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DETERMINATION OF STRUCTURAL NATURAL FREQUENCIES

The dynamic properties of structures are possible to evaluate by analyses of structural response to microtremor or ambient vibrations by Horizontal to Vertical Spectral Ratio (HVSR) technique or Nakamura technique. For this purpose it is necessary to adopt the following hypothesis:

- Structure is a single-degree-of-freedom model.
- The vertical component does not change during the propagation in the structure.
Results of analysis:

• Structural natural frequencies: longitudinal, transversal and torsional
• Modal damping
• Mode shapes
• Soil-structure interaction
  • Amplification
  • Resonance
Advantages:

- NDT
- Quick and simple (cheap) measurements
- No time dependent
- One can perform a series of measurements on the structure with only one device.
Calibrating FEM model, why?

• Accuracy of results obtained by FEM analyses depend on the accuracy of input data
• On the cultural heritage building sometimes must not be used any one method of testing except nondestructive
• The global behavior of the structure is possible to determine on the basis of natural frequencies
Calibrating FEM model, how?

During multi-step calibration process of FEM model is necessary to change and adapt:

• boundary conditions
• geometric properties
• material properties.
Continuous dynamic monitoring, why?

Changes of structural natural frequencies during the year are influenced by changes of:

- temperature
- humidity
- wind speed

It is necessary to have a enough large database of structures natural frequencies in different weather conditions if we want to check structure after various disasters such as earthquakes, explosions, fire or floods.
Used equipment:
- TROMINO device
  - Sampling frequency 512 Hz
  - Sampling period 10 - 20 minutes

Used software:
- GRILLA software
CASE STUDIES

1. St. Anastasia cathedral bell tower in Zadar
2. Peristyle of Diocletian's palace in Split
3. St. Krševan church in Zadar
4. Romans temple column in Nin
5. Ex Puppet Theatre in Zadar
6. St. John of Capistrano cloister in Ilok
Objective:
- Calibrate the FEM model using natural frequencies.
- Check the changes of natural frequencies in order to identify new damages.
- The rest was upgraded in 1885 (architect T.G. Jackson).
- 1890 appeared first cracks on old part.

Basic data:
- Total height: 54.9 m.
- Plan dimensions: 8.4 * 8.4 m.
- Ground floor and first floor (height of 16.6 m) were built in the 15th century.
1<sup>st</sup> mode Y direction
2<sup>nd</sup> mode X direction

3<sup>rd</sup> mode torsional

4<sup>th</sup> mode Y direction
5<sup>th</sup> mode X direction
The 1st mode
Y direction

The 2nd mode
X direction

The 3rd mode
torsional

The 4th mode
Y direction

The 5th mode
X direction
## COMPARISON OF NATURAL FREQUENCIES

<table>
<thead>
<tr>
<th>Mode</th>
<th>Direction</th>
<th>Calculated Values [Hz]</th>
<th>Measured Values [Hz]</th>
<th>Difference [Hz]</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Y direction</td>
<td>1.69</td>
<td>1.7</td>
<td>0.01</td>
<td>0.6%</td>
</tr>
<tr>
<td>2nd</td>
<td>X direction</td>
<td>1.70</td>
<td>1.7</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>3rd</td>
<td>torsional</td>
<td>4.98</td>
<td>4.5</td>
<td>-0.48</td>
<td>10.7%</td>
</tr>
<tr>
<td>4th</td>
<td>Y direction</td>
<td>6.53</td>
<td>6.9</td>
<td>0.37</td>
<td>5.4%</td>
</tr>
<tr>
<td>5th</td>
<td>X direction</td>
<td>6.81</td>
<td>6.9</td>
<td>0.09</td>
<td>1.3%</td>
</tr>
</tbody>
</table>
Objective: calibrate the FEM model using natural frequencies

Problem: very complex structure
Structural Analyses

3D model
Identification of natural frequencies registration data on

- 104 points
- 31 verticals
COMPARISON OF MEASURED AND CALCULATED FREQUENCIES

Identification of natural frequencies:

1\textsuperscript{st} mode

10\textsuperscript{th} mode

30\textsuperscript{th} mode

St. Rocco Chapel
East Colonnade
Vestibul - Protiron
Building block 1
Building block 2

-5% calculated values
-5%
+5%
+5%
Goals:

– calibrate the FEM model using natural frequencies

– assess changes in natural frequencies before, during and after reconstruction
## The 1\textsuperscript{st} mode

<table>
<thead>
<tr>
<th></th>
<th>calculated [Hz]</th>
<th>measured [Hz]</th>
<th>difference [Hz]</th>
<th>percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>4,124</td>
<td>4</td>
<td>0,124</td>
<td>3,1%</td>
</tr>
<tr>
<td>Model 2</td>
<td>2,44</td>
<td>2,5</td>
<td>-0,060</td>
<td>2,4%</td>
</tr>
</tbody>
</table>

**Model 1**

**Model 2**
Measured natural frequencies
Goal: satisfy my own curiosity

- Basic data:
  - height 12 m
  - diameter 80 cm
  - brick masonry in hydraulic lime mortar

Result: great surprise
The 1\textsuperscript{st} mode Y direction

The 3\textsuperscript{rd} mode Y direction

The 2\textsuperscript{nd} mode X direction

The 5\textsuperscript{th} mode torsional

The 4\textsuperscript{th} mode X direction
HVS R ANALYSIS RESULT

North-South component

Frequency [Hz]

10 Hz

8.0 Hz

12.75 Hz

17.5 Hz

22.57 Hz

27.4 Hz

Zagreb / Šibenik, 8 – 10 May 2014
# COMPARISON OF NATURAL FREQUENCIES

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<thead>
<tr>
<th>Mode</th>
<th>Direction</th>
<th>Calculated Values [Hz]</th>
<th>Measured Values [Hz]</th>
<th>Difference [Hz]</th>
<th>Percentage</th>
<th>Ratio M/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>Y</td>
<td>0.7545</td>
<td>8.0</td>
<td>7.2455</td>
<td>90.57%</td>
<td>10.60</td>
</tr>
<tr>
<td>2nd</td>
<td>X</td>
<td>0.7548</td>
<td>7.2452</td>
<td>90.57%</td>
<td>10.59</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>Y</td>
<td>4.362</td>
<td>12.75</td>
<td>8.388</td>
<td>65.79%</td>
<td>2.92</td>
</tr>
<tr>
<td>4th</td>
<td>X</td>
<td>6.417</td>
<td>17.5</td>
<td>11.083</td>
<td>63.33%</td>
<td>2.72</td>
</tr>
<tr>
<td>5th</td>
<td>Torsional</td>
<td>10.03</td>
<td>22.57</td>
<td>12.54</td>
<td>55.56%</td>
<td>2.52</td>
</tr>
</tbody>
</table>

We need to check our model and to repeat measurements.
Goal: assess the real behavior of the structure in relation to the two possible ways defined with two different FEM models

The basic structure consists of:
- RC columns and beams in longitudinal facades,
- semi-prefabricated RC ceiling with brick infill,
- infill brick walls at the ends of the building,
- in transverse direction there are no RC beams between the columns.
FEM MODELS

Model 1
1\textsuperscript{st} mod

Model 2
1\textsuperscript{st} mod
HVS R ANALYSIS RESULT
## COMPARISON OF NATURAL FREQUENCIES

<table>
<thead>
<tr>
<th>Mode</th>
<th>Model 1 Calculated [Hz]</th>
<th>Model 1 Measured [Hz]</th>
<th>Model 2 Difference [Hz]</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; mode</td>
<td>4.49</td>
<td>4.29</td>
<td>0.20</td>
<td>4.66%</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; mode</td>
<td>0.79</td>
<td>-3.50</td>
<td>81.6%</td>
<td></td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; mode</td>
<td>6.58</td>
<td>6.46</td>
<td>0.12</td>
<td>1.86%</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; mode</td>
<td>1.31</td>
<td>-5.15</td>
<td>79.7%</td>
<td></td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; mode</td>
<td>6.80</td>
<td>9.52</td>
<td>-2.72</td>
<td>28.6%</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; mode</td>
<td>2.27</td>
<td>-7.25</td>
<td>76.2%</td>
<td></td>
</tr>
</tbody>
</table>
COMPARISON OF NATURAL FREQUENCIES

