Experimental Methods on Monitoring of Materials Surfaces in Climate Change Conditions

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ABSTRACT

Climate Change is one of the most critical global challenges of our time and the burdened cultural heritage of Europe is particularly vulnerable to be left unprotected. Climate for Culture2 project explore the damage impact of climate change on cultural heritage at regional scale. In this paper the progress of the study with in situ measurements and investigations at cultural heritage sites throughout Europe combined with laboratory simulations is described. Cultural works of art are susceptible to deterioration with environmental changes causing imperceptibly slow but steady accumulation of damaging effects directly impacting on structural integrity. Laser holographic interference method is employed to provide remote non destructive field-wise detection of the structural differences occurred as climate responses. The first results from climate simulation of South East Europe (Crete) are presented. A full study in regards to the four climate regions of Europe is foreseen to provide values for development of a precise and integrated model of thermographic building simulations for evaluation of impact of climate change.

Development of a third generation user interface software optimised portable metrology system (DHSPI II) is designed to record in custom intervals the surface of materials witnessing reactions under simulated climatic conditions both on-field and in laboratory. The climate conditions refer to data-loggers (DL) readings of characteristic historical buildings in selected climate zones. New generation impact sensors termed Glass Sensors (GS) and Free water sensors (FWS) are employed in the monitoring procedure to cross-correlate climate data with deformation data. In this paper results from the combined methodology are additionally presented.

Keywords

Climate change, Cultural Heritage, structural monitoring, glass sensors, holographic interferometry, DHSPI.

1. Introduction

The undesirable effects of environmental conditions on art materials have long been realised and studied [1]. Relative humidity (RH) changes have been accused as most critical reason for structural alterations [2-4]. Repeated structural alterations through induced RH fluctuations being monitored directly from material surfaces through non contact laser holographic interferometry has shown the deleterious effects on the integration and sudden deterioration of organic materials with generation of irreversible structural damage and defect generation [5, 6]. The damage potential and damaging parameters of the RH change was also resolved in spatial and temporal terms by monitoring interchange with implementation of pulse and continuous wave lasers; resolution depended damaging effects were studied and illustrated [5, 7]. Climate change is widely accepted that is among the most critical challenges that would affect seriously in negative and irreversible manner the cultural heritage materials and the EU has launched already projects to study the issue [8]. The previously concluded Noah's Ark EU research project showed for the first time that climate change will have a severe impact on cultural heritage, but European cultural heritage decision makers and managers are not yet fully aware of the far reaching consequences of the impacts of climate change. The main climate changes threatening cultural heritage are rising temperatures, enhanced amounts of precipitation and as a consequence a wider variability of relative humidity, sea level rise and the shifting of climatic zones. The Noah's Ark project on climate change has concluded as main priority research in studying the responses and vulnerability of the typical cultural heritage materials [8].

In the currently funded EU project CLIMATE FOR CULTURE this recommendation has been included among the objectives. The study on the material responses is presented here and is realised through the application of a combination of close up monitoring and sensing technologies. The methodology employs non destructive remote monitoring system to directly record the surface displacement by use of Digital Holographic Speckle Pattern Interferometry (DHSPI). Close-up monitoring of possible surface damage phenomena are screened by 3D Microscopy (3DM). The new synergetic sensors using Glass Dosimeter (GD) concept and Free-water-sensors (FWS) are coupling for the overall environmental damage potential. These are used to provide direct assessment of the available water content of the air together with state-of-the-art microclimate monitoring by conventional data-loggers (DL) are used to deepen the study and understanding into climate induced damages on moveable and immovable cultural heritage in

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respect to RH changes [9, 10]. The above objective requires basic environmental data input from case studies for application in laboratory simulation studies [11, 12].

In this paper are presented selected samples and on-field campaigns during the course of the Climate for Culture project confirming the installation of sensors and monitoring with portable DHSPI interferometry system in this field of research form a powerfull complimentarity setup. The same applies as well for the laboratory simulations in the air-tight climate chamber. The displacement rates are differentiable within small changes in regards to the surrounding environment. It is thus proved that the application and methodology developed can be very useful on historical sites enhancing prevention strategies for individual monuments.

2. Methods and application

The techniques and sensors used in combination in the study are shown in table I.

Technique:	Sensor/s:
DHSPI Surface displacement in response to induced RH% change	GS Environmental corrosion
DHSPI – 3DM Surface topography	FWS RH threshold levels wall dampness
DHSPI – 3DM Surface damage	DL: Data loggers RH/T.

