruction of the sample, which can then be divided into 2D grey scale slices. The grey scale is a measure of the absorbed X-rays in the voxel (volumetric pixel element) which depends as such on the density of the material. The output is a virtual 3D image of the scanned object obtained after manipulation of the scans. The principle of micro-CT is presented in Figure 4.

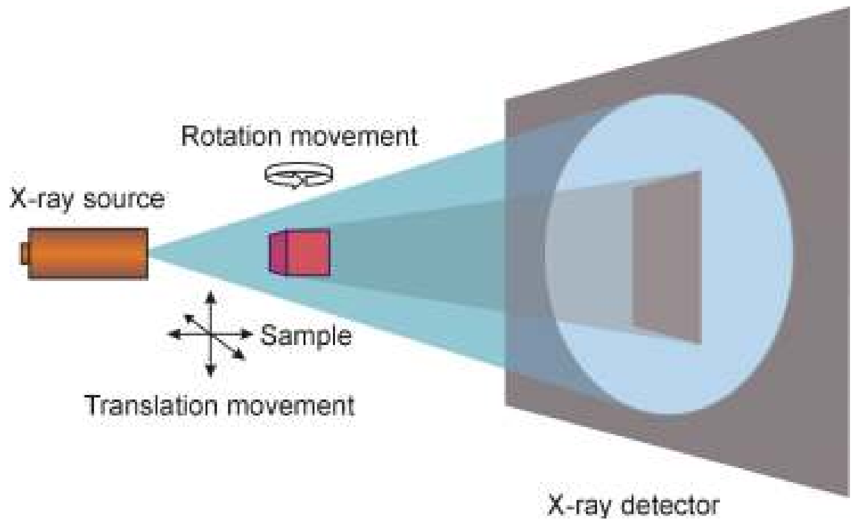

Figure 4: principle of micro CT

EXPERIMENTAL

The tested samples are:

- Drilled cores of ferruginous sandstone (6 cm diameter);
- Two subsamples with a diameter of 4 mm taking out of the drilled cores. One sample was taken from the inside of the core ("bulk" sample), while the other sample perpendicular to the surface of the stone which contains the surface crust ("crust" sample);
- Two ferruginous sandstone blocks, "small" (12 x 8 x 6 cm) and "large" (14 x 10 x 10 cm) lifted from the masonry; and,
- One mortar sample (15 x 8 x 5 cm).

The experimental conditions of the X-ray tomography are:

X-ray source: Feinfocus FXE-160.51, directional head, 150 kV, focal spot: 10 µm
Hardware filter: 1.05 mm Cu and 3.00 mm Al
X-ray detector: Varian 2520V PaxScan a-Si flat panel, CsI, 1880x1496 pixels, 127 µm pixel pitch
Distance source-detector: 830 mm
Distance source-object: 248.5 mm
Enlargement : 3.34x resulting in a voxel pitch of 38 µm (drilled cores) and 1.15x resulting in a voxel pitch of 109 µm (stone and mortar blocs)

The scans of the subsamples were analysed by means of Morpho+, the 3D analysis software package developed at the Centre for X-ray tomography of the Ghent University [16].

RESULTS AND DISCUSSION

Drillcores

Figure 5 illustrates the 2D-scan through a drillcore lifted from a moderately damaged stone block. The burrow and nest of the mason bee can be clearly recognised down to a depth of 5 cm below the wall surface. For the yearly digging of a new nest, pathways created by old burrows are preferentially used. Existing burrows inside the stony material may get filled with loosened ferruginous sandstone fragments. Figure 6 shows such an old burrow filled with stone fragments and then covered with a layer of fresh clay, probably picked up by the mason bee from the alluvial plain nearby. Figure 7 illustrates the backfilling of unused parts of older burrows. Within the same sample, bioturbations, created by burrowing organisms and giving rise to a textural feature of many ferruginous sandstones inherited from times of sedimentation, can be clearly visualised in the CT-scan. These bioturbations also appear darker coloured in the CT-scan indicative for their lower density and hence mechanical properties, but less so than the refilled perforations produced recently by the mason bees. It is remarkable that the original burrows of the marine organisms and the ones dug by the mason bees have quite comparable dimensions.

Figure 5: Photograph of a drillcore surface showing a recent mason bee burrow covered by a fleece (left) and corresponding CT-scan (right) (core diameter 6 cm).

