Close-range remote sensing for monitoring the weathering in wall surfaces of a historical building at Orval Abbey, Belgium

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Monitoring and evaluation of weathering processes of materials in historical buildings are crucial for the maintenance and conservation of such cultural heritage. For this purpose, spatial distribution of the surface condition, including the area, depth, and volume of weathering, should be examined. Detection and quantitative evaluation of changes in the surface condition of rocks have become possible by the availability of terrestrial laser scanning (TLS), and structure-from-motion multi-view stereo (SfM-MVS) photogrammetry approaches. We applied these technologies to the detailed, multi-temporal morphological measurements of a wall surface at a test site in the Orval Abbey, a historical building in Belgium. Time series of the high-definition topographic data including point clouds and digital elevation models (DEMs) were registered to each other, and the millimeter- to centimeter-scale changes were detected for the time periods of the surveys in three years. The changes are most likely induced by salt weathering. The spatial distribution of the surficial changes indicates the spatial variability in the surrounding condition of wetness and temperature, which significantly affects the rate of weathering.

Keywords: TLS, weathering, point cloud, digital elevation model

The degradation state of the Wareishi Rock Cliff Sculpture based on the multi-view stereo.

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The Wareishi Rock Cliff Sculpture, carved on a core stone of granite in A.D. 1300, designated as an important cultural property of the Hiroshima Prefecture, is located near a shoreline of the Sagi Island, Mihara City, Japan. The core stone appears above the sea level during the ebb, whereas a part or all sinks below the sea level during the high tide. The lower part of the core stone is now dark colored probably covered with algae. It is often pointed out that the Sculpture seems to have recently been degraded rapidly due to the direct influence of tidal ebb and flow. In this study, the present condition of the Sculpture will be argued based on a precise measurement and an appropriate direction of conservation ways will be discussed.

The present shape of the Sculpture was measured in order to estimate the degradation state exactly. The same measurement was also applied on a replica of the Sculpture made in 1986 and exhibited in the Hiroshima Prefectural History Museum. The difference between the present shapes of the Sculpture and the replica can be regarded basically as the degradation of the Sculpture during these 30 years.

The measurement is required to be simple without electricity because people can approach the Sculpture only during the ebb. For this reason, the multi-view stereo technique was examined in this study. This technique measures the unevenness information of targets through taking photographs from various viewpoints and matching the photos. This method provides 3D information as well as color information at the same time quite simply and quickly. Fifty seven photographs (ca. 70 cm wide for each) were taken on the Sculpture and 43 photographs (ca. 120 cm wide) on the replica using a digital camera “PowerShot G7X” of Canon Company. The measurement was carried out basically by one person and took ca. 6 minutes for the Sculpture and ca. 4 minutes for the replica.

As a result, the difference between the shapes of the Sculpture and the replica was detected mainly on the middle part of the core stone constituting a horizontal belt of ca. 20 cm parallel to the sea level. The total area of the places where more than 3 mm difference was detected constitutes ca. 0.56 % of the whole measured area.

