THE USE OF ICT FOR MONITORING THE HYGROTHERMAL BEHAVIOUR OF BUILDING STRUCTURES

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ABSTRACT

Temperature and moisture are two of the main factors in physical, chemical and biological deterioration of building materials. The continuous monitoring of temperature and relative humidity provides valuable information about the long-term performance and deterioration of building structures. Documenting performance through monitoring can greatly enhance the understanding of the long-term degradation of building materials and the deterioration of the constructions due aging.
The aim of this study is to develop a computerized monitoring system for building structures. The study is focused on concrete building structures and consists of laboratory work and field measurements. The laboratory work focuses on designing a monitoring network system, and developing a monitoring software application. The field measurements are carried out by monitoring the temperature and relative humidity of a repaired concrete facade.
The deliverables of the study will consist of two applications: (i) collecting of the moisture and thermal monitoring data and (ii) assessing the performance of building structures based on the acquired information. The results of the research will provide feasible methodologies and systems for monitoring and assessing the performance of building constructions, thus improving the quality of the building constructions. The scientific relevance of this research will be the improved correspondence between laboratory studies and observations of deterioration in practice.

Keywords: thermal, moisture, monitoring, assessment, building materials, sensor technology.

1. INTRODUCTION

Moisture originated damage in concrete building structures can be divided into three types of deterioration processes: chemical, physical, and biological. Examples of chemical deterioration processes are the alkali-silica reactions in concrete, reinforcement corrosion in concrete due to carbonation or chloride attack, the dissolution and leaching of calcium in concrete. Examples of physical deterioration processes are frost damage, damage due to restrained hygrothermal retraction/shrinkage and expansion/swelling, and deterioration due to expansive salt crystallization and hydration. Examples of the biological deterioration processes are mold, fungi, algae, moss, plant growth, and rot in organic materials. Biological, chemical, and physical deterioration processes may lead to mechanical and structural degradation in the form of loss of stiffness, excessive deformation, cracking, delamination, spalling, and, in severe cases, to structural failure. (Huovinen 1998; Carmeliet 2009)

According to Norris (2008), the current methods for temperature and internal relative humidity evaluation, which rely on destructive testing systems, are expensive and time consuming. In addition, these techniques require intensive labor and special equipment to gain access to remote locations. Handheld moisture meters are usually used in spot checks measurements to assess changes in the moisture content of the building components or to determine surface wetting patterns in order to determine sources and extent of wetness. For long-term monitoring of thermal and moisture conditions, data acquisition systems are usually used. A data acquisition system consists of a collection of temperature and humidity sensors and data loggers that are used for collecting the monitoring data for further processing and archiving (Lindblom-Patkus 2007).

Lynch (2002), introduced a clear need for a practical and economical method for monitoring the performance of building structures throughout their life time. Therefore, a sensor system for continuous monitoring of internal relative humidity and temperature is highly desirable both during construction and afterwards (Norris 2008). When a concrete structure is in service, continuous monitoring of temperature and internal humidity will provide information about the damage process of the concrete structure due to environmental effects such as freeze/thaw cycles, chloride diffusion, alkali-silica reaction, carbonation and dimensional changes caused by temperature changes.

An objective of the research was to test new possibilities offered by the ICT (Information and Communication Technology) to be used in the real estate and construction sector. For that purpose, a new RHT (Relative Humidity and Temperature) monitoring network system was developed. The laboratory work of the research focused on designing and testing the RHT monitoring network system including the calibration of the temperature and relative humidity devices. RHT monitoring software for configuring the network system and collecting data was developed. A field study for testing the RHT monitoring network system was carried out with on a repaired concrete facade. The facade was repaired by adding external mineral wool insulation and a rendering system. The thermal and moisture condition was monitored at regular intervals of 15 minutes since the year 2005.

The thermal and moisture RHT monitoring network system is useful for assessing the performance of building structures. Documenting the performance of building structures through monitoring can enhance the understanding of the long term deterioration of the building materials and the changes in the structural behaviour due aging.

2. RHT MONITORING NETWORK SYSTEM

One goal of the research was to develop a thermal and moisture monitoring method to observe the moisture and thermal performance of the repaired sandwich panel building facades. For that purpose, the RHT monitoring network system and RHT monitoring software were developed to gather and analyze the thermal and moisture data.