Table 1 Techniques and sensors

Typical materials used in artwork construction and cultural heritage decorative elements are used as samples for the experimental simulation in air-tight chamber. Wood and oil and acrylic paint are studied in laboratory simulations while on-field investigation is concerned with wall painting natural responses and defect mapping. In order to attempt detection of dimensional changes from complex organic and inorganic materials during Relative Humidity fluctuations, preliminary experiments have been realized related to observe the dimensional displacements of the materials during relative humidity of the environment in which they are located is being altered. The detection of these changes has been realized using a system developed on IESL based on Digital Holographic Speckle Pattern Interferometry [13, 14]. Relative humidity (RH) controls the amount of moisture contained in materials at equilibrium with the environment. This is almost independent of temperature. As relative humidity changes, the object's water content adjusts to the new relative humidity level, creating a new equilibrium. At higher RH, there is more water in objects. This occurs slowly, depending on the thickness and absorbency of the material.

Temperature and relative humidity affect three decay processes: chemical, biological and mechanical. In this research we focus mostly on mechanical deterioration of objects. Mechanical deterioration is related to either the amount of water absorbed by organic materials or thermal expansion in inorganic materials. The item changes size and shape, leading to cracking, splitting and warping. Stress or the application of different materials will affect the susceptibility of a piece to mechanical deterioration when the environment fluctuates. Fluctuating relative humidity and temperature stress mechanical stability of materials considerably. The extent of damage depends on the material. A change in temperature can expand or contract materials as diverse as metal, wood, stone and organic/inorganic combination of materials. Temperature change does not damage as many objects as significantly as relative humidity fluctuation does. A change in RH may cause swelling, warping, splitting, delamination and advanced dimensional changes in moisture-absorbing or hygroscopic materials.

In general under controlled condition alterations, RH equilibrium occurs slowly for the entire mass of an object. Therefore, seasonal smoothly induced changes have the lesser effect. Seasonal slow drifts, allowing slow equilibrium, are less harmful than abrupt changes. However, since surfaces undergo daily changes, stress propagation within the entire mass of structure occurs. Although usually small fluctuations are considered as not important, for some materials each cycle causes tiny fractures to grow. Repeated small changes contribute to decay since cause continuous reactions leading to fatigue accumulation and may finally lead to fracture. Deterioration increases as cracks are opened further and detachments in multilayered objects propagate. In this context, small RH fluctuations even in controlled Museum environments can lead to mechanical fatigue of materials. In case of abrupt environmental changes the decay mechanism may lead to fracture faster. The material undergoing abrupt environmental change reacts rapidly in order to achieve equilibrium with the environment and thus accidental randomly induced changes have the greatest effect. Sudden changes in abrupt rates of change challenge the mechanical stability inducing fast exchange processes between the surface and the surrounding environment in different rate of change than internal volume. Irreversible mechanical change may occur by accelerated fatigue process.

Here the aim is to simulate environmentally induced fatigue due to stimulated dimensional change of RH/T, T changes in correlation to RH induced change. Through the ratio and rate of change the reactions could be classified in natural impact due to seasonal change or extreme event impact due to climate induced change.

3. Climate Chamber Induced Simulations

3.1 Environmental chamber – Experimental Methodology

In order to simulate low to extreme relative humidity fluctuations a climate chamber was designed and constructed. The fluctuations in relative humidity have been produced with the use of silica gel (SiO^2) in order to obtain a stable value of environmental Relative Humidity equal to 14%. Further experiments will follow with the use of saturated salt solutions in order to obtain several values of relative humidity.

The climate chamber's dimensions are 50 cm x 40 cm x 40cm (Figure 1). The chamber consists of three parts. The lower part is a drawer where the salts or silica gel are placed. The control of the moisture level is achieved using two parallel plastic sliding shelves on top of the drawer which have overlapping openings. One of the two shelves is fixed while the second one slips inside-outside the chamber. When the movable tray is fully inside the chamber the holes of the plastic shelves coincide so each hole is totally open. When the movable tray is at its outer position, the holes of the movable and the fixed shelf do not coincide so the holes are fully closed and drawer can be removed. At any intermediate position there is an overlap of the two holes. The size of each hole is inversely proportional of the proportion of the overlap. In this way the moisture level can be controlled. In the upper part of the chamber, samples under study are placed. The whole construction is completely insulated from the environment with sealing rubber used at all edges and springs keep the chamber door and the salts drawer firmly closed.

Inside the climate chamber a data logger is placed in order to monitor the fluctuations of temperature and relative humidity. A HUMLOG 10, E+E ELEKTRONIK Ges.m.b.H., data logger is used to record humidity and temperature values. The RH measurement range of the device for these values is 10-95% RH with an accuracy of ±3% RH and a resolution of 0.5% RH. The temperature measuring range of the device is -20°C to 50°C with an accuracy of ±0.3°C at 0 – 40°C and a resolution of 0.1°C.

