USE OF BUILDING PERFORMANCE SIMULATION FOR STRUCTURAL ANALYSIS OF HISTORICAL BUILDING

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ABSTRACT
This paper presents a study performed on the tower of the Church of the Sacred Heart in Prague, Czech Republic, proposing the use of Building Performance Simulation (BPS), which is commonly used for the evaluation of building energy performance and indoor environmental quality, replacing time consuming real-time monitoring. By using BPS, we obtain the temperature development on structural elements surfaces (walls). The results from BPS were used as boundary conditions for a numerical thermo-mechanical analysis of the affected structure which is usually included to detect the cause of damage when thermal phenomena are suspected. The surface temperatures of selected structural elements were calculated using the DesignBuilder GUI software and the ENERGY+ calculation core, which is based on a dynamic one-dimensional model of heat transfer by conduction in multilayer structures and uses calculated convectional coefficients. The temperatures calculated by BPS were subsequently verified by short-term temperature measurements in the church tower. A comparison was made of three representative days of measurement to three days of a typical meteorological year with similar climatic conditions.

INTRODUCTION
The preservation of historical buildings often deals with issues related to structural damage arising from their thermal behaviour. Any intervention or restoration actions should be preceded by a rigorous identification of the cause of the existing damage. This statement applies to all buildings, but for historical buildings this is especially true. When thermal phenomena are suspected, the identification often involves a numerical thermo-mechanical analysis of the affected structure. The boundary conditions for the thermal simulation are usually determined by temperature monitoring. However, the monitoring should be performed at many spots and over a long period of time for an analysis that would provide reliable results. This may not be feasible in many practical situations.

This paper presents the possibility of replacing time-consuming monitoring of thermal behaviour of a structure with a computational model of the structure which is primarily designed for energy performance calculation and indoor environmental quality estimation, namely thermal comfort. The Determination of the structure’s surface temperatures was the main aim of this model. These temperatures were used as boundary conditions for a thermo-mechanical analysis. This example of historical building analysis demonstrates how to use this type of calculation software in other cases in which it is not possible to monitor a building in real-time in the long term.

DESCRIPTION OF THE TOWER
The Church of The Sacred Heart in Prague is the most famous Czech sacral building of the 20th century. It has been part of the national cultural heritage list as of 2010. The church consists of a nave and a tower characteristic by its rectangular shape.

The rectangular inner space of the tower is characterized by a cantilevered ramp, which, following the perimeter, leads up to a belfry on the top of the tower. It detaches from the walls where two massive circular openings appear on the longitudinal sides. The opening structure presents a glazed frame grid supported by an iron frame. This consists of two crossed iron profiles and a circular one connected to a concrete ring finally inserted into the masonry wall as shown in Figure 2.
ANALYSIS
Recently, visible cracks were detected on the external supporting walls on the church's tower. Most of these cracks began to appear next to the large circular windows. The structural analysis is focused on the longitudinal west wall which is the most damaged part of the structure.

As shown in Figure 3 and Figure 4, the radial cracks appear in the concrete ring and in masonry as well. The circumferential cracks affect the interface between these two materials. The extensive damage at the connection between the horizontal steel profile and the concrete ring caused a partial loss of the concrete as shown in Figure 5. The damage was identified both on the inside and on the outside of the wall in the concrete ring.

Based on a research and an expert evaluation of the crack pattern it was concluded that the possible cause of these cracks is the effect of temperature changes. In light of the massive structure and the character of the crack, this analysis is focused on short-term and long-term effects of temperature on the structure.

METHOD
A method of dynamic simulation of mechanical behaviour of the structure's numerical model was used for verification of the hypothesis of long-term thermal effects as the cause of the cracks. In this case, the Adina software was chosen. This software is usually used for thermo-mechanical analysis of a building's construction. These calculation tools can model the formation of cracks resulting from a mechanical strain caused by temperature. The development of the surface temperature value of the structure's individual parts is an important input condition of the load case. It is the usual practice that these boundary condition values are determined by measurements [6]. In the situation in which an effect of long-term thermal temperature changes is suspected, the measurement results can be relevant if the monitoring of the structure takes more than one year.

Due to the technical difficulty, the time-consuming character and the uncertainty of the entire monitoring process (a monitoring year might be atypical when it comes to climatic conditions), calculation tools were used to predict the surface temperature's development. In this case, the DesignBuilder GUI software along with the ENERGY+ calculation core were used. A short time measurement of exterior and interior air temperature, humidity and surface temperature monitoring on the inner west wall of the church’s tower verified the model in the DesignBuilder software. Three representative monitoring days were selected. The three selected days were compared to three days of a model (epw data) with a similar climatic condition.

MODELLING AND SIMULATION
As described in the previous chapter, two simulation models were used: building performance simulation focused on thermal analysis and thermo-mechanical analysis.

1. BPS
The selection of suitable calculation tools and appropriate input climatic data parameters is one of the most significant requirements for obtaining accurate results.