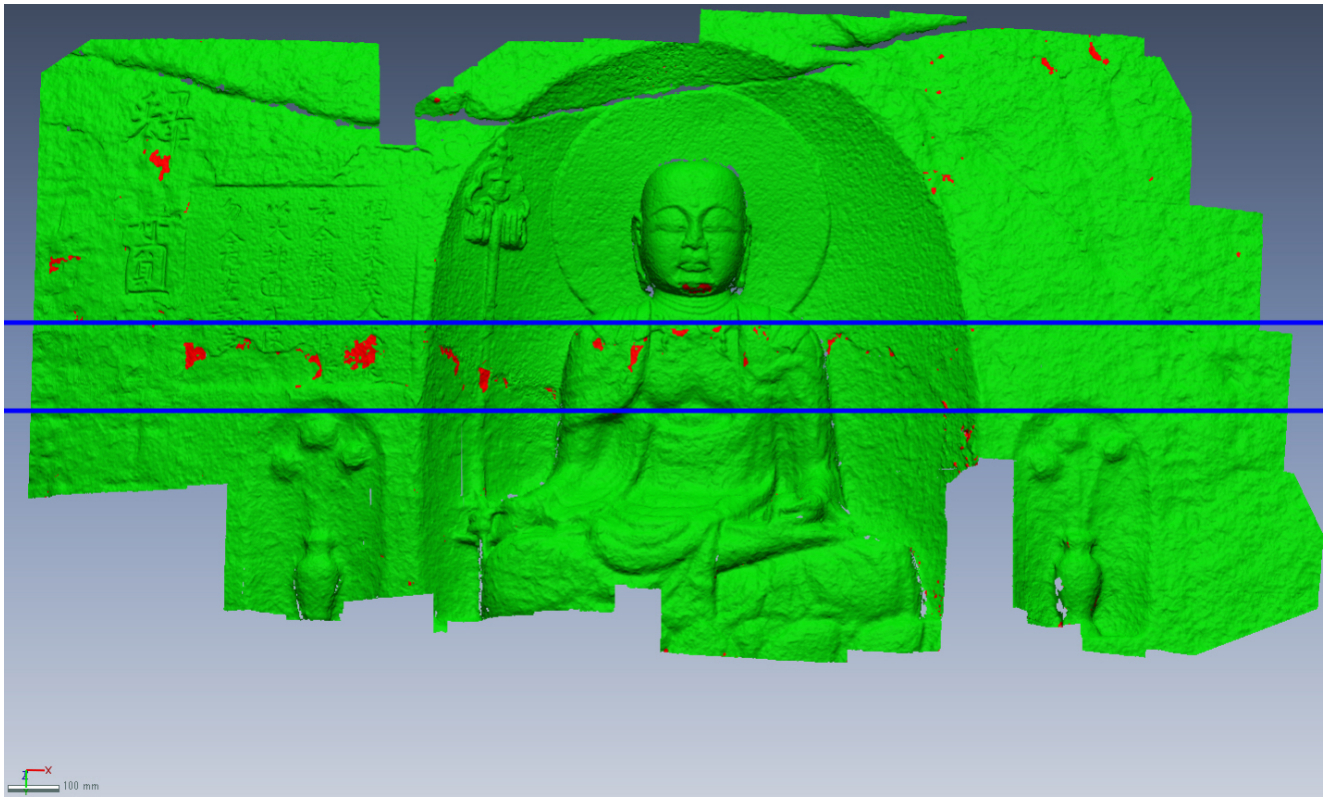
The upper surface of the beltlike deteriorated area almost concurs with that of the darkened area of the present Sculpture, whereas the lower surface of the deteriorated belt with the upper surface of the darkened area of the replica. In other word, the degradation of the Sculpture during these 30 years is detected mainly on the belt between the uppermost lines of algae on the Sculpture at present and at 30 years ago.

Because the luxuriant growth of algae is normally influenced by water, it is likely that the uppermost line is related to the average sea level during the high tide here. If so, the rising of the line may be related to the rising of the sea level. This hypothesis suggests that the recent degradation of the Sculpture occurred through the participation of the rising of the sea level. In fact, the lower part of the Sculpture, where the displacement is not obvious, does not retain the original surface of the Sculpture, indicating that the degradation occurred in the past when the sea level was lower. Accordingly, the detected degraded-area during these 30 years, 0.56 % of the whole, cannot be regarded so much large compared with the total degradation of the Sculpture during ca. 700 years.

As a conclusion, the degradation of the Wareishi Rock Cliff Sculpture does not seem to be recently accelerated so much but to be progressing at not so different pace as the history of the Sculpture. However, if the sea level rises up more in the future, it is possible that the degradation occurs on the

essential part for the Sculpture, e.g. on the face. In such a case, some conservation measures may be discussed such as establishing a transparent barricade keeping the Sculpture from the direct wave erosion.

