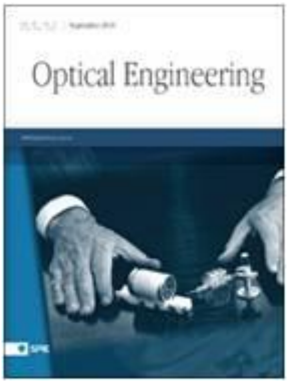

Application of Infrared Thermometry and Ultrasonic Velocity for the Investigation of the Building Materials of Historic Monuments of Dion, Greece

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ABSTRACT

The sanctuaries of Demeter and Asklepios are part of the Dion archaeological site that sits among the eastern foothills of Mount Olympus and covers roughly 100 hectares. The excavations finds from this area are dated since the Hellenistic, Roman and Early Christian times. The main building materials are limestones and conglomerates. Sandstones, marbles, and ceramic plinths were also used. The materials consist mainly of calcite and/or dolomite, whereas the deteriorated surfaces contain also secondary and recrystallized calcite and dolomite, gypsum, various inorganic compounds, fluoroapatite, microorganisms and other organic compounds. Cracks and holes were observed in various parts of the stones.

The most proper approach to select effective methods for the structural and surface consolidation, the cleaning, the protection and the overall conservation of these structures is the knowledge of the processes contributing to their deterioration.

The influence of the water presence to the behavior of the materials was examined by in situ IR thermometer measurements. Temperature values increased from the lower to the upper parts of the building stones and they significantly depend on the orientation of the walls. The results indicate the existence of water in the bulk of the materials due to capillary penetration. To confirm these observations measurements of the following physical characteristics of the building materials have been studied: open porosity, pore size distribution, water absorption and desorption, capillary absorption and desorption. The existence of water in the bulk of the materials due to capillary penetration, the cycles of wet-dry conditions, correlated with the intensive surface and underground water presence in the whole surrounding area, lead to partial dissolution-recrystallization of the carbonate material and loss of the structural cohesion and the surface stability.

Keywords: stone, deterioration, moisture absorption, capillary rise, IR thermometry, ultrasonic velocity.

INTRODUCTION

Deterioration of historical monuments is the result of chemical reactions of polluted air, soil and water with the building stone materials. The crystallization and hydration of weathering products result in their expansion causing the degradation of dolomite, limestone, marble, sandstone and other building materials. In most cases the stone surfaces are gradually covered by salts and black crusts containing calcium, magnesium, sodium, potassium sulphates, nitrates and other constituents. Also the water can easily penetrate and remain into the building stone materials, resulting in a destructive influence due to the absorption and evaporation of the moisture that affects their volume and causes cracks leading to the deterioration of the structure[1]. Under these conditions, the stone surfaces disintegrate into powder and the building materials gradually lose their mechanical strength and their artistic form[2-6]. In the case of marbles the main mechanism of deterioration is the sulfation of their surfaces, leading to the formation of gypsum layers on the stone surface, due to the solid state diffusion of Ca^{2+}[7-13]. Various destructive or non-destructive methods are used for the study of the weathering of the building stone materials of the monuments, being part of their conservation[14-16].

The aim of the present work is the study of the deterioration problems of stone monuments of Demeter and Asklepios sanctuaries in Dion archaeological site, one of the most important religious centers of ancient Greeks in central Macedonia. In earlier works[17-18] it was found that the main building materials of the monuments are limestones and conglomerates. Sandstones, marbles and ceramic plinths were also used. The materials consist mainly of calcite and/or dolomite. The surfaces of the building materials are partially covered by the weathering products of the primary minerals such as secondary carbonate (calcite-dolomite) precipitated from water solutions, recrystallized calcite and dolomite and in some cases gypsum. The presence of crusts of various inorganic/organic compounds, such as illite, kaolinite, sericite, rutile, Fe-oxides, Mn-oxides, fluoroapatite, fragments of fossils, is related to various sediments that covered the primary materials. No significant amounts of salts were found on the surface or inside the pore of the materials. The purpose of the investigation is the study of the influence of the water presence to the behavior of the materials by in situ IR thermometer measurements and laboratory measurements of their physical characteristics.

Figure 1: General view of the sanctuaries of a) Asklepios, b) Demeter.

EXPERIMENTAL

For the laboratory experiments, a series of samples of the various building materials were collected from different locations. The accurate sampling sites were previously mentioned and presented[17].

The physical properties of the materials were studied according standard methods[19].

The examination of characteristic pores of the materials was carried out by optical microscopy of thin sections of samples using a Leitz Laborlux 11 POL S microscope.

Ultrasonic velocity is a good index characteristic not only for determining the physico-mechanical behaviour but also for evaluating the weathering degree of the rocks. For this purpose a portable UK1401 ultrasonic tester was used in the present investigation, additionally to a “Pundit Lab ultrasonic tester”. Measurements were applied, indirectly, on the same surface of the stone. The estimation of the mechanical properties is based on the correlation of ultrasonic velocity in material to its physic and mechanical characteristics and physical statement[16,20-22].