3.2 On line experiments

A natural condition is simulated by the salt and silica use. A non-natural climate condition and the effect of its impact are achieved by inducing extreme changes. While the material thrives to achieve equilibrium the induced simulation involves the exit of the chamber accelerating the reaction of the material. The purpose of online experiments is to control and monitor on real-time the displacement provoked by the relative humidity fluctuations simulating natural impact, not small or smooth change but the impact while it happens. Therefore in this case the relative humidity will be controlled and altered while DHSPI system is partly inside the chamber and measurements are performed on line. DHSPI system and methodology is not affected by the RH changes.

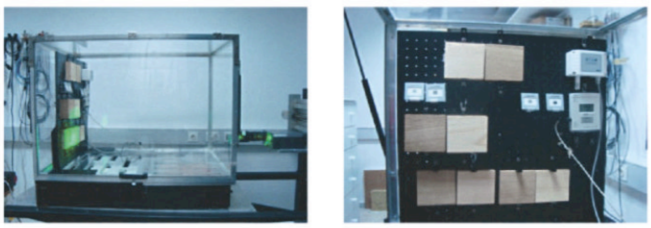

Figure 1. (a) Schematic representation of environmental climate box, (b)-(c) Pictures of environmental climate box.

Silica gel is hygroscopic and responds to the relative humidity (RH) of the surrounding air in the same way as most organic materials such as paper, textiles and wood. Like organic materials, the amount of moisture in silica gel will increase as the RH rises, and will decrease when the RH falls. Unlike organic materials that expand and contract with changes in moisture content, silica gel remains stable. Also, unlike organic materials, silica gel adsorbs and desorbs much larger amounts of moisture when the RH changes under normal conditions.

3.3 Digital Holographic Speckle Pattern Interferometry (DHSPI)

DHSPI allows continuous non contact monitoring of surface displacement. The method is quantitative registering deformations in real-time on optical nondestructive, whole-field investigation mode.

Surface deformations are detectable down to 266 nm. Object light is superimposed on a reference wave from the same laser and that image is recorded on a CCD video camera, digitized, and stored on a computer. By comparing subsequent images, deformations become visible as “dark and bright correlation fringes” showing isolines of equal displacements. The fringe patterns can be evaluated and transformed into 3-D graphs visualizing the deformation process of the surface.

Coherent interferometry techniques based on holographic principles, which measure phase variations of mutually coherent laser beams recorded at two different stages, have been employed to monitor changes in surface movement. The recorded phase difference provides a measurement correlated to the magnitude of displacement expressed in fractions of micrometers. In the first stage, the object under examination is examined in its reference state while in the second stage a dynamic or altered state is recorded. The software algorithms are based on phase-shifted interferometry aiming to maximise fringe visibility for out-of-laboratory application of portable system [15-17]. Following superposition, the two temporally separated states generate interference. The x,y displacement of the object at Z(x)=0 is equal to integer number of the fringe-pairs multiplied by the half of the wavelength used for the observation

$$Z(x) = \frac{N\lambda}{2}$$

N=1,2,3… represents the number of fringes and λ represents the wavelength of the light source which in the measurements described is equal to 532 nm.

DHSPI new software allows for recording responses of objects, wall-paintings, paintings, etc in everyday natural environmental conditions in remote automatic operation [18, 19]. This operation mode allows in Climate for Culture project to acquire naturally induced effects and classify reactions [20, 21]. The system is calibrated on the specific target ones and it is then allowed to automatically record every pre-specified intervals. It is foreseen in the processing software choice of the reference state at the post processing session. Thus the records are taken as raw data with the interferometric processing being performed at any time during the post-processing routines.

3.3.1 Samples used

The samples consist of 4 glass layered pieces (10cm x 10cm) covered with:

- Glue mixed with red organic pigment
- Blue acrylic PHTHALO, Talens, Van Gogh super fine quality, Phtalo Blue 570
- Egg
- Akrylic glue, Lascaux 498 H

At first samples construction aims to compare reactions of organic and inorganic materials in same RH fluctuations as complex mixtures are common in structures such as wooden icons, decorative art and panel paintings of historic interiors. Real time monitoring of reactions can provide further understanding on structural decay mechanisms.

3.3.2 Results on samples

Samples simulating unnatural climate change have been interchanged among controlled environments while dimensional reactions were recorded. First have been placed in the climate chamber with environmental conditions of 20°C and 14-16% RH for 4 days. Then, have been removed to laboratory conditions of 20°C and 36% RH and have been monitored for 10min using DHSPI. They have been kept in laboratory conditions for monitoring and have been placed back in the chamber for another 4 days. They were placed back in laboratory conditions of 20°C and 46%RH and they have been monitored again for 10min. Some raw data in form of interferograms and relevant analysis is presented as preliminary results from the experiment.