NATURAL FREQUENCIES

- Model 1
- Model 2
- Measured
- Difference 1
- Difference 2

Frequencies [Hz] vs Modes

Zagreb / Šibenik, 8 – 10 May 2014
ST. JOHN OF CAPISTRANO CLOISTER IN ILOK
ST. JOHN OF CAPISTRANO CLOISTER IN ILOK

Objective: calibrate the FEM model using natural frequencies

Problem:
- very rigid structure
- low rising structure
FEM model
AMPLITUDE SPECTRAL CURVES
HVSR ANALYSIS RESULT
N-S direction
HVS R ANALYSIS RESULT
E-W direction
Identification of natural frequencies

Comparison of measured and calculated frequencies

<table>
<thead>
<tr>
<th>Mode</th>
<th>West Wing</th>
<th>Tower</th>
<th>North Wing</th>
<th>East Wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4th</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5th</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- First mode
- Second mode
- Third mode
- Fourth mode
- Fifth mode

- Frequency [Hz]
- Identification of natural frequencies
- 2nd mode
- 5th mode
- 1st mode
- 3rd mode
- 4th mode

Legend:
- West Wing
- Tower
- North Wing
- East Wing
- Calculated values
- -5%
- +5%
A few examples of researches

- Passive characterization of low rising structures school buildings in Canada
- Guglia Maggiore of the Duomo in Milano
- Dynamic monitoring analysis of Mallorca cathedral
- Wooden structure testing
Passive characterization of low rising structures school buildings in Canada

In 77% of the 101 buildings it was possible to evaluate natural frequencies; of which in 28% was possible to estimate only the first three modes

by Helene Tischler et all
Guglia Maggiore of the Duomo in Milano

Dependence of natural frequency on day-night and vibration level

Zagreb / Šibenik, 8 – 10 May 2014
Dynamic monitoring analysis of Mallorca cathedral

By Pere F. Roca et all
Dynamic monitoring analysis of Mallorca cathedral

Changes of natural frequencies
Dynamic monitoring analysis of Mallorca cathedral

Multiple regression for temperature, relative humidity and frequencies
**WOODEN STRUCTURE TESTING**

**TOTAL REDUCTION OF NATURAL FREQUENCY 7%**

<table>
<thead>
<tr>
<th>freq. [Hz]</th>
<th>partial reduction</th>
<th>total reduction</th>
<th>periodo [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre 0.07g</td>
<td>5.25</td>
<td>2.38%</td>
<td>0.191</td>
</tr>
<tr>
<td>pre 0.25g</td>
<td>5.125</td>
<td>2.38%</td>
<td>0.195</td>
</tr>
<tr>
<td>pre 0.50g</td>
<td>5</td>
<td>2.44%</td>
<td>0.20</td>
</tr>
<tr>
<td>post 0.50g</td>
<td>4.875</td>
<td>2.50%</td>
<td>0.21</td>
</tr>
</tbody>
</table>

2,38% 2,38% 0.191
2,44% 4,76% 0.20
2,50% 7,14% 0.21

Zagreb / Sibenik, 8 – 10 May 2014
Before conclusions the question:

Would it be possible to prevent the collapse of these buildings that was implemented dynamic monitoring, of course, parallel with other types of SHM?

Tore civica in Pavia (March 17th 1989) - four killed
QUESTION

The bell tower of St. Magdalene church in Goch, Germany (May 24th 1993)
Cathedral of St. Nicholas in Noto, Sicily
(March 13\textsuperscript{th} 1996)
Bell tower of St. George church in Pleškovec (June 4th 2008)
Conclusions

• HVSR technique is good and efficient method for assessment of natural frequencies of structures
• Natural frequencies of structures are good references for calibration of the FEM model of structures
• Natural frequencies of structures combined with the results of other testing technique are a powerful tool for assessing the condition of the building and structural health monitoring
THANK YOU
FOR YOUR ATTENTION
AND PATIENCE

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D&Z doo Zadar Croatia