Two series of IR thermometer in situ measurements, in conditions of sunny or wet weather, were carried out by a portable infrared laser thermometer (Center 358, Infrared thermometer, Range:-18^o C~ 315^o C). The question was to determine the high of the capillary water at the base of building stones, at the contact with the soil, given that the aquifer is very high, quite near to the foundation level of the monument. The idea was to use an infrared thermometer, because the inside temperature of the wet part of a stone is different than the next dry part, of the same stone, for the same time and weather conditions. The environment temperature during the measurements was ~ 28^o C (sunny conditions) or ~ 9^o C (wet conditions). In this study, infrared thermometer measurements were used in the assessment of moisture in porous stones. Due to the difference between the thermal diffusivities of moist and the dry stones, IR thermometer measurements are capable of showing qualitative variations in respiration behaviour (i.e. moisture impact), appearing as surface temperature fluctuations[23-24]. The in situ measurements were focused in two monuments, Asklepios Temple, Altar in Demeter sanctuary, (Figure 1).

RESULTS

The results of the study of the physical and mechanical properties and characteristic pores of the materials are shown in Tables 1-2 and Fig.2.

Table 1. Physical and mechanical properties of the building materials of Asklepios and Demeter sanctuaries.

Material / Property	Conglo merate	Lime stone calcite	Lime stone dolom	Sand stone calcite	Sand stone dolom	Ceramic Plinth	Marble calcite	Marble dolom
Bulk density, γ (gr/cm^3)	2.56	2.42	2.81	4.04	1.84	1.82	1.99	1.61
Dry bulk density, γ(d) (gr/cm^3)	2.72	2.59	2.84	5.41	1.93	2.78	2.01	1.62
Porosity Open, Pop, %	5.69	6.45	0.99	25.46	4.61	33.67	1.15	0.86
Water absorption, Wab, %	2.24	3.69	0.47	9.31	3.42	18.41	0.98	0.65
Water desorption Wde, %	2.21	3.65	0.44	9.13	3.36	17.05	0.92	0.62
Capillary absorption Cab, %	1.80	3.40	0.43	7.72	2.90	17.00	0.86	0.61
Capillary desorption Cab, %	1.78	3.37	0.41	7.57	2.83	15.69	0.81	0.59
Remained % of capillary absorbed-environmental conditions	1.02	0.89	5.03	1.85	2.61	7.73	5.53	3.21
Remained % of capillary absorbed	0.31	0.37	0.79	1.12	1.85	0.29	2.35	1.14
Ultrasonic velosity, V (m/s)	1229.07	1434.40	1804.00	632.13	674.66	1007.60	1078.00	1069.20
Point load index, Is (MPa)	5.21	5.73	6.76	3.69	3.80	4.65	4.82	4.80
Uniaxial compressive strength, UCS (MPa)	96.06	104.07	118.49	72.78	74.44	87.43	90.17	89.83
Young's modulus E (MPa).10^4	3.15	3.46	4.01	2.25	2.32	2.82	2.92	2.91

Table 2. Pore size Distribution %

Material / Pore size(μm)	Conglo merate	Lime stone, calcite	Lime stone, dolom	Sand stone, calcite	Sand stone, dolom	Ceramic Plinth	Marble, calcite	Marble, dolom

100-200	23.87	30.49	73.17	23.34	49.63	22.28	46.18	71.82
200-300	76.13	20.71	-	53.15	34.70	45.68	18.21	15.48
300-500	-	21.96	21.26	12.11	11.85	12.29	0.76	0.89
500-700	-	11.76	5.05	8.64	3.54	13.68	19.31	8.54
>700	-	15.00	0.52	2.76	0.28	6.07	15.55	3.27