Keywords: weathering, sea level



Thermal response of building stones contaminated with salts

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Salt crystallization is a weathering process encountered in building stones. Salts appear inside the building stones mostly before to the beginning of the degradation. Therefore, it becomes necessary to detect these salts before an irreversible decay occurs. Currently, the existing portable and non-destructive methods used in cultural heritage do not identify the salt composition nor quantify their concentration. Thus, a new tool or protocol is required to advance in the characterization of salts within stones in the field.
Infrared Thermography (IRT) is a well-known and non-destructive technique (NDT) used in a passive way to detect salt presence linked to moisture and their resulting decay forms. To understand the stone behavior under salt crystallization and to predict its evolution, the active IRT was tested. The main objective was to trial this technique in order to obtain more information such as the type of salt, its precise location and its concentration.
Three building stones were studied: two natural limestones (Bajocian (BJ) and Sinemurian (SN)) and a reconstituted stone (RS) made with debris of these limestones. These three materials were used simultaneously in buildings of South of Wallony (Belgium) as their color and origin are close to each other. Forty-five disk-shaped samples of each stone were submitted to immersion/drying tests in water (used as reference) and in salt solutions of Na_2SO_4, NaCl and $MgSO_4$ at 7%, 14% and 26% in weight during 20 cycles. The weight of the samples and the surface color were recorded after each cycle. After 1, 5, 10 and 15 cycles, 3 samples were taken out for active IRT measurements.
Active IRT was conducted by means of a FLIR infrared thermography camera SC655 with two flash lights placed at 45° of the sample, symmetrically along the axis of the camera, producing a light of 4800 J for 5 ms. The flux of photons emitted by the flash excited the sample leading to an increase of its temperature, and the corresponding thermosignal was recorded by the camera. The thermosignal (TS) depends on i) the mineralogical composition and the physical parameters of the material: density, porosity and pore structure, specific heat, emissivity, conductivity and diffusivity, ii) the surface properties (roughness, color). Thermosignal (TS) images were recorded and thermal curves over time were extracted from them.
Macroscopic observations showed that all the stones developed efflorescences on their surface with different morphology depending on the type of salts. Only BJ and RS, the most porous stones, showed a notable sanding starting from cycle 10.
Colorimetry showed that Na_2SO_4 efflorescences tended to enlighten the different stones whereas NaCl and $MgSO_4$ darkened them. Weight increase of the samples was different depending on the stones and the salts properties. But the overall tendency revealed that the most concentrated the solution was, the most the weight increased.
To avoid the influence of color in the IRT response, the samples were black painted before the IRT analysis. For the most porous stones (BJ, RS), the TS depended on the salt concentration and the number of cycles. The Na_2SO_4 contaminated samples had the highest TS compared to $MgSO_4$ and NaCl that were similar and close to the initial TS. Especially for the Na_2SO_4, the TS increased with the concentration. It also increased with cycles until the beginning of sanding and cracking (cycle10). After that, TS decreased and stabilized to the initial value. On the least porous stone (SN), no change of the TS was observed in relation to the salt type, the concentration or the cycle number.
The active IRT seemed to be a non-destructive technique adapted to identify and quantify the salts.

Though, it is necessary to use it during the first’ s states of salt accumulation. Further tests will used longer heating of the samples thanks to halogen or ceramic lamps in order to have a deeper thermal response of the sample.

Keywords: Infrared Thermography, Salt weathering, NDT, Limestone

Infrared thermography and contact angle as a tool to assess potassium nitrate crystallization