The experimental methodology implies that the displacement reaction of each sample is being recorded fast after RH change is induced upon material enters in the laboratory environment. The experimental procedure allow to capture the dimensional reaction under a simulated "abrupt" change of RH in order to preliminary assess response rate and thus the potential of experiment with primary aim the classification among "natural -seasonal" or "climate - extreme events" impact by means of displacement rate vs time. Therefore the monitoring starts immediately after its exit from the Climate chamber. Sequences of images have been captured and processed, characteristic example of abrupt RH change from 16% to 46% while Glue mixed with red organic pigment sample is monitored as it is being adjust to 46% is being presented after 1, 5 and 10 min after the change in graph of figure 2.

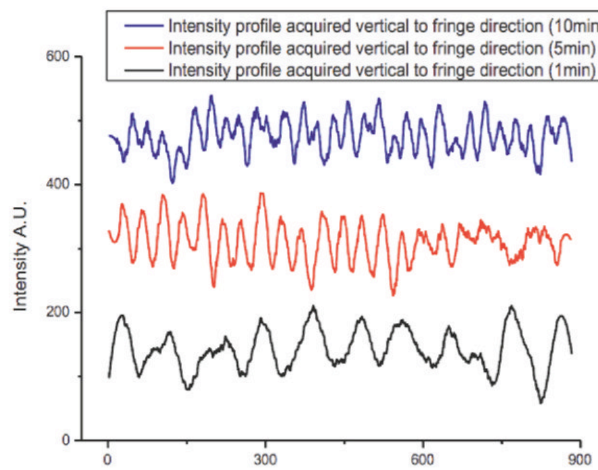

Figure 2 Glue mixed with red organic pigment sample displacement along x axis for 1, 5 and 10 min after RH change from 16% to 46% and 20°C

Intensity profiles distribution corresponds to visible macroscopic interference fringes along an axis. The number of intensity peaks along x axis corresponds to the number of fringe generation at the instance of surface displacement. This secondary spatial frequency is measurable along direction axes vertical to fringes of interferogram in x, y to assume the 2D quantification of a plane surface displacement. Increase or decrease in spatial frequency is a proof of dynamic process. The profile is a cosine alternation of interference of a shown fringe density formed among the instance of first record after the exit of the chamber and later instances eg 1, 5, 10 minutes. First it is observed an increase of the fringe frequency. It is a visual representation of the sample dimensional reaction as it accommodates with time to new RH/T conditions. Sample swells/shrinks and the surface displacement continuous steadily till equilibrium with the environment. The displacement is accumulative and drives the surface to a new position of equilibrium. Upon equilibrium the fringes reach plateau or start to decrease in comparison to previous condition. The reactions of the in the induced change affirms the importance of rate of change on ratio of RH change. Graphs are shown in figures 3, 4.

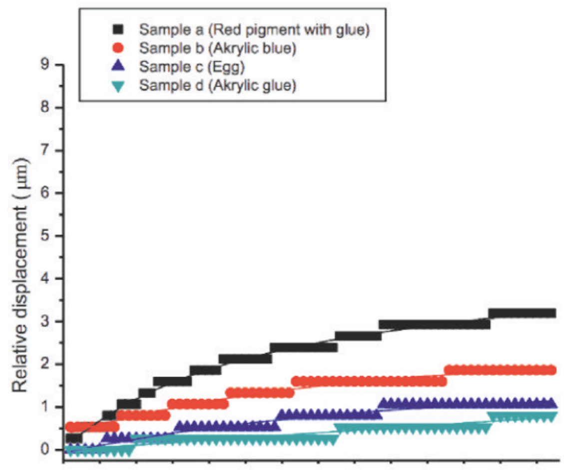

Figure 3 Graph of Surface displacement vs time for 16% RH to 46% RH and 20°C

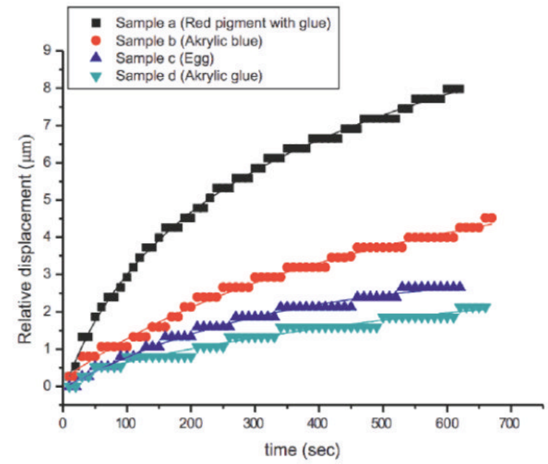

Figure 4 Graph of Surface displacement vs time for 16% RH to 36% RH and 20°C.