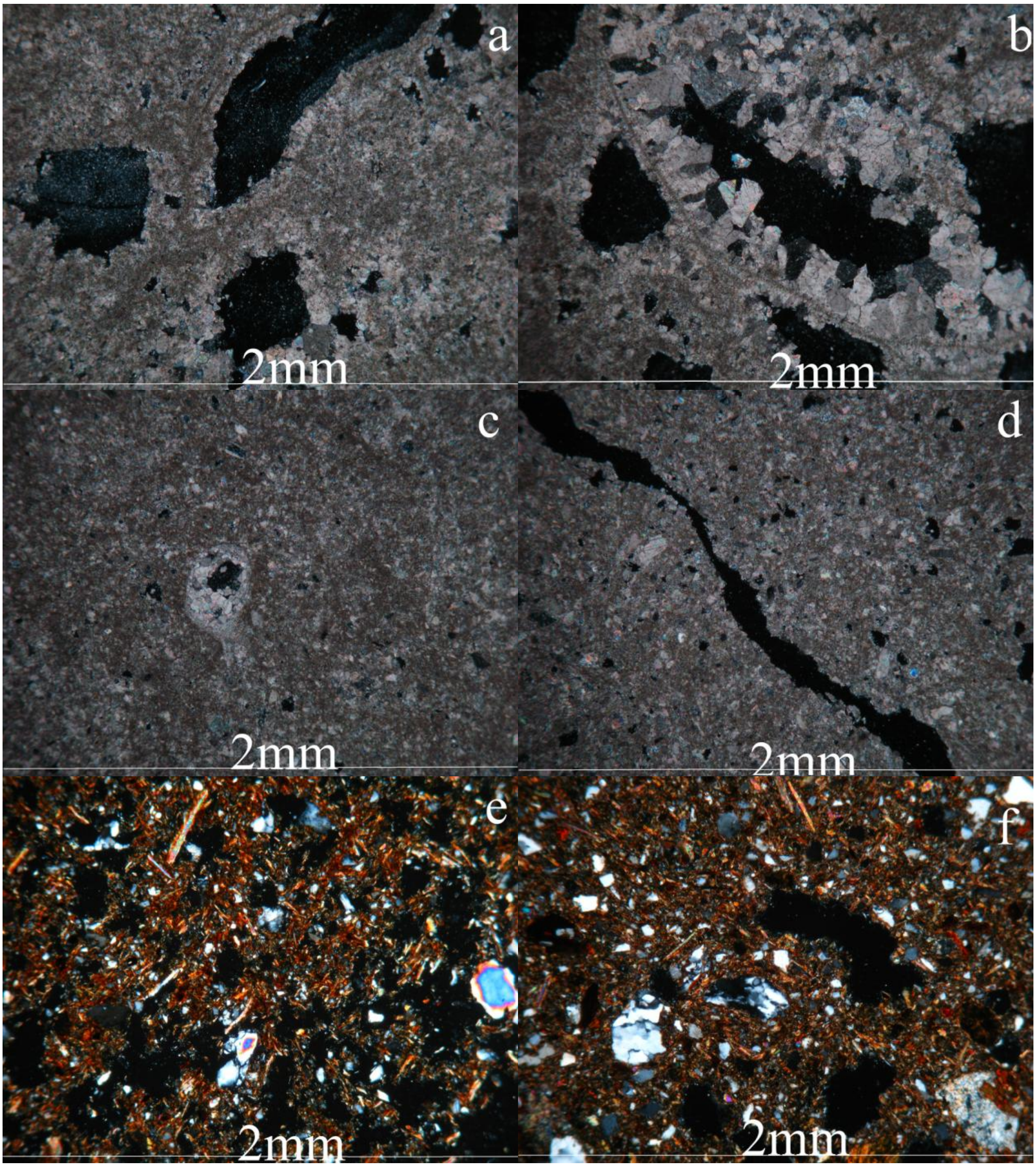

Fig. 2 Photomicrographs of characteristic pores of calcite limestone (a, b,), calcite sandstone (c, d), ceramic plinth (e-f).

The results of the IR thermometer in situ measurements are shown in Figures 3, 4 (sunny conditions) and Figures 5, 6 (wet conditions).