RHT monitoring network system overview

The RHT monitoring network system was built on Linet Light Network (Linet Oy Ltd.4 2007). The RHT monitoring network system consists of a controller (LIC04) and nodes where relative humidity and temperature sensors are connected to. The controller provides configuration services and enables communication with the data acquisition system. The network system may contain up to 200 nodes connected to a twisted-pair CAT5 cable with a maximum total length of 1000 meters. A schematic diagram of the RHT monitoring network system is illustrated in figure 1.

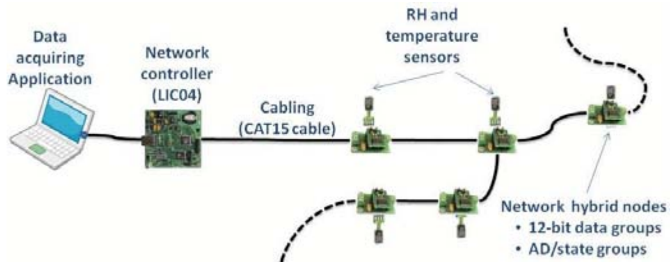

Figure 1. Schematic diagram of the RHT monitoring network system

As shown in Table 1, three different types of sensors were selected to be connected to the RHT monitoring network nodes for measuring temperature and relative humidity: PT100 sensors for temperature, and HMP44 and SHT15 sensors for relative humidity. The choice of HMP44 and PT100 sensors was based on their stability and accuracy, and for authors long experience using these sensors. SHT15 sensors were selected based on their low price and compatibility with the network nodes. The calibration of the relative humidity sensors was confirmed by the manufacturers.

Table 1 Relative humidity and temperature sensors used in the RHT monitoring network system

Sensor	**Manufacturer**	**Output data**	**Data group type**	**Accuracy**	**Price(2)**
HMP 44	Vaisala Oy, Finland	RH (%)	AD(1) / state	±2% (0 - 90 % RH) ±3% (90 - 100 % RH)	200€
SHT15	Sensirion AG Switzerland	RH (%) and T (°C)	12 bit data	±2% (0 - 90 % RH) ±2 - 4% (90 - 100 % RH) ±0.3°C	35€
PT100		T (°C)	AD / state	± (0.15 + 0.002 x t) °C	8€

(1) AD = Analogue / Digital
(2) Prices according to the year 2007

RHT monitoring software

The RHT monitoring software communicates between the host computer and the RHT monitoring network system controller, collects relative humidity and temperature data, and processes the collected data. The RHT monitoring software consists of four basic modules:

1) a system configuration module,
2) a Telnet simulation module,
3) a RHT calculation and output module, and
4) a data processing module.

The flow chart of the RHT monitoring software modules is shown in figure 2.

The system configuration module contains two parts: the configuration of the monitored target cross-section and the configuration of the sensors and nodes of the RHT monitoring network system as shown in Figure 3.