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Infrared thermography (IRT) is a non destructive and non invasive technique that detects temperature and/or emissivity parameters. In building heritage, the infrared thermography is used commonly for the detection of humidity and moisture transfer, defects or cracks as well as for the visualization of different materials and restoration phases. Last researches were focused on the study and comprehension of weathering process such as salt crystallization. Due to the fact that IRT detects temperature variations, thermodynamic processes such as crystallization (exothermic reaction) or evaporation (endothermic reaction) should be detected. The aim of this research is to study with IRT evaporation, crystallization kinetics and thermodynamics of potassium nitrate. This salt was chosen since it is commonly found in weathered parts of buildings. In addition, it has an enthalpy of more than -400 kJ/mol that could be detected by the IRT camera. An essential parameter in salt crystallisation is the nature of the substrate in contact with the solution. The specific surface or the hydrophilic / hydrophobic character of a material depends mainly on its artificial finish or on the products applied during or after restoration. For this reason, the evaporation of droplets of a potassium nitrate solution was carried out on four different substrates. The first was a black adhesive tape (3M), which served also as a reference material and was stuck to a glass slide. Its emissivity was determined to be 0.96 in the wavelength analyzed by the camera. The second was the glass slide. The third and fourth were a marble with polish and saw finish respectively. On these last three substrates, a tiny piece of 3M was stuck to serve as reference for the IRT analyses. Thanks to angle contact measurements the hydrophobic or hydrophilic character of the different substrates was quantified.

The evaporation of six droplets from a solution of KNO_3 at 80% wt saturation was recorded with passive IRT on each susbtrat. Temperature was set at 20˚C, 50ºC and 75ºC and humidity was kept constant at 35% RH. The droplets were placed on four different substrates. The image recording was carried out with a speed of 6.25 frame/second, enough to observe all the phenomena produced. In addition, the variations in the signal were recorded and graphed in several points of the droplets and compared to the black tape reference.

Droplet evaporation could be easily quantified due to the emissivity variations and the measurement in fixed points of the droplet. The heat released by phase change was not always observed. Creeping (efflorescence development) was visualized in specific points of the droplet, similarly to other salt types such as sodium chloride or sodium sulfate. A greater evaporation during efflorescence growth, involving all the already formed crystals, was observed in most of the droplets at the three temperatures, with a wicking effect recorded for the first time in this kind of process. Furthermore the spreading of the solution and further crystallization seemed to be closely related to the hydrophobic or hydrophilic character.

Keywords: infrared thermography, salt crystallization, potassium nitrate

Application of repeated impacts method of the Schmidt hammer test to coastal cliff surface at Shimane, Japan: evaluation of the degree of weathering

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The processes by which two types of cliff surface develop have been discussed in order to shed light on the mechanism of rockfalls on the Isotake coast of Shimane, Japan. We found that the cause, which differentiates the two types of surface topography, is salt weathering due to the precipitation of calcareous sinter, leading to the development of tafoni formed by small-scale fragmentation of cliff materials. The weathered surface is frequently removed by salt weathering in the tafoni, keeping the surface fresher. This is reflected in the results of the Schmidt hammer rebound test, which clearly distinguish two types of weathered surfaces, with higher rebound values at the surface of the tafoni than at the surface of cliffs without tafoni. Continuous fragmentation of the pyroclastic rock due to the salt weathering by calcareous sinter causes the recession of the coastal cliff, but this fragmentation also keeps the cliff surface relatively intact, preventing rockfall disasters. The analysis of the results of the Schmidt hammer test in this study can be applied to any kind of rock surface, because the condition of the weathered surface was extremely fragile. Data from different kinds of rock with differing degrees of weathering will improve this method and future estimates of the characteristics of weathering determined via the Schmidt hammer test.

Keywords: Schmidt hammer test, tafoni, rockfall, salt weathering

Non-Destructive Techniques coupled to environmental monitoring to assess the decay of building stones in urban area

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Historic building stones are vulnerable to climatic conditions and atmospheric pollutants. For that reason, the cultural, societal and economic interests to make restorations as durable as possible are undeniable in an aggressive and evolving atmospheric environment, particularly in areas with important human activities (traffic, housing, agriculture and industry).
In this context, to carry out a more effective restoration management, the aim is to be able to predict the surface state of the stones according to the evolution of their environment. For this purpose, we used the combination of non-invasive micro-environmental monitoring and non-destructive techniques (NDT) on a newly restored monument.