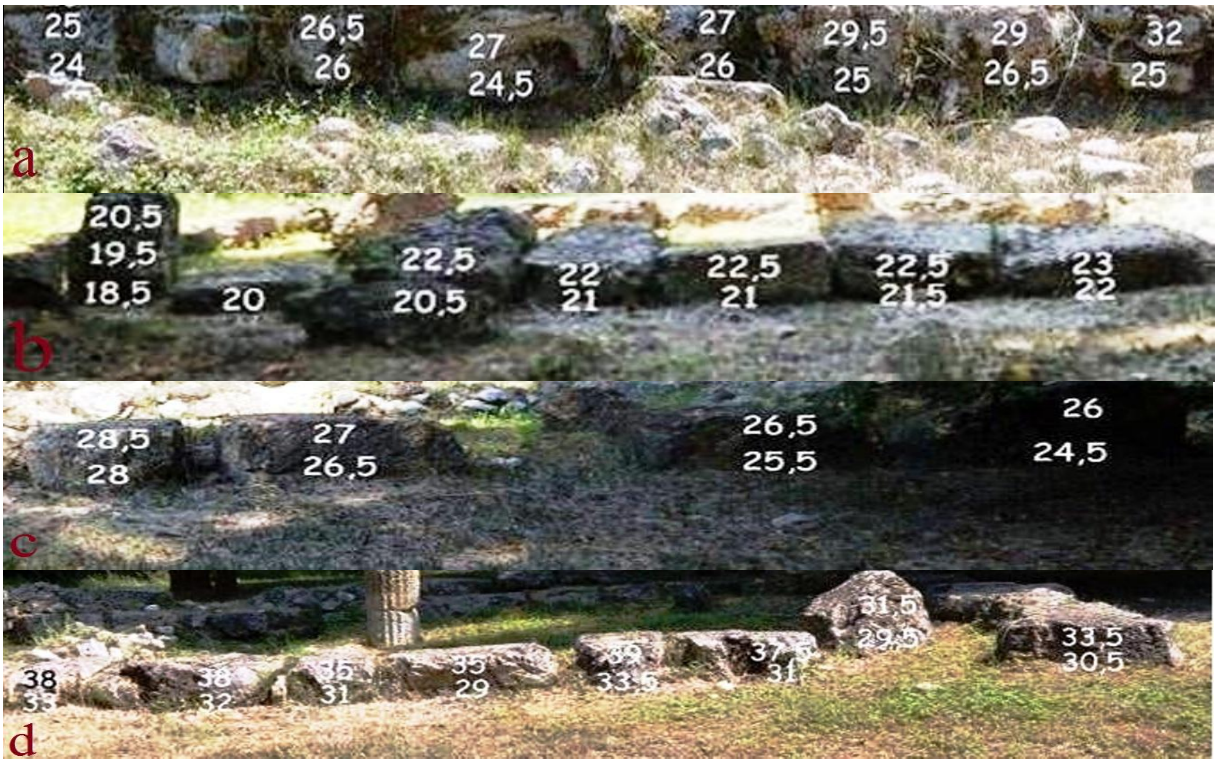

Fig. 3 IR thermometer measurements, sunny conditions, Asklepios temple, a) north side, b) east side, c) south side, d) west side

Fig. 4 IR thermometer measurements, sunny conditions, Demeter sanctuary, Altar, a) north side, b) east side, c) south side, d) west side.

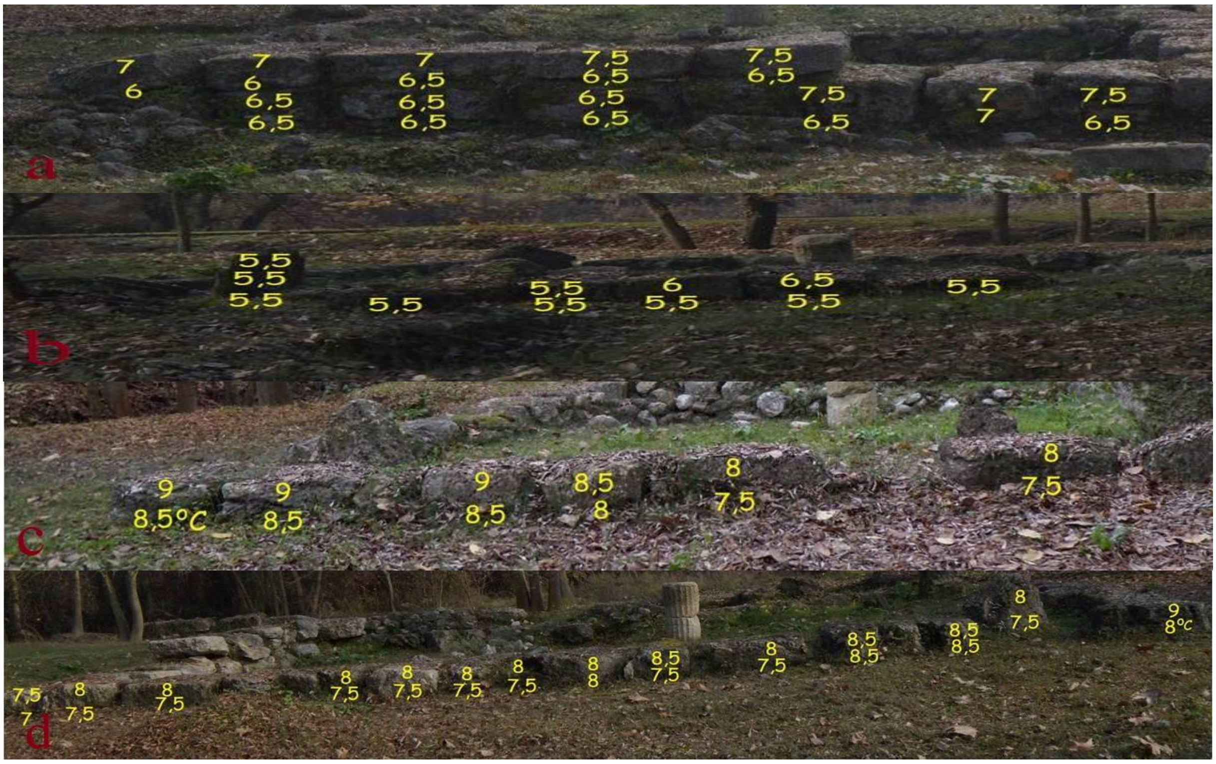

Fig. 5 IR thermometer measurements, wet conditions, Asklepios temple, a) north side, b) east side, c) south side, d) west side

Fig. 6 IR thermometer measurements, wet conditions, Demeter sanctuary, Altar, a) north side, b) east side, c) south side, d) west side.

