Preventive impact assessment strategy by monitoring deformation threshold for early risk assessment

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Small and slow -but steady-
change within
Safe average change T/RH

Interferometric surface monitoring*
via DHSPPI system


➢ Environmental changes have an impact on the structure of materials, slowly but steadily the structural mechanical status of each body as expressed in its elasticity towards changes is affected

➢ Hygroscopic materials undergo through time successfully changes in response to relative humidity changes (RH), wherein the safe limits of RH is depending on the type of material, construction and age

➢ Materials and structures are in sometime altered and then “broken”

➢ The moment the material can not successfully tolerate the changes of RH are the moments when the physical-mechanical parameters change.

➢ Determination of these moments can predict alteration at an earlier stage to warn for increase risks of damage, before irreversible damage
1. Selecting an environmental zone - e.g. zone 4, zone 1
2. Selection of extreme values of RH-time, season, average daily
3. Selection of specimens that are susceptible to changes in RH

1. Simulation of selected RH values in an airtight chamber using salts
2. Sample preparation and placement, free on scales
3. Surface deformation measurement in real time for each RH cycle
4. Relative displacement (RD) (in μm) and rate of displacement (RoD) (μm/h)

1. Repeat cycles-steps 5 and 6 -through time
2. Calculation of Volumetric Deformation ε
3. Correlation ε to RoD
4. Find deformation limits and RoD over which irreversible damage is caused

Our goal is to correlate volumetric deformation with RoD and to find the limits of deformation over which irreversible damage is caused.
Data from Historical Sites examples

Dubrovnik Cathedral crypt-CR

Brezise castle -SL

Sensors
DHSPI, 3DM

Eisodia Theotokou

Agia Triada - Archanes

Agios Fanourios
Valsamonero GR

Staunton Harold Church
UK

This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 226973

FORTH Institute of Electronic Structure and Laser

Climate for Culture
Terms and conjectures

- Interferometry detects microscopic optical-path changes $L - \Delta L$ of surfaces $(L_x, L_y, L_z)$, with $d$ being the initial surface position $t_0$, reference surface distance from the surface to the detector;
- when $d > N\lambda/2 = D$ (N integer) interferometry detects displacement $D$ as multiples $N$ of $\lambda/2$ (microns)
- If the surface changes occur as continuous process of function of time $t$, displacement $D$ is not static event and an infinite transition of relative $D$ in surface position may be captured.
- Relative Displacement (RD) is the change of the surface of the sample at any time $t = t_v$ in comparison to the reference state at $t = 0$ (differentiation)
- Rate of Displacement (RoD) - Relative Displacement reveals how quick the sample reacts to any load that is applied as a function of time
- Deformation is the change of volume of sample to original volume of the sample

\[
\frac{\Delta V}{V} = \frac{(d_{i+1} - d_i) \times (L^2)}{d_0 \times (L^2)} = \frac{d_{i+1} - d_i}{d_0} = \frac{RD_{i+1} - RD_i}{d_0} = \frac{\Delta d}{d}
\]
Selection of day with max RH fluctuation

16/09/2011: RH recording

Variation with mild (safe) changes to mainly cause swelling effect.

RH Fluctuation values
• INCREASE of 22% (RH) in 4h (average 5%/h)
• decrease of 9.2% (RH) in 4h (average 2.3%/h)

8h RH(%) fluctuation in Catholicon of the Dominican Monastery of St. Peter (16/09/11)
8h RH(%) fluctuation in simulation experiment

Simulate process
Actual data - historical site ZONE 1
Skokloster castle, Sweden

RH Fluctuation values
• DECREASE of 34% (RH) in 4h (average 8%/h)
• increase of 10% (RH) in 4h (average 2.5%/h)

Simulation of
• decrease of 34% (RH) in 4h
• raise of 10% (RH) in 4h

Selection of day with max RH fluctuation

Variation with strong (safe) changes to mainly cause shrinking effect.

8h recorded data - Skokloster castle
8h simulated data in environmental chamber

Simulation process
Materials and methods

Laboratory Experimental setup

- Automatic remote surface recording /pre-set intervals
- Installation of GS, FWS and Krah & Grote data loggers
- Saturated salt solutions
- Samples: 2 wood densities, 1 fiber orientation, 3 thicknesses

Saturated salts solutions

<table>
<thead>
<tr>
<th></th>
<th>Sodium Chloride (NaCl)</th>
<th>Potassium sulfate (K₂SO₄)</th>
<th>Magnesium nitrate-Sodium chloride (Mg(NO₃)₂ - NaCl)</th>
<th>Magnesium nitrate (Mg(NO₃)₂)</th>
<th>Silica gel</th>
</tr>
</thead>
</table>

- (a) Hardwood-Oak
- (b) Softwood-Pine

(a) Oak radial , (b) Pine radial

Glass sensors

Krah & Grote data logger

Perforated holder and wooden samples

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 226973
Surface measurements of RoD - RH increase-24h cycle, zone 4