The studied monument, Saint Joseph Chapel, is a neogothic style monument built in 1876 and constituted from local limestones. The main façade is located in front of a very busy road in the center of Reims (France) and restored from March to September 2012. Two façades of the Chapel Saint Joseph were studied, the restored one and a non-restored, especially isolated from the street.
Two different wireless sensor platforms, were used for each façade. Temperature (T) and relative humidity (RH) were monitored by Smartmote and Waspmote (Libellium), while O_3, NO, NO_2 and SO_2 levels were measured only by Waspmote. The frequency measurement was: every minute for Smartmote and every hour for Waspmote.
In addition, magnetic susceptibility and colorimetry were used to follow the evolution of building stone surface. The colorimetry was set up to control and quantify the evolution of the surface color. If blackening is observed, traffic pollutants will be the main agent of decay, whereas if it is greening, biological activity will be the most important decay factor. The magnetic susceptibility is directly linked to the level of soiling because of the presence of metals constituting the atmospheric particles. The value is also different from a material to another such as stone and mortar. The measurements, established on 200 points on each façade, were repeated at one year intervals.

The first information extracted from the environmental monitoring was that the annual temperature variations could be divided in two periods of interest: high T and low RH from April to September, and the reverse from October to March. The concentrations of the pollutants were higher on the street oriented façade than on the courtyard façade. The highest NO_2 concentrations were recorded along the first period except during spring holiday when the traffic was limited. However, the ratio of SO_2 was higher in winter during the second period, especially when daily temperature decreased.
These observations confirmed the correlation between NO_2 and both temperature and traffic, between SO_2 and household heating, and finally a higher risk of weathering for the façade directly exposed to street pollution.

Initial measurements showed that the weathering features of the non-restored façade were soiling, greening and material losses.
The magnetic susceptibility data were higher in areas with little or no leaching by rainwater and prone to

particle deposits. Magnetic susceptibility also allowed distinguishing natural stones from restoration mortars.
The surface of the non-restored part had a higher minimum-maximum deviation of luminance due to the soiling, with luminance values ranging from 40 to 83. This parameter ranged between 70 and 85 for the restored part.
Comparing the two monitoring campaigns, May 2015 and May 2016, there was no significant evolution of the magnetic susceptibility. By contrast, luminance varied much more on the non-restored façade than on the restored one, especially on surfaces where the humidity was high and constant.

Even if the first NDT results showed that the surface of the street façade evolved slower than the protected façade, environmental monitoring pointed the risk for the façade in front of the street to be more affected by pollution despite of its recent restoration. Thus, those first results showed the necessity to use NDT measurements and microscale monitoring over the long term to precise the weathering kinetics and to anticipate future restorations.

Keywords: cultural heritage, preventive conservation, WSN, NDT

Influence of micro climatic conditions on salt weathering

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This study evaluated the influence of micro-climatic conditions on rock weathering in the Yoshimi hyaku-ana cave. Air temperature and relative humidity (RH) were measured at hourly intervals. Samples of weathering debris, which had fallen from the cave wall, were collected on a monthly basis and analysed by X-ray Powder Diffraction (XRD) to identify the mineralogy of the salts within the debris. The results showed that, within the range of temperature and relative humidity investigated here, there were significant decreases in air temperature with increasing distance from the cave entrance, but no significant differences in relative humidity between the sites. The amount of salts and debris near the cave entrances was greater than from inner cave wall surfaces, which may be linked to the micro climatic conditions. Gypsum (CaSO4.2H2O) was the only secondary mineral identified in the fallen debris which may be related to the higher humidity within the cave. Gypsum (CaSO4.2H2O) also has a very low solubility and is therefore liable to crystallize under a wide range of environmental conditions. The highest rates of salt weathering were observed under the more humid conditions during spring and summer, with lower rates of salt weathering in the drier conditions during autumn and winter.