DISCUSSION

The results of the study of the physical properties of the materials (Table 1, 2 and Fig. 2) show that exist great differences in the values of open porosity, water and capillary absorption between the various building materials. Despite this, it is observed that in all cases of materials the values of capillary absorption are close to the corresponding values of total water absorption indicating that capillary absorption is enough for the materials to reach moisture saturation conditions. It is also shown that a significant amount of the capillary absorbed water remains in the material after desorption in environmental conditions. In the specific conditions of the archaeological area a permanent intensive presence of surface and underground waters for all periods of the year and high temperature values in the dry periods of summer are observed, leading in repeated cycles of wet-dry conditions of the materials. From these results and observations, in correlation with the observed main weathering products, secondary and recrystallized calcite and dolomite, follow that the main deterioration problem of the materials is the moisture presence due to capillary action. The cycles of wet-dry conditions lead to partial dissolution-recrystallization of the carbonate material and loss of the structural cohesion and the surface stability.

The ultrasonic velocity measured values (Table 1) were ≈ 1200-1800 m/s for limestone, ≈ 600-700 for sandstone, ≈ 1000-1100 for marble., indicating the intense weathered state of the materials, the values for non-weathered materials being ≈ 4300 m/s, ≈ 2800 m/s and ≈ 6500 m/s correspondingly.

Since a moist porous material presents emittance variations, moisture detection in porous stones by means of IR thermometer measurements is feasible. IR thermometry monitors the water movement in porous materials and detects its impact by recording temperature variations on the stones' surfaces. The presence of moisture (lower temperatures) that arises as a result of the capillary movement of water causes deterioration of the building material. In such cases, the optical properties are altered, the density, specific heat capacity and thermal conductivity are also affected and so any temperature changes are much slower in a moist area, as the energy required to raise the temperature of a moist area would be much greater than an area that is unaffected by water. In all cases of IR thermometer in situ measurements, the recorded temperatures on the side surfaces of the walls increase with the distance from the ground. The temperature differences depend mainly on the environmental conditions (sunny or wet), also on the kind of the material and the orientation of the wall, being greater in sunny and smaller in wet conditions. The IR thermometer measurements correlated with the water and capillary absorption and desorption results (Table 1) and also the permanent intensive presence of surface and underground waters indicate that the main deteriorating factor of the materials is the moisture penetration due to capillary action. In sunny conditions, moisture penetrates into the materials only by capillary absorption (greater temperature differences, Figs 3, 4), while in wet conditions rain water and environmental humidity contribute also to the total moisture absorption (smaller temperature differences, Figs 5, 6).

CONCLUSIONS

1. From the combination of in situ IR thermometer measurements and laboratory experiments follows safe results about the deterioration problems of the materials.
2. The main weathering factor of the materials is the moisture penetration due to capillary action.

3. In sunny conditions, moisture penetrates into the materials only by capillary absorption, while in wet conditions rain water and environmental humidity contribute also to the total moisture absorption.
4. The existence of water in the bulk of the materials due to capillary penetration correlated with an intensive surface and underground water presence in the whole surrounding area lead to loss of the structural cohesion and the surface instability of the building materials.

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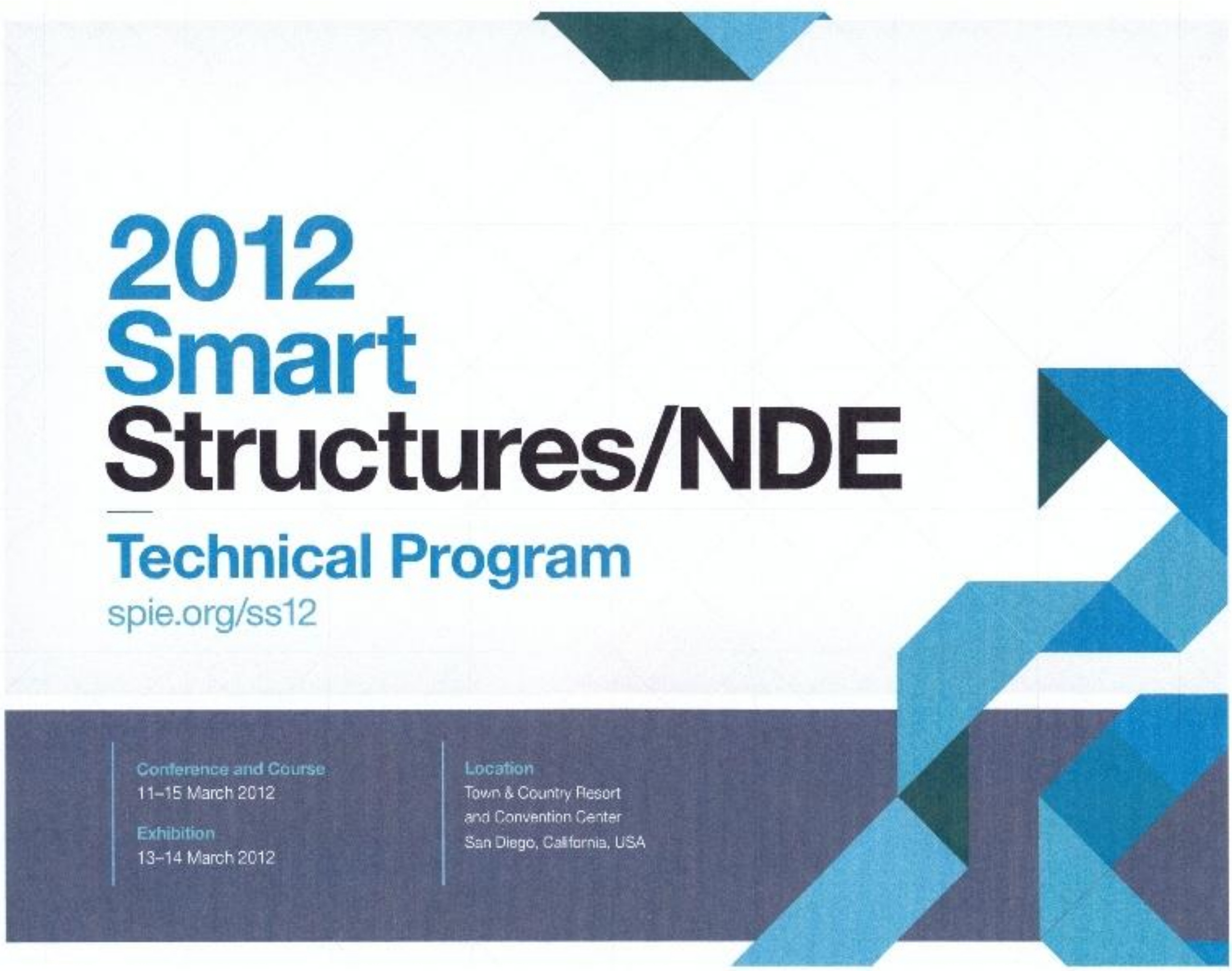

