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Historical Analysis and Structural Monitoring Cases – studies for An Integrated Approach.

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Abstract The paper focuses on the structural analysis of monumental buildings, particularly upon the relationship between both instrumental measurements and the preliminary studies and the general comprehension of the construction history of each single building, including e.g. the historical evolution, materials, decay.

A couple of case – study in the north of Italy are presented: the Trostburg Castle in South Tyrol and the S. Agata Church in Brescia. In these cases, cracks have been controlled by a long - time monitoring to investigate if structural damages could be influenced by the construction of underground galleries just near their foundations.

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Collected data are discussed in comparison with the different approaches related to the knowledge of buildings, in order to evaluate limits and possibilities of proposed methods. Results underline how a deep investigation of an ancient and complex building, usually made up by a long time process of transformations and stratifications, allows to better understand the general structural behaviour.

The strong comprehension of the constructive history of each single structure and a carefully discussed cracks board can provide a wider support to plan and make the diagnostic and structural investigation, e.g. this method helps in the choice of the type of tests and instrumentation to be employed and helps to localise where measurements should be taken, empowering the effectiveness of the results. Moreover, it allows to control and to understand results.

Keywords: Stratification, crack board, monitoring, structural damage, room-book

Introduction

The structural behavior of an historical/monumental building is usually described throughout the general analysis of geometry, materials, loads and by the instrumental measurements of physical parameters. These measurements may regard both the characterizations of structures and materials, usually their resistance, both the measurements of relative displacements between different parts of a structures, when a structural decay is active.

The employment of linear traducers or extensometers is quite common to monitor structural cracks of historical masonries. Linear transducers, more frequently Linear Variable Differential Transformer (L.V.D.T.), are technical devices which transform an input signal in an output analogical/digital signal (Matarazzo and Arena 2005). They are usually fastened to the masonries, across single or multiple cracks following the main displacement direction and connected to a remote memory by cable or wi-fi (Ceriotti et al. 2009). Beside the cracks measurements temperature has always to be controlled, because of the direct influences which temperature determines upon the volume of masonries and, therefore, upon the natural widening/narrowing of each crack.

Extensometers as L.V.D.T. are more effective than traditional comparators, particularly to measure planar cracks because accuracy is usually accepted between ± 0.002 and ± 0.02 mm (UNI 4546 1984, C.N.R. 131 2001). They are useful when little displacements (absolute or relative) have to be kept under control for a certain period, because measurements can be repeated frequently and data recorded, without direct intervention.

A couple of cases – studies in the north of Italy are presented: the Trostburg Castle in Tyrol and the S. Agata Church in Brescia. In these cases, cracks have been controlled by a long - time monitoring to describe the connection between the construction of underground galleries just near the foundation of the buildings and the influence on an already damaged structural situation.

The S. Agata church

The S. Agata Church was built since 13th century in the very center of Brescia, then widened and modified during the following centuries. The building consists in a wide aula with a single nave composed by a gothic masonry structure, covered by three vaults, and by a squared - shape presbyter built on a bridge foundation across the river Garza, which flows underground this part of the city (Volta 1989). Vaults were originally built according to a cross scheme and later changed into a ribbed vault structure, to obtain a wider paintable surface. Therefore, the vaults structure presents specific elements of weakness, already highlighted by the presence of several cracks groups corresponding to the most stressed structural boundaries.

A campaign of studies upon the church has been carried out since 2007, to describe the structural situation. An instrumental control of the cracks has installed, before (and after) the digging of the tunnel for the new underground line which, in the very centre of the city, passes just beside the foundation of the church, parallel to the southern façade.

The whole church has been considered and surveyed as a unique building because, at the state of the research, the constructive history and the geometrical exam of each part, did not show clear traces of constructive phases, suitable for a comparative evaluation of the structural behaviour. The careful survey of the whole building and the local exams of each crack has indicated a higher concentrations of damage (cracks, reparations, patches of plaster) in the higher part of the building, particularly near the pendentives structure and above the vaults surface.