Keywords: salt weathering, environmental monitoring, gypsum

Processes of structural deterioration of an abandoned old concrete bridge in Kozushima Island, facing the Pacific Ocean

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Many concrete structures face serious structural deterioration several decades after construction necessitating countermeasures. This study focuses on the impacts of weathering on the structural deterioration of concrete, by investigating a concrete bridge constructed around 1942. The bridge was used for transporting building stone in Kozushima-Island. The current physical and mechanical properties were investigated by non-destructive methods and chemical properties were analysed from small samples. The results shows that the central part of the bridge now has low strength as a result of sea-salt weathering under tidal conditions.

Keywords: deterioration, weathering, Concrete, Kozushima Island

A formative process of raised rims along joints on shore platforms made of andesite at Oh Island coast, Okinawa, Japan

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Raised rims are well developed along polygonal joints on andesite layers forming intertidal shore platforms at Oh Island coast, Okinawa, Japan. The landform is called "tatami ishi" and has been declared a national natural treasure. The rims have widths of 5-10 cm and have relative heights of 1-5 cm from the bottom of adjacent depressions (called pools). To explore the process of rim formation, measurements of the hardness and moisture contents of the andesite surface were conducted at the rims and pools. A schmidt hammer and a moisture meter were used for the former and latter measurements, respectively. The schmidt hammer testing showed that the rims and pools have no significant difference in hardness . This result does not support the existing explanation that the elevated rims are formed due to case hardening, i.e., cementation by concentration of calcium, silica and/or iron. Temporal changes in the measured moisture content during ebb tide showed that the value at the pools decreased drastically in low tide due to strong drying caused by direct insolation, while rims maintained higher moisture contents by capillarity in narrow joints. These results suggest that (1) the higher moisture content prevents drying and thus salt weathering on the surface of andesite along the joints, which results in little deterioration of the surface strength, and (2) the surface lowering occurs as a result of strength reduction due to salt weathering prevailing on the place apart from the joints, i.e., on the pools. This leads to the conclusion that the rims and pools are landforms controlled by the difference in fluctuation of moisture contents.

Keywords: Raised rims, Shore platform, Moisture contents , Hardness, Weathering, Andesite

Quantification of color change of building limestone due to humidity variations

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Colorimetry is a Non Destructive Technique (NDT) commonly used in cultural heritage. It allows quantifying the subjective nature of color in order to characterize, identify or distinguish materials or to control their weathering stage. Indeed, whether it is by biocolonisation, salt crystallization or pollutant accumulations, the weathering processes often lead to a color change. This technique is then often used directly on the field on buildings, or in the laboratory. But climatic conditions (temperature, relative humidity and even rain) can be quite different from the field and the laboratory, and in the field, from one day to another. It is well known that color is highly dependent on humidity. A wet stone has often a different color than a dry stone. So, when using this technique to compare color data from one day to another, for example during monitoring campaigns, it is hard to have the same climatic conditions and to know if the color variations are significant. Color change of materials due to humidity is mainly related to mineralogy, porosity, pore distribution and specific area. All materials will not have the same behavior.

In order to quantify color change due to humidity, 4 building stones were sampling, characterized and submitted to different humidity conditions before color measurements.
Materials were building stones used in monuments of North-Eastern Paris (France): one building limestone (Bj) from the Bajocian layer of the Paris Basin (France) and one reconstituted stone made with debris this limestone (Rs) and that was used as substitution stone during restoration works; one limestone from de Lutetian layer of the Paris basin (Cv) and one limestone from the Portlandian layer usually used to replace the Lutetian (Sv). All of them have light color with yellowish tendency.
Each material were characterized by microscopy, water and mercury porosity and adsorption-desorption kinetics were measured. Results showed similar characteristics of the four materials, especially between the pairs.

Color was measured on 6 samples (5x5x1 cm^3) of each stone at different states: dry, after adsorption at 33%, 75% and 97%, wet and during drying. The colorimetry was set up with a Minolta CR400 chromameter.
Results showed that the parameter that changed the most with humidity was the Luminance (L*).
Maximum adsorption of stone was around 1% in weight except for the reconstituted stone that was around 2.5%. Even the maximum of weight increase at 97% of RH was for the RS, only the Bajocian limestone showed a color variation ΔE up to 3, meaning that the color change was visible to the naked eye.
Color change (ΔE) after immersion showed that the wet restoration stones (Rs and Sv) had a higher change of color ($\Delta E > 15$) than the original stones (Bj and Cv).
During drying, the value of luminance was directly correlated to the saturation. ΔE was significant (>3) until the saturation reached 15% for Bj, Rs and Cv and 5% for Sv.