Graphs 3, 4 demonstrate the importance of rate of change with the 10% difference in the ratio among 16 to 46% RH opposed to 16 to 36% RH cases to prove able to double the surface reaction in same time window.

3.4 Chamber monitoring concluded

The observations of the stimulated study in chamber laboratory simulations of induced climate conditions support the potential use of laser metrology to study different material composition under stimulated conditioning for a number of cases where materials reaction is essential. The records of mechanical reactions as can be visualized through interference of the different spatial position of surface while it is displaced in order to accommodate the impact of environmental effects can be used as a nondestructive repeatable and remote directly quantitative tool to visualize directly from the sample or object of difference small structural effects. The wavelength dependence of measuring and the holographically recorded optical displacement is thus revealing a highly sensitive tool capable to resolve deformation reactions in time and space and thus to discriminate minor dimensional changes among materials providing direct impact assessment and to allow classification of the physical impact and damage functions evaluation.

4. Natural Induced Displacement: On-Field Monitoring

The seasonal fluctuations are studied in-situ with the techniques and methods shown in table I. Inside the case studies have been installed the experimental sensors in suitable places according to the sensor specifications. The dataloggers were also used to monitor the site throughout the measurement campaigns and in some sites long after it. Data collected from the examined site is later simulated by salts inside the chamber. An example of campaign is described and selected results are presented.

4.1 In situ measurements

Surface monitoring and microclimate data collection was performed in heated and unheated areas inside the Brezice castle in Slovenia shown in figure 5 (AC). Three different areas were indicate: A. Chapel and C. Knightshall as unheated; and B. Auditorium as heated; to perform: (a) Experimental DHSPI monitoring of surface reactions of examined areas, (b) GS experimental sensors, and d) data loggers RH/T data collection, e) 3DM in cracks and f) FWS inside holes. In following examples e-f results are not presented.

Figure 5 a) Examined areas in castle shown in photos and b) marked as A-C in topographic.

4.1.1 Examination in unheated Chapel

Six different areas have been examined using passive DHSPI monitoring in the chapel. One area has been examined through means of monitoring and all other five have been examined in order to indicate detachments and cracks. Same areas have been also examined by 3D microscopy in order to correlate results obtained with both techniques. The experimental procedure of DHSPI monitoring started at 18:00 and finished at 02:00 lasting 8 hours of continuous surface monitoring. Interferograms were recorded every 5 minutes. Graph in figure 6 demonstrates the RH/T fluctuations during monitoring inside the chapel.

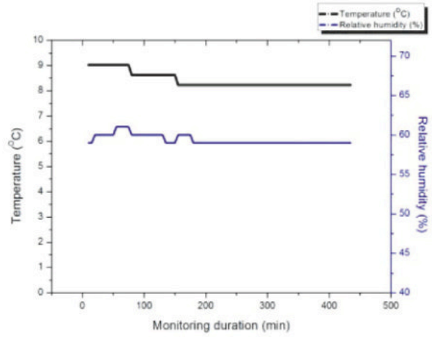

Figure 6 Temperature and relative humidity fluctuations during monitoring

The corresponding surface displacement shown in graph in figure 7 is the deformation of the surface as a function of monitoring duration time. The displaced surface demonstrates different reaction in its right and left part as a deep crack along the subsurface obstructs a homogeneous displacement. Right area corresponds to a higher deformation compared to the deformation of the surface of the left area.

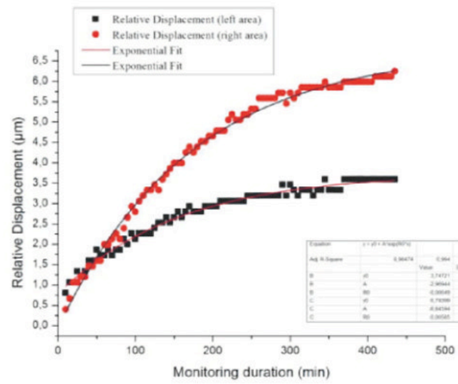

Figure 7 Surface relative displacement during 8 h monitoring.

The deformation of the surface for both cases follows an exponential fit that is being expressed by equation (1):

(1)

In order to calculate the rate of the change the derivative of equation 1 for both fits is calculated and concludes the graph shown in figure 8.