On the basis of this evaluation, two couples of cracks have been considered particularly suitable to be monitored by extensometer. A couple of extensometers controlled the displacements along then main cross section of the building, due to the vertical translation of the southern foundations; a second couple was placed over the most damaged vault structure, which presented deep cracks and, therefore, was suitable to be affected by vibrations and macro-displacements of the whole structures. Results did not highlight relevant displacements clearly due to the digging of the tunnel, even if two of the four monitored cracks have duplicated their width after two years.

The Trostburg castle

The same approach was adopted in a better way during a research campaign (2002-2006) to survey the Trostburg Castle in Ponte Gardena (Bolzano) and to evaluate the worsening of the structural damage due to the creation of a tunnel "under" the castle.

Trostburg is located on a rocky outcrop which emerges from the slope of the Castelrotto plateau at an altitude of 627m, and dominates the eastern shore of the Isarco River. The extension of damages and the high size and complexity of the building caused the necessity to gather information, regarding all of the castle, borrowing the arrangements of the "Raumbuch" or "Room - book" (Petzet and Mader 1995). Such a tool allowed to find information, room by room, in a systematic and detailed way without carrying out a selective action in advance; each room, photographed and redesigned exploted in its six or more sides, it foreseen the gathering on single surfaces of the appearance of structural decay, such as cracks, separations, off plumb etc. In particular, relating to the crack board, the cracks were classified and described noting wideness and depth in millimeters, the formation – old or recent

– the current evolution state – active or not -, the possible correlation with construction joints, the presence of repairs, the vector displacement between the edges of the lesion and the possible plan mismatch (Doglioni 2000). Of great efficiency proved to be the possibility to gather more information in different moments; as well as laying the bases to monitor the instability phenomena in the long term, it facilitated the confrontation with a photographic survey punctually carried out for some cracks before the creation of the tunnel, contributing to show where and "how much" they had worsened.

Only in a second moment such observations were made-up and given back through the production of elaborations (planimetries at different levels, summaries, sections and axonometries) to be compared.

The patient and systematic data gathering and cataloguing was also widened to the gathering of useful information for the understanding of the construction evolution of the building, the complex volumetry of which immediately evidences the complex evolution and which knowing about became an essential help for the interpretation of the structural damages; jointly with the bibliography (Von Zallingher-Thurn 1978) and construction geometric data – size and material – gathered during the course of the research, it was therefore possible to further articulate and precise the suppositions relating to the evolution of the castle, from the first defensive structure to those relative to the noble residence of the Von Wolkenstein earls (Balboni and Corradini 2005).

A first phase is relative to the first fortification, the dungeon (1240-1250), built on the rocky spur at higher level; maybe in a period shortly after were built the “palace” (first two floors built in the second half of the 13th century) and a first boundary wall, closely coinciding to the current perimeter of the court, which contributed to closing and defending the rest of the rocky surface heading slightly downward towards the valley.

Between the 13th and 14th century the building was further extended towards the west, with the building beyond the defensive perimeter of buildings at a much lower quota, built occupying the slope towards the valley. The following remaking of the perimeter walls to the south-west were interpreted as the effects of the earthquake attested in 1332, and it shows the high vulnerability of the area.

The requirement to conform the defense system brought about the construction in the second half of the 16th century of ramparts to the east defending access, partly obtained using embankments to connect the spur with the mountain slope.

The most important interventions of the modern era can be traced back to Engelhard Dietrich von Wolkenstein, in large part finalized to adapt the building to the new needs represented by the 17th century and for residential use. New plasters and external decorations refined the antique fortification appearances as like new environments are re-organized inside the antique rooms; but above all new habitable rooms were obtained raising the buildings arranged around the ancient court. The castle therefore substantially obtained the aspect still apparent in photographs of the end of the second part of the 19th century, before the demolition in 1884 of the last two floors always in the south-western portion, made necessary because of the the worsening of structural damages.

Even though in the necessary quick exposition, the continuous building process for further additions is evident, each time obtaining the necessary spaces, both in terms of surface and height.

Construction of structural hypothesis The analysis of data relative to the appearance of damage, interpreted in tight relation with the other information relating to the building, such as material and construction evolution aspects, has allowed to recognize and trace some cases of instability to “macrofamilies” inherent kinematics extended to the 9 constituent parts of Trostburg identified in the study, or, in some cases, to the complete castellan complex.