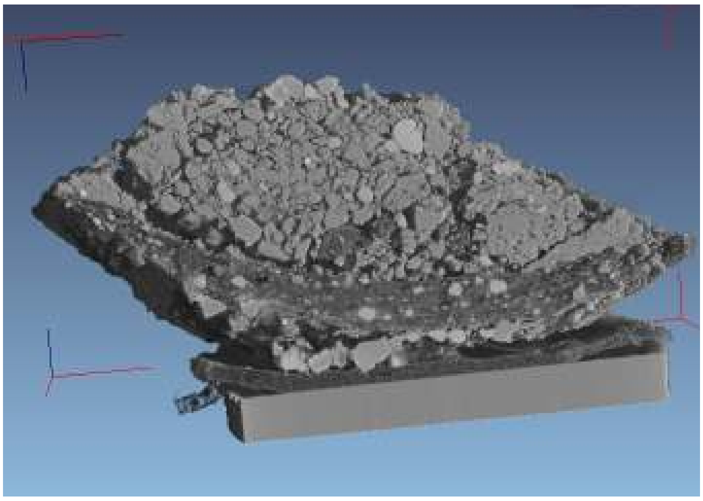

Figure 6: Visualisation of a mason bees' burrow filling: ferruginous sandstone fragments loosened during digging of a younger burrow and covered with a protective layer of clay (dark grey) (length of the image: approximately 6 mm).

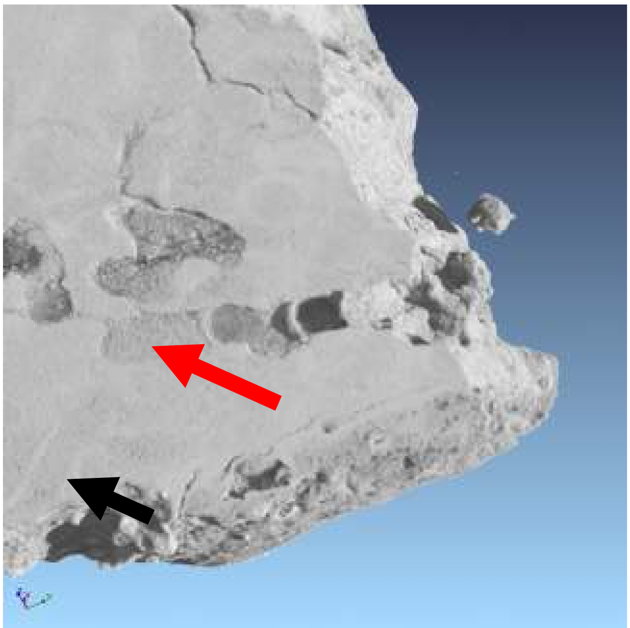

Figure 7: Reconstruction of CT-scans of a the outer part of a ferruginous sandstone drillcore. The black arrow marks a bioturbation dug by burrowing animals during the sedimentation process of the ferruginous sandstone. These bioturbations are characterised by an almost uncemented sand filling, hence of lower density and darker coloured, surrounded by a more strongly cemented rim, hence denser and light coloured. The red arrow marks a perforation filled with ferruginous sandstone fragments produced during digging of a burrow by a new generation of mason bees. The burrow filled with sandstone fragments is darker coloured indicative for its lower density (size of the image: 4 cm).

Subsamples

The CT-scans of the two subsamples with a diameter of 4 mm were analysed by means of Morpho+ software to evaluate their internal porosity changes. In this study a significant different porosity was detected between the "crust" sample and the "bulk" sample. When analyzing the partial porosity according to the Z-axis (going from the surface into the interior of the stone) a lower value was obtained at the surface compared to the interior part, due to the formation of a dense surface crust. The results are discussed in detail elsewhere [17].

Ferruginous sandstone block samples

Perforations are preferentially dug in the weaker parts of the ferruginous sandstone. Ferruginous sandstones may present a succession of weakly and more strongly cemented zones following concentrations of goethite cement in mostly flattened nodular forms (corresponding to Liesegang rings) [1, 2]. Bioturbated sandstones are built up of weakly cemented burrows surrounded by a more strongly cemented rim. These burrows provide easy access to mason bees. Figure 8 illustrates how such a bioturbated sandstone has become moderately damaged by the perforations of mason bees. The corresponding CT-scan illustrates the correspondence between the original bioturbations and the digging by the mason bees. As the bioturbations have layered sequences, which is the case for the stone block presented in figure 8, or represent entire sandstone blocs, its load bearing capacity is in danger. Therefore, the conservation of such a stone, although visually moderately damaged, can not be recommended.