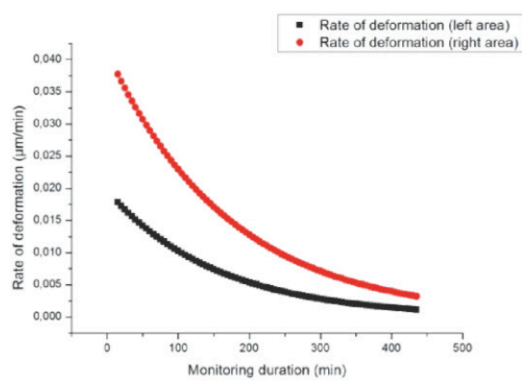

Figure 8 Rate of deformation of left and right area during continuous 8hour- monitoring

As seen in graphs the right part indicates higher deformation rate during continuous monitoring. This fact could lead to a possible conclusion that the right area is more subjected to environmental fluctuations and therefore could demonstrate a more "dangerous" and unstable behavior.

4.1.2 Examination in heated Auditorium

The heating system used was turned on at 06:00 in the morning. Simultaneously the RH-T data logger has detected the first raise in the room's temperature. To compare the surface's movement through the night with the raise of the temperature an overnight surface monitoring on the specific area was performed. The area inside the heated auditorium was examined through means of DHSPI interferometric monitoring for 16 hours during night, started at 18:00 till next morning at 10:00. By the raise of temperature instantly a crack detected inside the monitored area was affected seen as increasing displacement in number of interference fringes. In figure 9 the crack is seen at the onset of displacement with red color visualizing the tip along the crack.

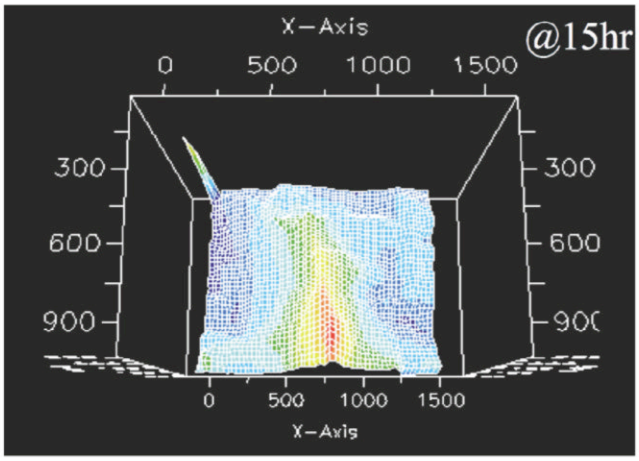

Figure 9 Detail of a crack reaction in heated auditorium by temperature rising.

In figure 10 it is shown RH/T temperature fluctuations during overnight for 16hours of continuous monitoring.

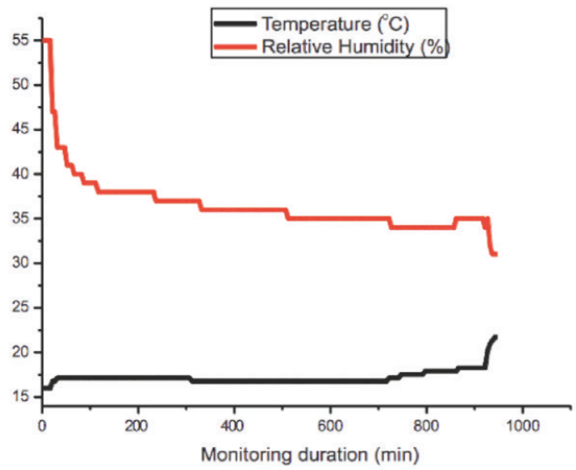

Figure 10 RH/T fluctuations during monitoring

The deformation rate seen in figure 11 is presented as a function of the monitoring duration.

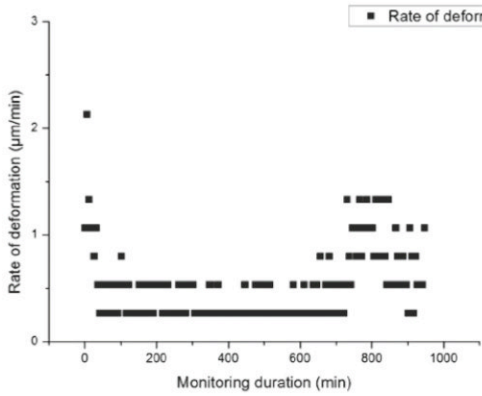

Figure 11 Rate of deformation of heated area during continuous 16hour-monitoring.

The rate of the surface deformation rises along with temperature increase. Deformation starts from 700 to 750 min with peak of deformation rate at 800min. The deformation follows the temperature rise instantly but the rate decreases after 100 min indicating accommodation with the surrounding conditions. The table II presents the reached values of GS as were resulted in the different rooms and in table III is presented the difference between the values E0 and E1 resulting the DEs values of GS.