Conference 8345

Concurrent Sessions

SESSION 9a

Room: Pacific Salon IV-V
Wed. 10:50 am to 12:10 pm

Sensing Technologies for Wind Turbines

Session Chairs: **R. Andrew Swartz,** Michigan Technological Univ. (USA); **Francesco Lanza di Scalea,** Univ. of California, San Diego (USA)

10:50 am: **Probabilistic characterization of wind turbine demand envelopes for operational structural integrity assessment,** Antonio Velazquez Hernandez, Raymond A. Swartz, Michigan Technological Univ. (USA) .... [8345-55]

11:10 am: **Localization and quantitative depth estimation of defects in wind turbine blades using infrared thermography,** Arun Manohar, Jeffery D. Tippmann, Francesco Lanza di Scalea, Univ. of California, San Diego (USA) .... [8345-56]

11:30 am: **Deflection calculation of a composite wind turbine blade using finite difference method from measured strain,** Il-Bum Kwon, Ki-Sun Choi, Yong-Hak Huh, Dong-Jin Yoon, Korea Research Institute of Standards and Science (Korea, Republic of) .... [8345-57]

11:50 am: **Wind turbine inspection tests at UCSD,** Jeffery D. Tippmann, Arun Manohar, Francesco Lanza di Scalea, Univ. of California, San Diego (USA) .... [8345-58]

Lunch/Exhibition Break ...12:10 to 1:40 pm

SESSION 9b

Room: Pacific Salon VI-VII
Wed. 10:50 am to 12:10 pm

Nano-engineered Sensors for SHM

Session Chairs: **Fuh-Gwo Yuan,** North Carolina State Univ. (USA); **Ming Wang,** Northeastern Univ. (USA)

10:50 am: * **Ultra-fast nano-oscillators based on carbon nanoscrolls for nano-scale energy harvesting and storage,** Zhao Zhang, Teng Li, Univ. of Maryland, College Park (USA) .... [8345-59]

11:10 am: **Smart photonic coating as a new visualization technique of strain deformation of metal plates,** Hiroshi Fudouzi, Tsutomu Sawada, National Institute for Materials Science (Japan); Yoshikazu Tanaka, Ichiro Ario, Hiroshima Univ. (Japan); Tsuyoshi Hyakutake, Naru Nishizaki, Public Works Research Institute (Japan) .. [8345-60]

11:30 am: **Wireless sensor array based on DNA decorated single-walled carbon nanotubes for gas monitoring,** Yu Liu, Yi Zhang, Mehmet R. Dokmeci, Ming Wang, Northeastern Univ. (USA) .... [8345-61]

11:50 am: * **Strain gradient monitoring using a $Ba_{0.67}Sr_{0.33}TiO_3$ flexoelectric sensor,** Wenbin Huang, Fuh-Gwo Yuan, Xiaoning Jiang, North Carolina State Univ. (USA) .... [8345-62]

Lunch/Exhibition Break ...12:10 to 1:40 pm

* Indicates paper that will also be presented in the NSF Poster Session, p. 33.