The CT-scan of the small tested stone block, presented in figure 9 (left), illustrates some holes dug by mason bees. Through image treatment of the scans of successive 2D-slices the structure of the dug holes present in the stone block could be reconstructed, as shown in figure 9 (right). This reconstruction shows the branched structure of the dug holes which is as such lowering the mechanical properties of the stone. Also in this case, replacement is recommended.

Similar results were obtained for the mortar sample presented in figure 3 for which conservation is neither recommended.

 

Figure 8: Bioturbated ferruginous sandstone (length: 14 cm ; width: 10 cm) heavily attacked by mason bees (recent perforations marked by light grey clay lining), extracted from the Maagdentoren (left). The corresponding CT-scan (right) shows the original burrows by sea organisms (worm-like faint grey bioturbations), most clearly visible in the upper part of the scan, and similar zones which attracted the mason bees whose perforations are visible in the middle and the lower part of the scan.

 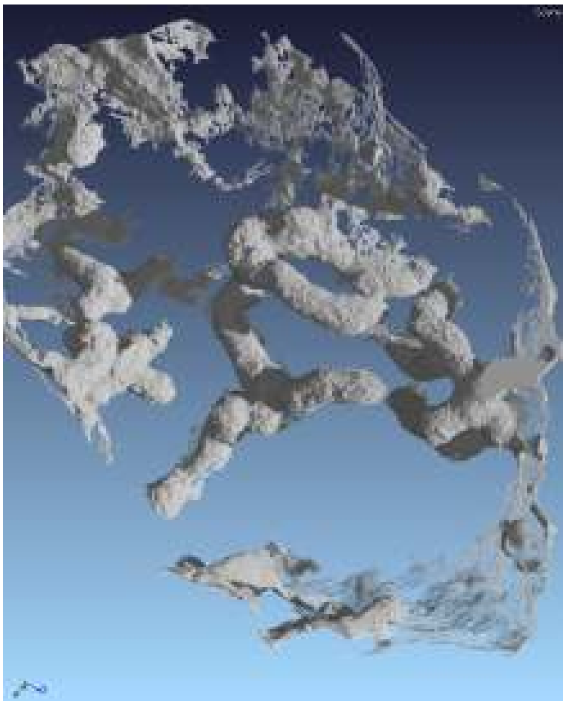

Figure 9: Ferruginous sandstone block (size: 12x6x8 cm), CT-scan of the block (left) and negative-density 3D-reconstruction showing the internal distribution and connectivity of the burrows dug by mason bees (right).

CONCLUSIONS

The ferruginous sandstone of the Maagdentoren in Zichem is prone to a specific biological deterioration process triggered by mason bees of the species *Osmia cornuta*. Since a few decennia, the activity of mason bees has become worrisome and is probably linked to environmental protection measures for the surrounding landscape. These solitary bees preferentially attack the weaker parts of the sandstone and the mortar to lay their eggs, most so at the south-east side of the tower. Locally the damage has caused crumbling of the stone materials, so that a durable conservation of such biologically damaged stones becomes questionable.

In order to evaluate the conservation possibilities of stone and mortar perforated by mason bees, an investigation of the internal structure of damaged building materials was carried out by means of X-ray tomography (CT-scan).

From the obtained scans, it could be concluded that the burrowing depth by each mason bee is approximately 4 to 5 cm. Preferentially, for the digging of a new nest, existing old burrows are followed which get either prolongated or backfilled with loosened ferruginous fragments.

Original burrowings by marine organisms have led to bioturbated sandstones with heterogeneous texture and durability. Weakly cemented zones occurring throughout these sandstone blocks are preferentially followed by the mason bee burrows. Insofar the bioturbations affected by the mason bees have a layered structure, the load bearing capacity of the stone is in danger. The conservation of such a stone, even when visually only moderately damaged, is not recommended.

Moreover, through image processing of the CT data the structure of the perforations could be reconstructed revealing a branched nature, due to progressive attack by generations of mason bees, apparently returning to their site of birth. When these branched perforations progress inside the stone material, its mechanical properties are endangered and hence also in this case, replacement is recommended.

From this investigation it could be concluded that this very fast biological destruction process of the 14^{th} century tower needs urgently to be stopped. In situ destruction of the mason bees, which are irreplaceable pollinators, by means of spraying is from an ecological point of view not acceptable. Rather it is recommended to dissuade the mason bees from returning each spring to the stone structure by providing alternative housing in the near neighbourhood, as is already commercially organised in some fruit producing regions. This way, a symbiosis could be realised between natural landscape protection and heritage conservation. If such an approach would prove inadequate, one should opt for allowing the former agricultural activities in the near neighbourhood of the tower, or let the tower gradually decay over time as nature takes control.

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