Table 2 Glass sensor values

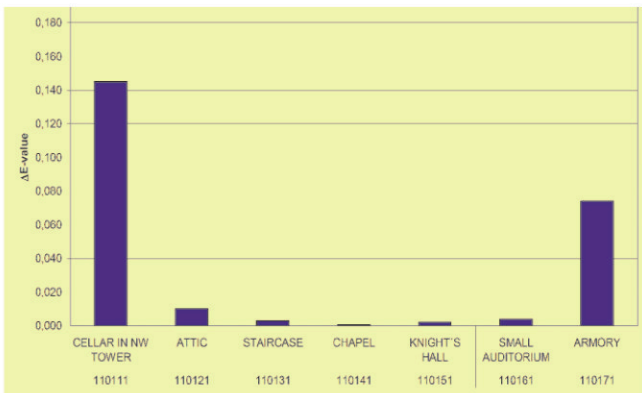

Table 3 DE values of GS

Glass Sensor No.	Location	E0- value	E1- value	DE- value
110141	CHAPEL	0.046	0.046	0.000
110161	SMALL AUDITORIUM	0.046	0.050	0.004

The results of the two systems DHSPI and GS correspond to each other for the unheated a maximum rate difference of 0.035µm/min and DE = 0.000 whereas for the heated auditorium 1.5µm/min and DE = 0.004.

Comparing the unheated with the heated case it is affirmed the microclimate stability of former to affect less the surface of internal walls. In the unheated case the internal walls are not stressed daily and the surface achieves smooth equilibrium with environment.

5. Conclusions

Comparing the GS values with the deformation results it is noticed that the smaller surface displacement captured by DHSPI is 0.035μm/min and the zero DE value DE = 0.000 of GS correspond to the unheated room. The heated room undergoing higher fluctuations it is correspondingly increases the values of surface displacement to 1.5μm/min and of the Glass sensor to DE = 0.004. The values of both are corresponding equally to the data loggers readings which is T =0.5 / RH 2% for the unheated and increases to T =+2.0 / RH -2% for the heated. The preliminary results confirm the hypothesis that the two experimentally developed devices have high complimentarity and could be further developed for in situ monitoring applications. The FWS values are also confirming the humidity damage potential accordingly in agreement with the dataloggers, Glass Sensors and DHSPI. Hence the systems and techniques implemented can be used as Climate impact indicators. Further experiments are on progress and more extended publications are expected in advance.

6. Discussion

This is an on-going research and in this paper presents exemplary results of the studies. The remote measurement directly from the concerned surface undertaken during the Climate for Culture project onfield case studies are taken under natural environmental fluctuations and are reproduced in laboratory simulations. The methodology aims to study the mechanism of fracture under smooth but steadily increasing fluctuations in Climate change era as it is reported by the meteorologists of the consortium.

The achieved resolution of surface reactions in both natural and induced stimulation can assist the understanding of fatigue accumulation through gradual small alterations and define safety, if not damage-free, threshold of RH/T alteration. The methodology could allow differentiating damaging phenomena. Displacement differs in different RH conditions. Thus deformation rate under different RH conditions can be used as parameter in multiparametrical analysis providing for first time a key indicator for damage threshold directly from the surface of interest. Fast automatic DHSPI data can remotely aid the aim to follow the reactions of precious historical wall paintings or valuable furniture and decorative elements and set the risk factor as a risk alarm. The priorities and needs of a site can be clarified and allow to avoid expensive climatisation or RH strict control.

The future study involves correlation of GS, FWS, DL, DHSPI readings for definition of probable use in "expert" software. The direct deformation readings could be also classified and compared with Hygrothermal building modeling simulations.

The investigation in the climate chamber with induced RH changes taken from sites and actual recordings of meteo data is in progress.

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8. References

[1] Thomson, G. 1990. The Museum Environment, 2nd Ed.; Butterworth-Heinemann, Oxford.

[2] Michalski, S. 1993. Relative humidity: a discussion of correct/incorrect values. ICOM Committee for Conservation Tenth Triennial Meeting, Washington, DC, August 22–27 1993, 2, pp. 624–629.

[3] Mecklenburg, M.F., Tumosa, C.S., Erhardt, D. 1994. Structural response of painted wood surfaces to changes in ambient relative humidity. In Painted Wood: History and Conservation; Getty Conservation Institute, The Getty Conservation Institute, Los Angeles, pp. 464–483.

[4] Mecklenburg, M.F.; Tumosa, C.S.; Wyplosz, N. 1995. The effects of relative humidity on the structural response of selected wood samples in the cross-grained direction. Mater. Res. Soc., 352, pp. 305–324.

[5] Tornari V. 1996. "Applications of Holographic Interferometry in Preventive Conservation and the Diagnosis of Works of Art", MPhil Thesis, RCA/V&A /ICMST & British Libraries.

[6] Tornari V. and Papadaki K. 1995. "Application of Holographic interferometric nondestructive testing on art works diagnostics", Conference Preprints "The Conservation of Modern Sculpture", Tate Gallery London, September.