This study showed that stones with close petrophysical properties could have different color change behavior enough to distinguish them on a building. It also showed that stones were highly sensitive to humidity, but that this change was related to how this humidity is located in the porous network (adsorption-desorption or absorption-drying). Further experiments would test color variation with

humidity of stone contaminated with salts.

Keywords: colorimetry, relative humidity, limestones

Use of strain gages in the control of frost action

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Frost action is one of the major weathering factors of building stones. Freezing of water inside the porous network causes dilation due to the volume change of water (9%) and the movements of liquid water due to cryosuction. On a monument, the particularity is that frost enters the stone only through the exposed façade. The surrounding blocks and the milder indoor conditions protects the other faces. To assess the effect of freeze-thaw on stones, standard tests are commonly used or adapted in terms of temperature or time of freezing. All these tests, even the adapted ones, consist in freezing the samples after prior immersion in water and thawing them in room temperature water. All the stone faces are exposed to damage, though this does not reproduce the real monument conditions.
These standardized tests assess the decay produced by the ice by means of loss of material (visible or by weight measurements) and tensile strength decrease. In both cases, if the test itself is not destructive enough to produce material detachment, these evaluation methods are irrelevant. In addition, this kind of tests cannot be performed out of the laboratory and in real monuments with immovable materials.

In this study we tested an alternative solution to these constraints with a non destructive setting that allowed to produce freezing on only one face of the stone and the use of strain gages attached along the stone to assess microscopical structural damages. This setting was tested on a common building Lutetian limestone.
Two kinds of water saturation were tested: i) partial saturation obtained by continuous capillary water supply, and ii) partial saturation obtained by a previous total immersion during 48 hours. In the first one, the capillary fringe reached 6cm height of the sample and a differential damage produced between the bottom and the top of the sample was expected. In the second one a homogeneous damage along the sample was expected.
To produce the freezing, a cooling plate was placed vertically in contact to one vertical face of the prismatic sample. The rest of the faces were sealed with a thermal insulator to avoid evaporation and cooling.
To assess frost action strain gauges were set up at different heights of the sample with different orientations from the direction of freezing penetration. To control the freezing penetration inside the sample, thermocouples were placed at different depths within the stone specimen. Even this was a partially destructive method, it was necessary to control if freezing was produced within the stone and at which moment, and then to establish the best experimental protocol. Previous tests showed that the cooling plate had to be set up at -15˚C in order to reach temperature below 0˚C inside the sample.
Five cycles of continuous freezing were applied. Cycles were divided in 12 hours of freezing at -15˚C and 12 hours of thawing at +10˚C. During the whole time of the two tests, the sample was water supplied by capillary absorption from a bottom water tank.

For both tests, the sample could be divided in three parts according to its dilation behavior: the capillary zone (up to 6 cm), the fringe zone (6 cm) and the upper zone not soaked.
Results showed the deformation perpendicular to the freezing direction was negligible except for the fringe zone where it could reach 6.10^{-4}. The deformation parallel to the freezing direction showed an expansion during freezing and a contraction during thawing whose intensity was correlated to saturation.

Only at 6 cm this deformation was close to zero. A small residual deformation was recorded only with the total saturation.
The use of gauges small enough (2mm) to produce the less damage possible even when removed after the test, could be applied in real stone monuments. In addition, they measured the damage produced on the surface not only by ice but also by temperature changes or liquid water movements. The gauges allowed measuring the immediate damage before it reached the inside of the stone and before a visual degradation. This original test also showed the importance of the capillary fringe in the frost action on building stones.

Keywords: frost weathering, unidirectional freezing, strain gages, limestone