Here for shortness, to better go through the elaboration and data discussion modalities, concentration will be put on the structural decay which concerns the “palace”, without however abandoning the necessary overview for which it was possible to advance assumptions.

The building is approximately 13x7m, and with its four floors above ground (27m) dominates the northern façade of the building. Notwithstanding the apparent regularity, it also unveiled an articulated evolution, among which to be mentioned is the construction in at least two different periods of the last two floors, raising an original two storey construction. On the lower levels, a

vertical wooden structure creating a frame that supports the overlying horizon testifies the knowledge of the delicate structural situation that came about over time.

The damage concerns in particular the northern and southern side wall masonry. The damage is mainly vertical and is inevitably influenced by the specific vulnerabilities, being concentrated near doors and windows, some of which created breaking into the wall, and in the joints of antique openings; the organization of the survey allowed to individuate and give the right evaluation even to some important damages, but which for different reasons - in some cases hidden by coverings or recouped in recent era - in a first analysis did not seem important.

The position of the cracks, found along both sides of the building, size and the displacement vector among the edges is traceable in large part to a general vertical translation towards the valley at the western part, notwithstanding the apparently incoherent presence of buildings, which at a quick glance would be appear to carry out a “buttress” role.

However, on a second look, it can be noticed that the “crack line” which runs across the "palace" continues southbound, concerning the whole building. Simplifying, it seems to divide the most antique portions of the building, created on the highest rock spur, from the successive extensions occupying the rocky slope towards the valley, and it is coherent with decays and collapses of the building recorded in the past. Generally the single bodies in the west are damaged in correspondence with the joint with the pre-existing parts; on the contrary for the palace the cracks concern the walls that having foundations on an always lower level towards west cover the length of the area in question

Monitoring project and results In light of the data gathered, to verify and clarify the assumptions made, a structural monitoring campaign was launched by installing 13 extensometers connected to three units for automatic acquisition to measure the evolution over time of damage, subsidence and movement, verifying the relative dimensional changes occurring over a long cycle (for a total period of 4 years). The careful work has allowed an important sorting of the damage, distinguishing those, perhaps of some significance, but traceable to a specific phenomena of local damage, and those considered more effective to provide evidence for the hypothesis related to main structural decays.