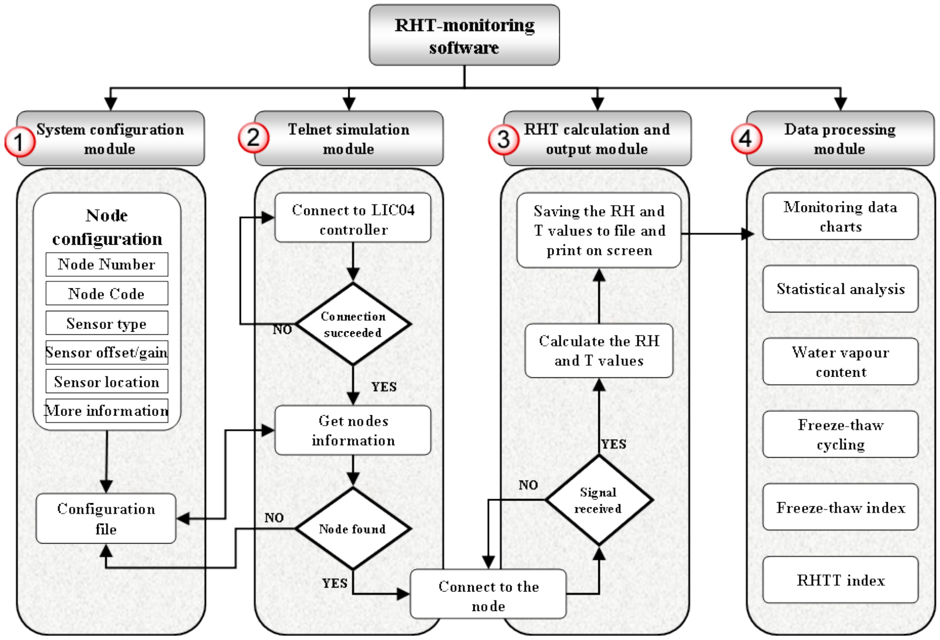

Figure 2. Flow chart of RHT monitoring software

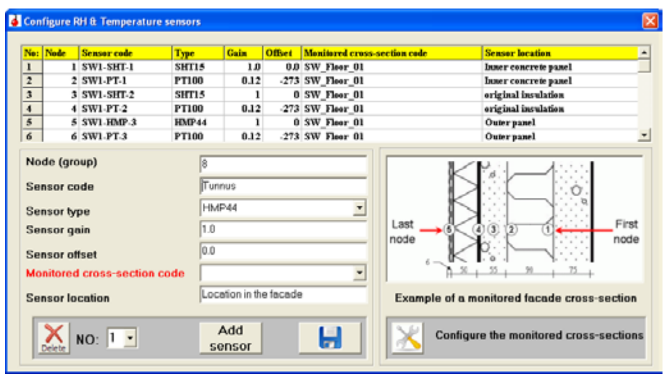

Figure 3. Configuration of the sensors and nodes of RHT monitoring network system

The Telnet simulation module is used in communication with the LIC04 controller of the RHT monitoring network system. The user inputs information about the controller IP address (Internet Protocol address) and the communication port between the LIC04 controller and the host computer, and then the Telnet terminal sends and receives data continuously from the LIC04 controller. The RHT calculation and output module gets the node and sensor information from the system configuration module, then calculates the values of temperature and relative humidity taking, in consideration the offset and gain of every sensor. Results are displayed on the screen and saved in an ASCII file. The graphical user interface of the RHT calculation and output module is shown in Figure 4.

The data processing module processes the temperature and relative humidity monitoring data. The data processing module was developed using Visual Basic for Applications under Microsoft Excel. The flow chart of the data processing module is shown in Figure 5.

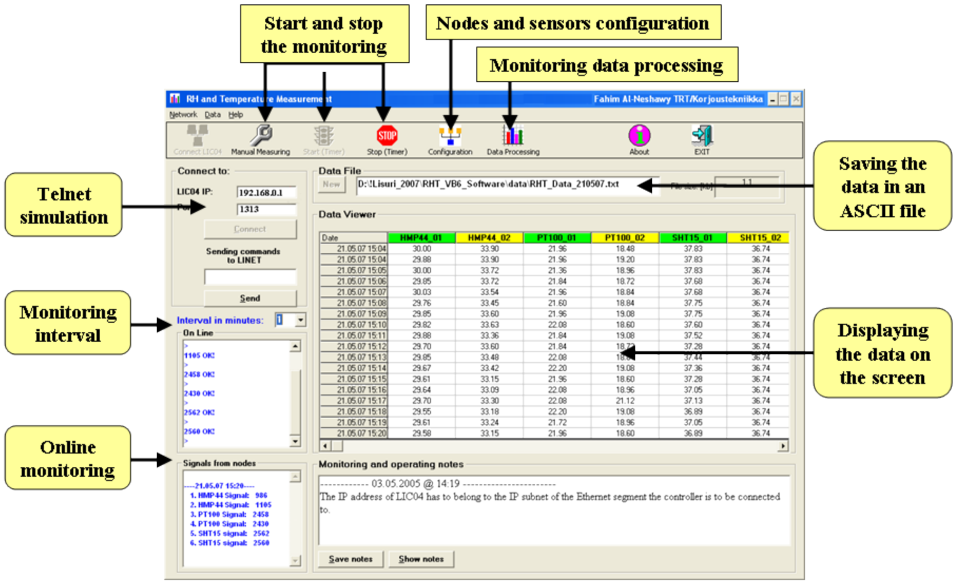

Figure 4. The graphical user interface of the Telnet simulation, the RHT calculation and the output module