[7] Tornari V. and Papadaki K. 1995. "Continuos wave and pulse Holographic Interferometry used for monitoring environmental effects on materials used in artefacts", in Proc. of the 1st International Congress on Science and Technology for the safeguard of Cultural Heritage in the Mediterranean Basin, Catania - Siracusa , November.

[8] Noah's Ark Project, 2007. deliverable 12 - Production of the vulnerability atlas and deliverable 15 - Freelyavailable guidelines on adaptation of cultural heritage to climate change, EU 6th Framework Programme, Project no. SSPI-CT-2003-501837-NOAH'S ARK, http://noahsark.isac.cnr.it

[9] Fuchs D. R. and Leissner J. 1992. "Environmental monitoring using glass sensors: relevant features for small scale mapping at monuments" 3rd International Conference on Non Destructive Testing, Microanalytical Methods and Environmental Evaluation for Study and Conservation of Works of Art, Viterbo, Italy 4-8 October 1992, 1 (1992) 975-988.

[10] Camuffo, D., Van Grieken, R., Busse, H.J., Sturaro, G., Valentino, A., Bernardi, A., Blades, N., Shooter, D., Gysels, K., Deutsch, F., Wieser, M., Kim, O. and Ulrych, U. 2001. Environmental Monitoring in Four European Museums. Atmospheric.

[11] Mikolajewicz U., Gröger M., Maier-Reimer E., Schurgers G., Vizcaino M. and Winguth A. 2007. Environment ,35/1001, pp. S127-S140. Long-term effects of anthropogenic CO2 emissions simulated with a complex earth system model. Climate Dynamics 28(6), pp. 599-633.

[12] Mikolajewicz U., Santer D. D. and Maier-Reimer E. 1990. Ocean response to greenhouse warming. Nature 345, pp. 589-593.

[13] Hatzigiannakis K., Bernikola E., Tornari V. 2012. "A new portable Digital Holographic Speckle Pattern Interferometry system for artworks structural documentation", LACONA IX proceedings, eds K. Birkholzer, N. Luxford C. Korenberg, M. Strlic and D. Saunders, Archetype, pp 210-212.

[14] Χατζηγιαννάκης Κ., Ανδριανάκης Μ., Μπερνικόλα Ε., Τσιρανίδου Έ., Τορνάρη Β. 2012. "Φορητό Σύστημα Ολογραφικής Συμβολομετρίας Κοκκιδίωσης για εφαρμογές οπτικής Μετρολογίας σε έργα τέχνης", submitted in 4o Εθνικό συνέδριο μετρολογίας.

[15] Tsiranidou E., Orphanos Y., Yingjie Y., Tornari V., 2004. "Detection-depended parameters of internal defect mapping in fringe-based analysis", in the Proceedings of the 6th International Conference on "Vibration measurements by laser techniques; Advances and Applications" Ancona, Italy, 21- 25 June 2004. Edited by Tomasini, Enrico P. Proceedings of the SPIE, Volume 5503, 2004), pp 391-398.

[16] Cuixia D., Yingjie Y., Tornari V. 2007. Electroholographic display with SLM (Proceedings Paper)"; Proceedings Vol. 6695, DOI: 10.1117/12.735771 Current SPIE Digital Library Optics and Photonics for Information Processing, Abdul A. Awwal; Khan M. Iftekharuddin; Bahram Javidi, Editors, 669515, 20 September 2007.

[17] Orphanos Y., Tornari V., Dabu R., Blanaru C., Stratan A., Pacala O., Ursu D. 2006. "Non-destructive speckle interferometry diagnosis method for art conservation",: International Conference Advanced Laser Technologies ALT'06, Sept. 8-12, 2006, Brasov, ROMANIA, SPIE volume 6606.

[18] V. Tornari, "Laser Interference-Based Techniques and Applications in Structural Inspection of Works of Art", Analytical and Bioanalytical Chemistry; 387, 761-80 (2007)

[19] V. Tornari, "Spatial Coordinates in Interferometry Fringes: A Timeless Artwork Multipurpose Documentation", Journal of basic and applied physics, ISSN 2304-9332 online, Aug. 2012, Vol. 1, Iss. 2, pp. 39-48

[20] Bernikola E., Nevin A., Tornari V. 2009. "Rapid initial dimensional changes in wooden panel paintings due to simulated climate-induced alterations monitored by digital coherent out-of-plane interferometry", Applied Physics A 95, pp. 387-399.

[21] Tornari V., Bernikola E., Nevin A., Kouloumpi E., Doulgeridis M., Fotakis C. 2008. "Fully non contact holography-based inspection on dimensionally responsive artwork materials". Sensors 2008, 8, DOI 10.3390/sensors.