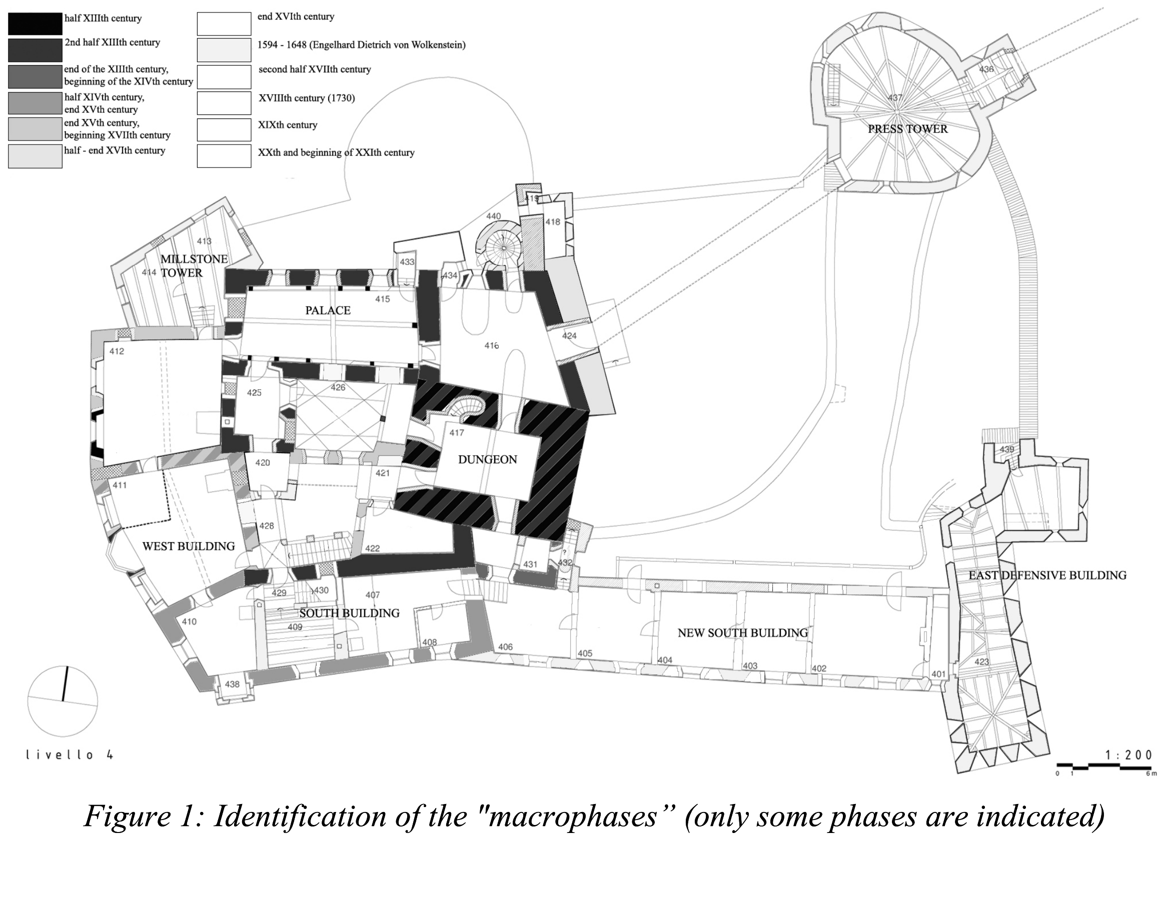

Figure 1: Identification of the "macrophases” (only some phases are indicated)

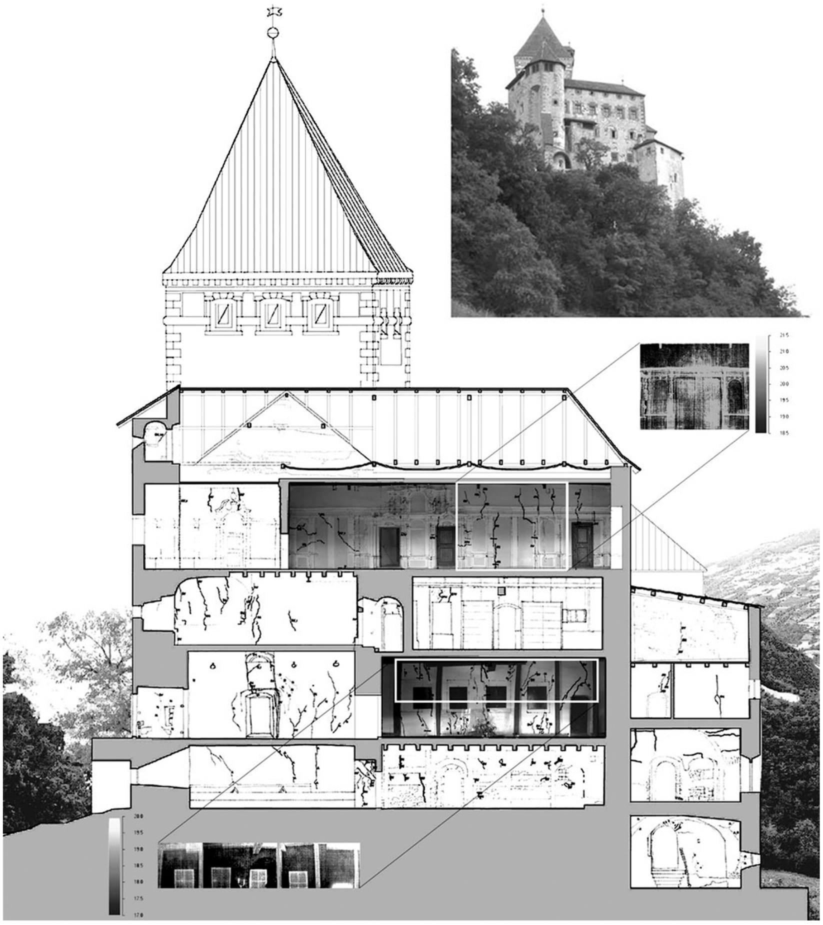

Figure 2: Section on the Palace, thermography of the Palazzo Romanico, level 4 and level 7. (Detachment is detected as colder area. Air temperature 21°C, RH 80%, June 2009)