Conference 8346

SESSION 9

Room: Royal Palm IV
Wed. 10:50 to 11:50 am

Application of Sensors to Monuments of Cultural Heritage

Session Chair: **Antonia Moropoulou,** National Technical Univ. of Athens (Greece)

10:50 am: **Application of non-destructive techniques to assess the state of Hagia Sophia's mosaics,** Antonia Moropoulou, Asterios Karagiannis-Bakolas, Kyriakos C. Labropoulos, Nikolaos K. Katsiotis, Maria Karoglou, Ekaterini T. Delegou, National Technical Univ. of Athens (Greece) [8346-33]

11:10 am: **Investigation of the contribution possibilities of non-destructive methods of testing for the diagnosis and quality control of building materials with emphasis given on sustainable construction,** Nikolaos S. Katsiotis, National Technical Univ. of Athens (Greece); Theodoros E. Matikas, Univ. of Ioannina (Greece); Antonia Moropoulou, National Technical Univ. of Athens (Greece) .... [8346-34]

11:30 am: **Application of infrared thermometry and ultrasonic velocity for the investigation of the building materials of historic monuments of Dion, Greece,** Panagiotis Spathis, Aristotle Univ. of Thessaloniki (Greece) .... [8346-36]

Lunch/Exhibition Break 11:50 am to 1:20 pm

Conference 8347

Concurrent Sessions

SESSION 7a

Room: Royal Palm V
Wed. 10:50 am to 12:10 pm

Ultrasonic Technologies for NDE/SHM I

Session Chairs: **Xiaoning Jiang,** North Carolina State Univ. (USA); **Anthony D. Cinson,** Pacific Northwest National Lab. (USA)

10:50 am: **Obtaining more information from time-of-flight-diffraction measurements,** Stuart B. Palmer, Steve Dixon, Phil Petcher, The Univ. of Warwick (United Kingdom) .... [8347-35]

11:10 am: **A multipoint ultrasonic detection approach to fretting crack detection in an aircraft component,** Zhigang Sun, Kuo-Ting Wu, Cheng-Kuei Jen, Alain Blouin, National Research Council Canada (Canada); Nezih Mrad, Defence Research and Development Canada, Ottawa (Canada); Hugo Bélanger, L-3 MAS (Canada) .... [8347-36]

11:30 am: **Waterless coupling of ultrasound from planar contact transducers to curved and irregular surfaces during non-destructive ultrasonic evaluations,** Kayte M. Denslow, Aaron A. Diaz, Mark Jones, Ryan M. Meyer, Anthony D. Cinson, Mondell Wells, Pacific Northwest National Lab. (USA) .... [8347-37]

11:50 am: **Acoustic emission based monitoring of surfaces subjected to friction,** Kassahun M. Asamene, Mannur Sundaresan, North Carolina A&T State Univ. (USA) .... [8347-38]

Lunch/Exhibition Break ...12:10 to 1:40 pm

SESSION 7b

Room: Sunset
Wed. 10:50 am to 12:10 pm

Imaging-based NDE/SHM of Civil Infrastructure II

Session Chairs: **Shen-En Chen,** The Univ. of North Carolina at Charlotte (USA); **Lingyu Yu,** Univ. of South Carolina (USA)

10:50 am: **Scanning array radar system for bridge subsurface imaging,** Chieh-Ping Lai, Yu-Jiun Ren, LR Technologies, Inc. (USA); Tzu Yang Yu, Univ. of Massachusetts Lowell (USA) .... [8347-39]

11:10 am: **Highway speed ground penetrating radar system developments,** Dryver R. Huston, Tian Xia, Anbu Venkatachalam, Xianlei Xu, The Univ. of Vermont (USA) .... [8347-40]

11:30 am: **Extended defect diagnosis using time-reversal tomography technique,** Shuntao Liu, Fuh-Gwo Yuan, North Carolina State Univ. (USA) .... [8347-41]

11:50 am: **Civil infrastructure damage detection and condition monitoring with digital image correlation photogrammetry,** Timothy E. Schmidt, John Tyson, Trilion Quality Systems (USA); Christopher Niezrecki, Peter Avitabile, Univ. of Massachusetts Lowell (USA) .... [8347-42]

Lunch/Exhibition Break ...12:10 to 1:40 pm

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Contents

8346-34, Session 9

Investigation of the contribution possibilities of non-destructive methods of testing for the diagnosis and quality control of building materials with emphasis given on sustainable construction

N. S. Katsiotis, National Technical Univ. of Athens (Greece); T. E. Matikas, Univ. of Ioannina (Greece); A. Moropoulou, National Technical Univ. of Athens (Greece)

In this work, the contribution potential of non-destructive methods of testing is studied in order to assess, diagnose and assert building materials' diagnosis & quality control, with emphasis given on sustainable construction.

To this end, the following techniques are implemented: fiber-optics microscopy, digital image processing, scanning electron microscopy, pulse/lock-in thermography, acoustic emission as well as ultrasounds.