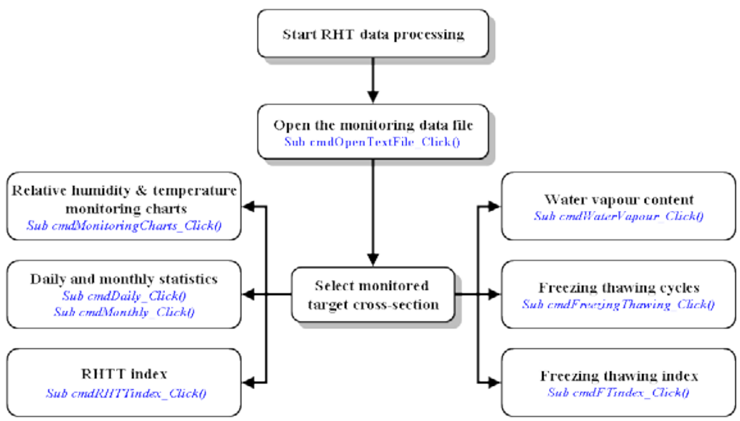

Figure 5. The flow chart of the data processing module

3. USING THE RHT MONITORING NETWORK SYSTEM IN FIELD RESEARCH

For testing the developed RHT monitoring network system, field research was carried out to monitor the relative humidity and temperature of a repaired concrete facade. The building, shown in Figure 6, is a four-storey apartment building built with concrete sandwich elements. The concrete facade was repaired by adding 70 mm external mineral wool insulation and 6 mm rendering system. The monitoring system was installed in the facades facing northeast and southwest. The nodes and sensors were installed on the second and on the fourth floor of the building. The sensors were installed through the cross-sections of the facades as shown in Figure 6. The thermal and moisture condition was monitored at a regular interval of 15 minutes to register the rapid change, especially in the rendering system.

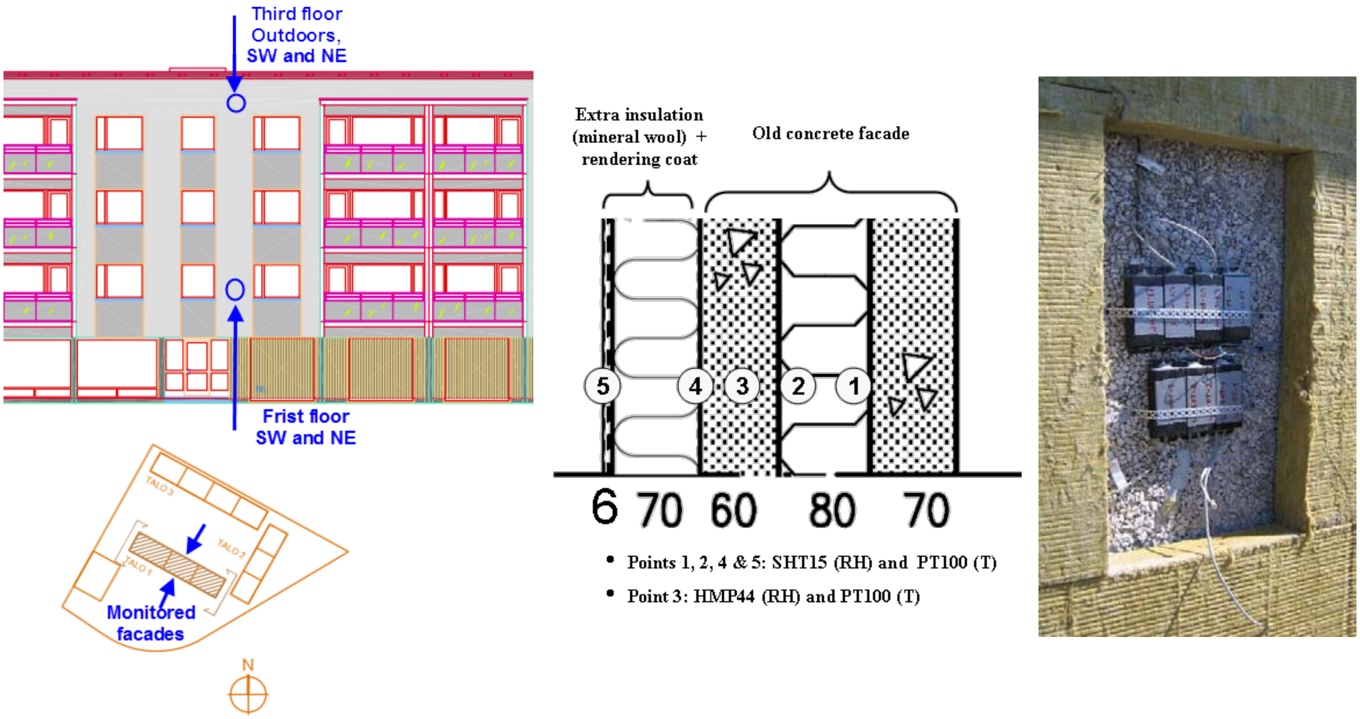

Figure 6. The repaired facade of the monitored building, and the location of the installed temperature and relative humidity sensors.