In red line softwood from left to right 1, 2, 5 cm: monitoring for
In black line hardwood from left to right 1, 2, 5 cm

- Softwood follow RH at higher rate
- 1cm thickness follow RH changes at higher rate

six different intensity cases of deformation characteristics are revealed corresponding to typical risk indicators

- linear interpolation (on 16 h soft drying out process)
Surface Measurements of RoD, RH decrease–24h cycle – 24h data for 4 days, zone 1, MC, 1 cm

- decrease of 34% (RH) in 4h, 8.5%/hr
- increase of 10% (RH) in 4h

Rate of Deformation Hardwood 1 cm (μm/hr) vs. Time (hours)
Rate of Deformation Softwood 1 cm (μm/hr) vs. Time (hours)
ΔRH (%)

MC calculation from wood

\[ Y_{MC} = \frac{M_x - M_0}{M_0} \times 100\% \]

\[ Y = \text{Moisture (g)} \]
\[ M_x = \text{initial weight (g)} \]
\[ M_0 = \text{final weight (dried-out) (g)} \]

- Dried mass, total destruction of sample:
- minimum one natural or drilled hole

-MC pointwise sensor Inserted in samples prior to recording of surface reference values
-Rod association to MC
Surface measurement of RoD – RH decrease – 24h data for 4 days, zone 1, MC, 2 cm

- Blue dashed line is the change in RH
- Larger RH changes result to greatest responses

• Simulated RH vs moisture content as measured by the meter.
• MC follows the variation in RH
Surface measurement of RoD – RH decrease – 24h data for 4 days, zone 1, MC, 4.5 cm

1, 2, 4.5 cm results 3 observations:
- the thinner and
- softer the sample is, the more vulnerable it is
- the thicker the sample a difficulty in uptake and output in the humidity environment is observed.

Experimental confirmation:
- Softwood more susceptible than hardwood
- Thinner more vulnerable than thick
### MC moisture content Comparison between different samples average increase-decrease per cycle

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<tr>
<th></th>
<th>1&quot; Day Start</th>
<th>1&quot; Day End</th>
<th>2&quot; Day End</th>
<th>3&quot; Day End</th>
<th>4&quot; Day End</th>
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<tr>
<td>1cm</td>
<td>10.17</td>
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<td>10.35</td>
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<td>10.3</td>
<td>10.35</td>
<td>10.52</td>
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<td>9.17</td>
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<td>+17%</td>
<td>-13%</td>
<td>+15%</td>
<td>-12%</td>
<td>+16%</td>
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<td>Average increase 16%</td>
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<td>2cm</td>
<td>8.87</td>
<td>9.38</td>
<td>9.21</td>
<td>9.6</td>
<td>9.82</td>
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<tr>
<td>MCmax</td>
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<td>-14%</td>
<td>+15%</td>
<td>-8%</td>
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<td>Average decrease 10%</td>
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<td></td>
<td>Average increase 14%</td>
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<td>4,5cm</td>
<td>9.46</td>
<td>9.73</td>
<td>10.07</td>
<td>10.27</td>
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<tr>
<td>MCmax</td>
<td>9.46</td>
<td>9.73</td>
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<td>% of change</td>
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<td>Average decrease 9%</td>
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<td>Average increase 12%</td>
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Risk indication is possible through remote ND surface displacement measurements, per:
- different density (light softwood $\approx 0.30-0.45$, heavier hardwood $\approx 0.45-0.65$ density)
- different thicknesses

From measured data we accept and assume

- $\Delta \text{RH}\% < 5\% \implies \Delta \text{RH} = 0$
- When $\Delta \text{RH} = 0$ Rate of Deformation ($R_oD$) Stable (Threshold Value, T.V.)
- $U = d/t$, rate = $\mu$m/hr

$$R_oD = \begin{cases} 
\text{Threshold Value}, \Delta \text{RH} = 0 \\
\text{Experiment Value}, \Delta \text{RH} > |5\%|
\end{cases}, R_oD > 0$$

- Softwood Threshold Value $>\;$ Hardwood Threshold Value
- $1\text{cm T.V.} > 2\text{cm T.V.} > 4.5\text{cm T.V.}$

Impulse response function of Rate of Deformation to external change for RH fluctuations higher to 5%
Measurement of 24h cycle – shown 24h data for 4 days, zone 1

Accepted data Softwood 1cm
Experimental data Softwood 1cm

Acceptance criteria for the final results:

- $\Delta RH \leq -5\%$ = higher RoD
- $\Delta RH = 0$, RoD steady

Higher rates on drying out conditions

This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 226973
Higher rates on drying out conditions
3rd Experiment – 24h cycle – 24h data for 4 days, zone 1

softwood 2cm

Accepted data Softwood 2cm
Experimental data Softwood 2cm

Rate of Deformation (μm/Hr)
Time (hr)

ΔRH (%)
Time (hr)

Higher rates on drying out conditions
3rd Experiment – 24h cycle – 24h data for 4 days, zone 1

hardwood 2cm

![Graph showing rate of deformation and RH variations over time.]