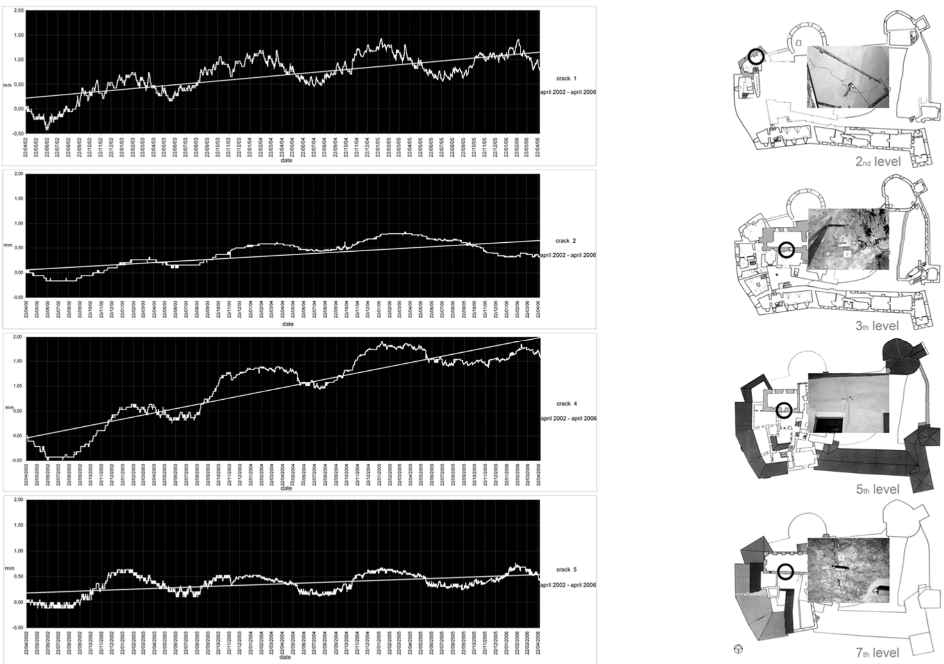

Figure 3: Palazzo Romanico, extensometers N° 1, 2, 4, 5 data series (April 2002 - April 2006)

All the controlled cracks present a progressive increasing of their width, without direct relationship with the temperature trend. Instruments recorded almost the same displacements at every levels.

Small differences are due to the particular position and shape of each single crack, which correspond to different standard deviation values (0.9028-0.3031). Long time trend present a slow, progressive and irreversible widening, whose tendency overcomes the seasonal cycle.

Data confirm the supposed relative displacements between the eastern and the western parts of the Palace, which can be assumed as a linear downward translation long the min axes of the building combined with a rotational movement towards the base of the so called “millstone tower”. Moreover, it is interesting to notice that the displacement is maximum between the 5th and 6th level (crack n°4), while its intensity is lower at the top of the building (crack n°5) and near the foundations (crack n°2), close to the supposed rotation fulcrum at the conjunction between the “palace” and the “millstone tower”. The origin of the described structural damage and the connection with the digging of the tunnel can be differently evaluated. In any case, it is definitively clear that cracks widening has an active and progressive trend, independent from the seasonal trend and not completely due to the spontaneous or natural decay of a weak and stratified historical structure.

Conclusions

An historical building is usually the product of a long time process of transformation and stratification of several single parts. Results highline how the structural monitoring of such a structure can be empowered by a deep comprehension of its constructive history.

Structural decay, itself, can be evaluated in its historical evolution throughout a widely and historically discussed cracks board which provides a wider support to the planning and to the execution of a structural diagnosis.

A methodological consequence concerns the evaluation of the results, because the efficiency of the monitoring is directly proportional to how defined the interpretative structural model is. This way, random or bad results can be reduced and, in the ultimate analysis, the execution of the diagnostic investigation aims at the verification of the theory and not the gathering of elements useful to the formulation of the theory.

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