4. RESULTS OF THE FIELD MEASUREMENTS

The temperature and relative humidity monitoring data process, shown in Figure 7, cover the ambient outdoors conditions, the structure response to the outdoors conditions and the potential of the deteriorations due to the temperature and relative humidity change. Examples of the temperature and relative humidity monitoring results are presented from the year 2005 to the beginning of the year 2010.

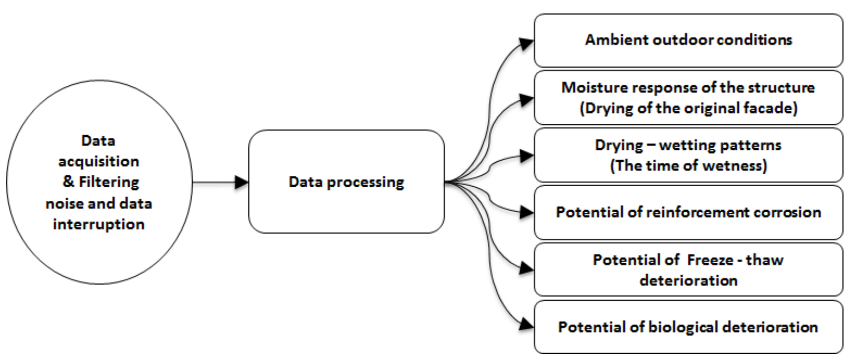

Figure 7. The process of the temperature and relative humidity data analysis.

Ambient outdoor condition

The temperature and relative humidity of the outdoor ambient air was also monitored at the northeast and southwest cardinal directions on the third floor. The daily average relative humidity and temperature of the northeast outdoor environment are shown in Figure 8.

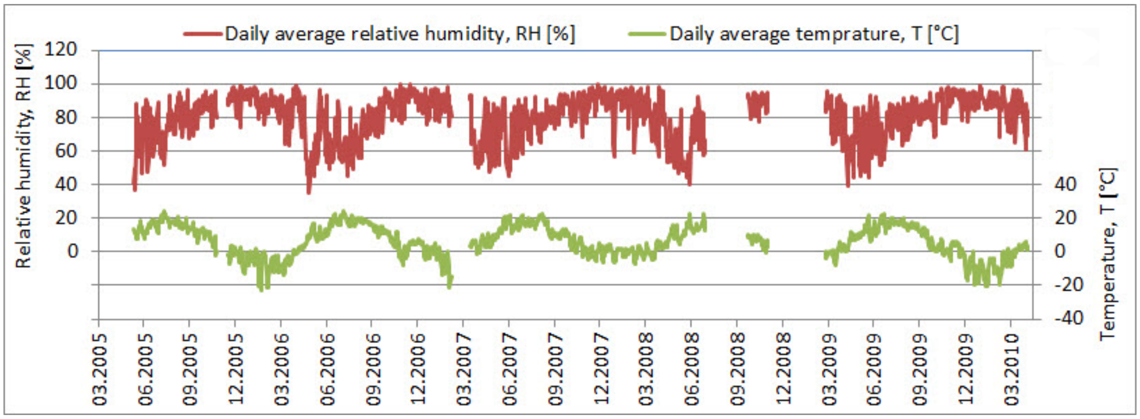

Figure 8. Outdoors relative humidity and temperature during the May 2005 and May 2010.

The maximum temperature of the outdoor ambient air was during July yearly and the minimum temperature of the outdoors was during February.

The time of wetness

The time of wetness, or TOW, is defined as the time of the month when the relative humidity is above 80% and the temperature is above the freezing point as shown in Equation 1. (Mukhopadhyaya et al., 2005).

$$TOW_{(i)} = \left(\sum_{h=i}^{k} t_{counter(i,h)} \right) \tag{1}$$

where:

i	is a spatial index for the considered part of the structure
$t_{counter(i,h)}$	is the time of wetness, h

$$t_{counter(i,h)} \begin{cases} = 1, \text{ if } T_{(i,h)} \geq 0°C \text{ and } RH_{(i,h)} \geq 80\% \\ = 0, \text{ if } T_{(i,h)} < 0°C \text{ and } RH_{(i,h)} < 80\% \end{cases}$$

$T_{(i,h)}$	is the temperature of the considered part of the structure, °C
$RH_{(i,h)}$	is the relative humidity of the considered part of the structure, %
k	is the total sum of hours in a particular month.