Furthermore, in addition to the above, the maturity method for measurement of compressive strength is applied and correlated to the array of full field non-destructive methods of testing.

The results of the study clearly demonstrate how effective non-destructive methods of testing can be, in revealing and determining highly applicable & reliable data in a real-time, in situ and efficient manner.

8346-35, Session 9

Application of infrared thermometry and ultrasonic velocity for the investigation of the building materials of historic monuments of Dion, Greece

P. Spathis, Aristotle Univ. of Thessaloniki (Greece)

The sanctuaries of Demeter and Asklepios are part of the Dion archaeological site that sits among the eastern foothills of Mount Olympus and covers roughly 100 hectares. The excavations finds from this area are dated since the Hellenistic, Roman and Early Christian times. The main building materials are limestones and conglomerates, Travertines, marbles, sandstones and ceramic plinths were also used. The materials consist mainly of calcite and/or dolomite, whereas the deteriorated surfaces contain also gypsum, recrystallized calcite and dolomite, various inorganic compounds, fluoroapatite, microorganisms and other organic compounds. Cracks and holes were observed in various parts of the stones.

The most proper approach to select effective methods for the structural and surface consolidation, the cleaning, the protection and the overall conservation of these structures is the knowledge of the processes contributing to their deterioration.

The influence of the water presence to the behavior of the materials was examined by in situ IR thermometer measurements. Temperature values increased from the lower to the upper parts of the building stones and they significantly depend on the orientation of the walls. The results indicate the existence of water in the bulk of the materials due to capillary penetration as it is observed an intensive surface and underground water presence in the whole surrounding area. To confirm these observations measurements of porosity, capillary rise, water and water vapor permeability were realized. These conditions led to loss of the structural cohesion and the surface stability of the material.

Stone consolidation treatments were applied to restore the cohesion of the weathered stones. The consolidation materials used were Rhodorsil RC 70 (Ethyl Silicate) and Rhodorsil RC 70 with Hombicat UV 100 or P25 Degussa (Titanium oxides). Non-destructive testing (IR thermometry and ultrasonic velocity) and evaluation was performed in order to assess the effectiveness of the consolidation, which was found to depend on the building material and the consolidation material used.

8346-36, Session 10

Critical and subcritical damage monitoring of bonded composite repairs using innovative non-destructive techniques

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Infrared Thermography (IrT) has been shown to be capable of detecting and monitoring service induced damage of repair composite structures. Full-field imaging along with portability are the primary benefits of the thermographic technique. Pulsed, pulsed phase and lock-in techniques are subsequently employed increasing the resolution of the system ensuring smaller defect as well as higher depth discrimination. In the case of loaded structures, on-line lock-in thermography may be performed in order to monitor damage propagation or/and concentration in the composite structure. Mechanical stresses in structures induce heat concentration phenomena around flaws. This gives the opportunity of critical and subcritical damage identification and monitoring during fatigue, as long as cycle loading plays the role of the heating source. At the same time, the Electrical Resistance Change Technique (ERCT) may be used as an innovative method for damage identification and monitoring. The measurement of electrical resistance changes of Carbon Fiber Reinforced Polymers (CFRPs) under load enables the monitoring of strain and damage accumulation. Along with the aforementioned techniques Acoustic Emission (AE) method is used in order to provide more information about the critical and subcritical damage. Damage accumulation due to cyclic loading imposes differentiation of certain parameters of AE like duration and energy. Within the scope of this study, infrared thermography is employed along with AE and ERCT methods in other to assess the bonded repair integrity and to monitor critical and subcritical damage induced by the mechanical loading. The combined methodologies were effective in order to identifying damage initiation and propagation of bonded composite repair.

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Environmental barrier coating (EBC) durability modeling using a progressive failure analysis approach

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Ceramic matrix composites (CMCs) are getting the attention of most engine manufacturers and aerospace firms for turbine engine and other related applications. This is because of their potential weight advantage and performance benefits. As a protecting guard for these materials, a highly specialized form of environmental barrier coating (EBC) is being developed and explored in particular for high temperature applications that is greater than 1100 °C [1, 2]. The EBCs are typically a multilayer of coatings and are in the order of hundreds of microns thick. CMCs are generally porous material and this feature is somewhat beneficial since it allows some desirable infiltration. Their degradation usually includes coating interface oxidation as opposed to moisture induced matrix which is generally seen at a higher temperature. Variety of factors such as residual stresses, coating process related flaws, casting conditions, may influence the strength of degradation. The cause of such defects which cause cracking and other damage is that not much energy is absorbed during fracture of these materials. Therefore, an understanding of the issues that control crack deflection and propagation along interfaces is needed to maximize the energy dissipation capabilities of layered ceramics.

Thus, evaluating components and subcomponents made out of CMCs under gas turbine engine conditions is suggested to demonstrate that these material will perform as expected and required under these aggressive environmental circumstances. Progressive failure analysis (PFA) is being performed to assess the crack growth of the coating