Higher rates on drying out conditions
3rd Experiment – 24h cycle – 24h data for 4 days, zone 1

Accepted data for Softwood 4,5cm

Rate of Deformation (£m/Hr))

Time (hr)

Higher rates on drying out conditions
Repeatability and resemblance of form of response regardless of thickness and density

Different quantitative response depending on thickness & density

Experimental results lead to hazard classification

Higher rates on drying out conditions

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Measured 24h cycle – shown 1 day, zone 1 m & RD, weight & Relative Displacement

Measured data:
max R_oD values at max RH decrease
• Weight measurement on balance
Mass and Relative Displacement follow the RH of the environment.
Mass and relative displacement fully follow the RH of the environment.
Mass and relative displacement fully follow the RH of the environment in all measurements.
Correlation diagram of percentage change per hour: deformation, mass, and MC/ in 24hours cycle

<table>
<thead>
<tr>
<th>ΔRd/d</th>
<th>Δm/m</th>
<th>ΔMC/MC</th>
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<tbody>
<tr>
<td>-0.84%</td>
<td>-0.16%</td>
<td>-2.85%</td>
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<td>-1.20%</td>
<td>-0.36%</td>
<td>-5.47%</td>
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<td>-2.44%</td>
<td>-0.39%</td>
<td>-3.64%</td>
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<td>-0.86%</td>
<td>-0.13%</td>
<td>-1.22%</td>
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<td>-0.44%</td>
<td>-0.08%</td>
<td>-0.56%</td>
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<td>1.36%</td>
<td>0.13%</td>
<td>0.34%</td>
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<td>1.41%</td>
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<td>0.65%</td>
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Physical quantities and relative displacement follow same alterations
Correlation diagram of percentage change per hour: deformation, mass, and MC/ in 24hours cycle hardwood 4.5 cm

Physical quantities and relative displacement follow same alterations
### Max & Average of: deformation $\Delta d/d$

<table>
<thead>
<tr>
<th></th>
<th>4.5cm Hardwood</th>
<th>4.5cm Softwood</th>
<th>2cm Hardwood</th>
<th>2cm Softwood</th>
<th>1cm Hardwood</th>
<th>1cm Softwood</th>
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<tbody>
<tr>
<td>$\Delta d/d$</td>
<td>-0.02%</td>
<td>-0.03%</td>
<td>-0.09%</td>
<td>-0.15%</td>
<td>-0.44%</td>
<td>-0.84%</td>
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<td>-0.05%</td>
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<td>-0.26%</td>
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| Abs Average | 0.02% | 0.04% | 0.13% | 0.16% | 0.45% | 0.49% |
| max %       | -0.05% | -0.16% | -0.44% | -0.52% | -2.36% | -2.39% |

Where:
$\Delta d = RD_{i+1} - RD_i$

d = the thickness of sample

- Relative displacement and rate of displacement confirm the thick hardwood - density and type of wood - less susceptible to RH change
- 4.5 hardwood max 0.05% compared to 1 cm softwood with max 2.4%
- Max values are obtained at max $\Delta RH$ at 4<sup>th</sup>-5<sup>th</sup> hour of cycle
• Diagrams of RoD for 24h cycle with the values of the mean absolute values of deformation confirm the methodology to use the Rate of Deformation for risk assessment.
  • the higher rates of deformation correspond to deformations higher of the mean accepted value
  • Threshold Values can be assigned individually from rate of deformation
Rate of deformation above the threshold value without loading

Where:
\[ \Delta d = \text{RD}_{i+1} - \text{RD}_i \]
\[ d = 1000 \mu \text{ (the initial thickness of sample)} \]

• Rate of deformation above the threshold value with negligible loading

After day 5: The rate of change increases and become denser within the 24-hour cycle even at stable values (\(\Delta RH<5\%\))

\(\Delta RH<5\%\) after 5 day:
• Variability in speed of reactions
• Variability in amplitude and frequency in rate of deformation above the threshold value
Conclusions

- Measurements provide systematic and repeatable data
- Rate of displacement from surface measurements as risk indicator is confirmed
- Materials of same properties but different characteristic are detectable and responses diversity accessible
- The lighter and thinner the wood the more susceptible to RH changes is
- Shrinking promotes higher rates of deformation
- Repeatable drying-out accumulates fatigue even in threshold values (≈5%ΔRH) considered as safe
- Small and smooth but constant loading may not be negligible for materials impact but kicks off changes in material reaction
- Risk index can be expected from ND remote DHSPI measurements of surfaces
Thank you for your attention