The time of wetness of the rendering coat of the repaired facade during the year 2005 to 2010 are shown in Figure 9.

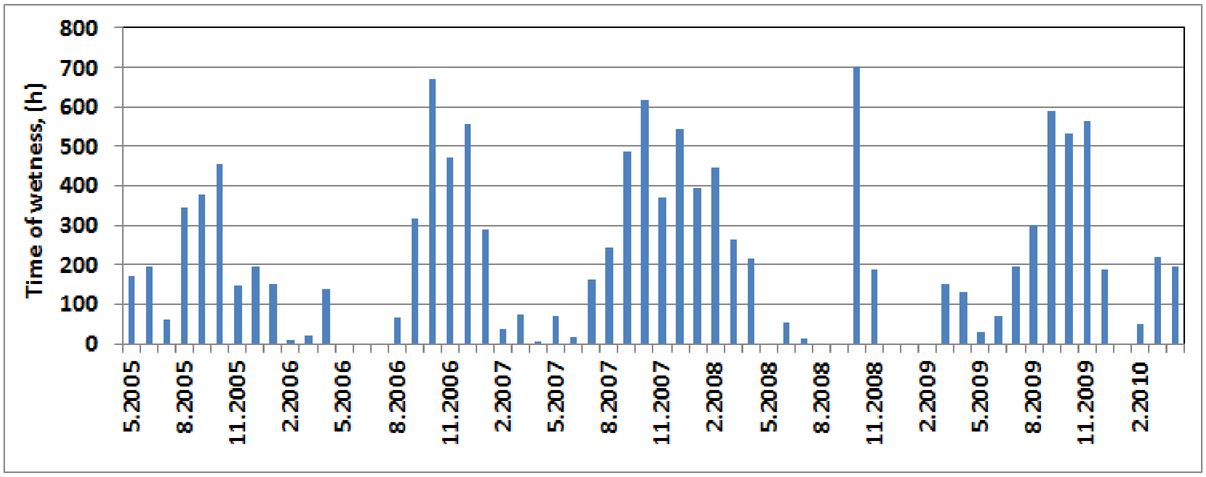

Figure 9. The monthly time of wetness of the rendering coat of the repaired facade.

The time of wetness is used for calculating the potential of the facade deterioration. The results show that the potential of deterioration is higher in the period between August and March yearly.

Drying of the original facade

Figure 10 shows the drying effect of the original outer panel of the sandwich panel under the external wall insulation and rendering systems. The average daily relative humidity of the outer concrete panel dropped from 83% to 44 % within the first year. During the year 2006 and 2010, the daily average relative humidity varies between 40% and 60%. The temperature of the original outer concrete panel was above 0 °C. These results indicate the protection of the original concrete facade against the reinforcement corrosion and frost action after adding the external insulation and rendering system.

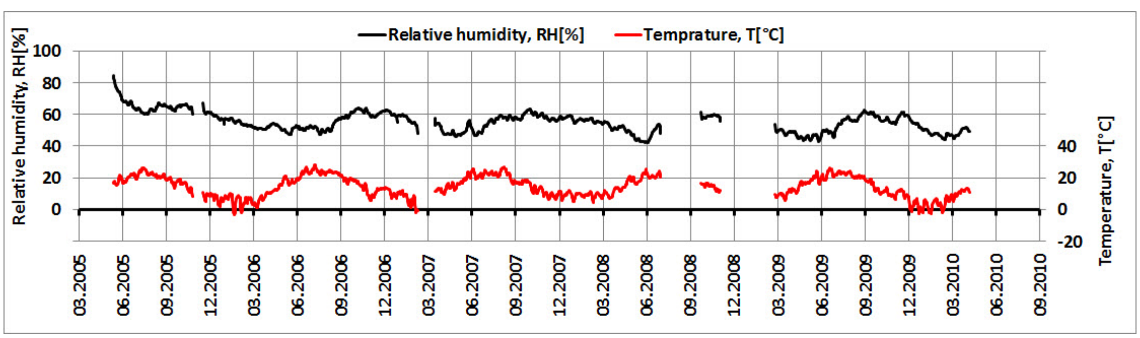

Figure 10. The daily average temperature and relative humidity of the original outer concrete panel of the repaired facade.

Time-dependent relative humidity and temperature RHTT index

According to Mukhopadhyaya et al. (2005), the RHTT index is defined as the potential for any moisture damage when sustained high moisture levels and warm temperatures occur simultaneously for an extended period of time. As shown in Equation 2, the RHTT index is defined as the product of the time-of-wetness (TOW) factor and the intensity of hygrothermal loading level in the structure by which the critical conditions are exceeded (RHT). The degree of moisture damage due to any of degradation mechanisms is directly proportional to the time-of-wetness (TOW) factor.

$$RHTT_{(i)} = TOW_{(i)} \times RHT_{(i)} \qquad (2)$$

where:

i	is a spatial index for the considered part of the structure
$TOW_{(i)}$	is the calculated time of wetness within the considered part of the structure, (h)
$RHT_{(i)}$	is the calculated RHT index within the considered part of the structure

The long-term moisture response indicator RHT index is calculated by multiplying the temperature ($T_{potential}$) and moisture ($RH_{potential}$), for moisture damage as shown in Equation 3.

$$RHT_{(i)} = \sum_{h=1}^{k} T_{potential\,(i,h)} \times RH_{potential\,(i,h)} \qquad (3)$$

where:

$T_{potential}$ is the potential temperature for moisture damage, °C

$$T_{potential(i,h)} \begin{cases} = T_{(i,h)} - T_{critical}, & \text{if } T_{(i,h)} > T_{critical} \\ = 0, & \text{if } T_{(i,h)} \leq T_{critical} \end{cases}$$

$RH_{potential}$ is the potential relative humidity for moisture damage, %

$$RH_{potential(i,h)} \begin{cases} = RH_{(i,h)} - RH_{critical}, & \text{if } RH_{(i,h)} > RH_{critical} \\ = 0, & \text{if } RH_{(i,h)} \leq RH_{critical} \end{cases}$$

$T_{critical}$ is the user-defined critical threshold value of temperature level above which moisture damage is more likely to occur, °C

$RH_{critical}$ is the user-defined critical threshold value of relative humidity level above which moisture damage is more likely to occur, %

In this paper, RHTT1 and RHTT2 indices were calculated. The RHTT1 indicate the potential of biological deterioration, where the critical relative humidity is greater than 80% and the critical temperature in greater than 5 °C. The RHTT2 indicate the potential of reinforcement corrosion, where the critical relative humidity is greater than 80% and the critical temperature in greater than 0 °C. The calculated values of the RHTT1 and the RHTT2 indices for the rendering coat of the repaired facade are shown in Figure 11. The values of the RHTT1 and RHTT2 indices indicate low biological and corrosion damage potential due to thermal and moisture loading in the rendering coat. Although acceptable values for RHTT indices for various building materials are not available at this moment , the important feature of the RHTT index is that the higher RHTT index values indicate an increased severity of the hydrothermal response and higher damage potential.

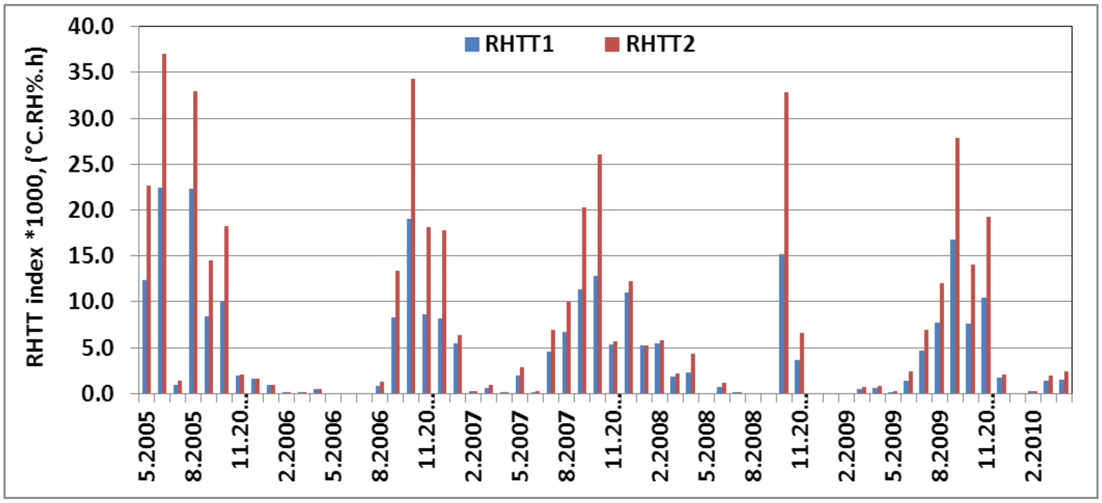

Figure 11. The values of the RHTT1, the RHTT2 indices for the rendering coat of the repaired facade.

Freezing thawing index

The freezing thawing index (FT) is defined as the number of freezing or thawing oscillations when temperature oscillate around 0°C for those structures that are almost at the moisture saturation level, $RH_{critical}$ (Mukhopadhyaya et al., 2005). According to Fagerlund, 2001, the critical moisture saturation level for concrete structures varies between 75% and 90%. The FT index is defined in Equation 4.

$$FT_{(i)} = \sum_{h=2}^{k} Counter_{(i,h)} \tag{4}$$

where:

$Counter_{(i,h)}$ is a freezing or thawing oscillator when temperatures oscillate around 0°C

$$Counter_{(i,h)} \begin{cases} = 1, \text{ if } T_{(i,h)} * T_{(i,h-1)} < 0 \text{ and } RH_{(i,h)} \geq RH_{critical} \\ = 0, \text{ if } T_{(i,h)} * T_{(i,h-1)} \geq 0 \text{ and } RH_{(i,h)} < RH_{critical} \end{cases}$$

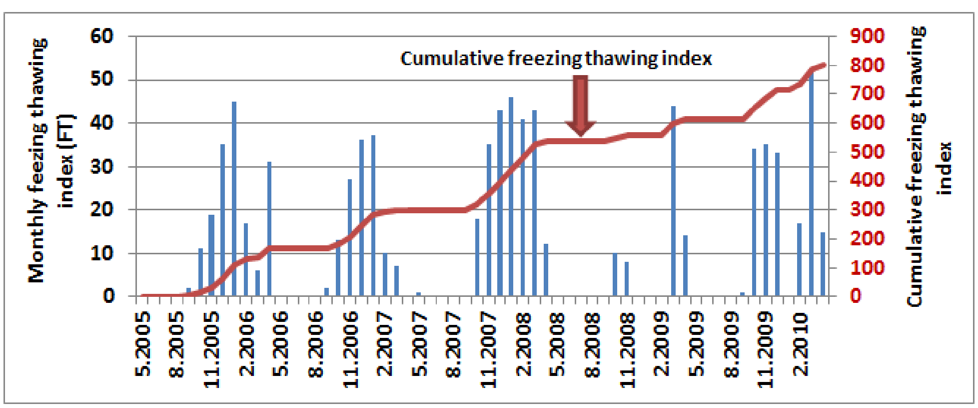

Figure 12. The values of the freezing thawing index for the rendering coat of the repaired facade.

The results of the freezing thawing index with critical moisture of 75% for the rendering coat of the repaired facade are shown in Figure 12. The higher the number of cycles indicates the greater potential for frost damage.

5. CONCLUSIONS

A need for a new method for monitoring of temperature and moisture in repaired building facades was recognized. Specifically, the new method had to be non-destructive, yet able to measure the thermal and moisture conditions at exact and predefined locations inside the structures. The approach chosen to fill the defined need was the RHT monitoring network system that uses sensors and nodes that are embedded inside the building structures at the time of construction, and a controller connected to a host computer for reading the sensors internally from outside the structure.

The results of the thermal and moisture monitoring show drying of the original outer concrete panel after adding external wall insulation and rendering system . This study uses a long-term moisture response indicator called the RHTT index derived from the relative humidity and temperature values over a period of time for any specific area of the wall cross-section. Although acceptable values for RHTT indices for various building materials are not available at this moment, the important feature of the RHTT index is that the higher RHTT index values indicate an increased severity of the hygrothermal response and higher damage potential. The freezing thawing index (FT) is defined as the number of cycles when the temperature oscillates between the freezing and thawing point for the facade components that are almost at the moisture saturation level. Increased freezing thawing index values indicate an increased severity of the frost action and a higher damage potential.

The RHT monitoring network system has proven to be a successful new method for monitoring of thermal and moisture in repaired building facades. The RHT monitoring network system is also reliable, inexpensive, easy and fast to assemble and use which fulfill the requirements for a new monitoring method.

6. REFERENCES

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