In order to consider a replacement for the monitoring of actual conditions, all relevant boundary conditions have to be taken into account by the calculation. These boundary conditions, which could affect interior and exterior surface temperature, should be considered in appropriate detail. In this case, a one-dimensional dynamic model of heat transfer was used. Modelling the thermal behaviour of a building at an unsteady state (dynamic model) involves...
important factors that modeling in a steady state does not.
The BPS calculation makes it possible to take into account such climatic phenomena as solar irradiation, air temperature and humidity, wind velocity and direction, night sky radiation as well as the indoor operation on the scale of the building’s multi-zone model (macroscale) over a long period of time (a year) with fine time resolution (minutes). Criteria for simulation software are specified in the standard. [2]

α) Software

The surface temperatures of the structure were determined using Design Builder tools for dynamic simulation of the building’s energy performance, which are based on the Energy Plus calculation core. The Design Builder software is commonly used for analysis of a building’s energy and thermal load. It can estimate the thermal load of a building to maintain the required conditions, the energy use of a HVAC system and many others parameters depending on the geometrical shape description of a building, selection of HVAC systems, occupant definition etc.

It is evident from the above mentioned that the Design Builder software is used mainly for determination of the indoor environment components and energy balance in the zone model. One of the parts of the energy balance calculation is performing a calculation of heat transfer through structures. It is possible to acquire the development of the surface temperatures of selected structures of the wall as a partial result of this calculation. It was the main reason for using the Design Builder software to solve the problem of surface temperature development during a model year. The software offers advanced modelling tools which allow to model the unusual shape of this church as well.

β) Boundary conditions

Modelling of a historical building is specific in many ways. Firstly, there are no significant internal heat and humidity loads in the tower of the church. The development of temperature and humidity depend only on external climatic conditions and the material characteristic of the structures. Due to very low traffic to the belfry, the model does not count with any occupancy of the tower. There is no heating or air conditioning in the tower. Because of the poor construction of the window (single glazing in a steel frame) and missing detailed data about air-tightness the model considers an estimated 0,7 air exchange per hour.

A typical meteorological year EPW (EnergyPlus Weather files) for the location of Prague was used. This data is provided by WMO (World Meteorological Organisation). TMY2 data files were used, containing hourly values for one year. This data provides rather typical than extreme weather values. It is necessary to take that into account in a follow-up research of the cracks in the structure. There is high possibility that an extreme temperature occurred in the actual history of the church. The criteria for this data are specified in the standard. [2]

γ) Model

It is not necessary to model the whole shape of the church just to obtain the desired development data regarding the surface temperature of the tower. The simplified model of church’s tower considers the tower geometrical and energy independent of other parts of the building. The model works as a two-zone model: one for the large open space of the tower and the other for the smaller area of the belfry at the top of the tower. Other parts of the church (the administrative part, the main spiritual space and the crypt) were considered adiabatic blocks. Heat transfer into the tower is expected through the roof, external walls and the floor next to the ground. Due to the similar character of the indoor environment in the tower and the nave (no HVAC systems and similar wall construction) there is no expected heat transfer between these two parts of the building. This applies for the church’s crypt as well. The Administrative space is adjacent to the tower mainly through the corridor which is not heated. Therefore there is no heat transfer in the simplified model between these two parts either.

Figure 6 Church zoning – model in DesignBuilder

The cross-sectional thickness is changing with the height of the wall. For this reason the tower of the
The church had to be modelled from several blocks ("building block") which were connected to one zone. In this case, it is possible to get results exactly for a specific part of the tower. In this situation, the results of the temperature next to the large window were required. Another zone in the model is the belfry, separated by a ceiling. The masonry was designed as a multilayer structure with material characteristics according to a library provided by the Design Builder software (table 1). These materials correspond with materials obtained in-situ.

<table>
<thead>
<tr>
<th>Table 1 Material characteristics of the perimeter wall</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials in the DesignBuilder Library</strong></td>
</tr>
<tr>
<td>&quot;Cement/Lime plaster&quot;</td>
</tr>
<tr>
<td>&quot;Brick&quot; (full bricks masonry with cement mortar)</td>
</tr>
<tr>
<td>&quot;Brick – Burned&quot; (salt glazed clinker bricks masonry)</td>
</tr>
</tbody>
</table>

The surface temperature of the concrete ring around the large window is very important for purposes of a thermo-mechanical analysis. This concrete circular frame was simplified to a concrete block in the wall next to the large window in the same zone. This concrete block was modelled with the same volume as the real concrete circular ring. These two concrete blocks were placed on the west and the east side. Heat transfer is calculated within one zone, for this reason the impact of this simplification was minimal. The windows consist of a single glazing slab. In this case the windows were characterised by a high heat transfer coefficient of $U = 6.2 \text{ W/m²K}$.

8) Results

A time step of 30 minutes was chosen for the dynamic simulation. The result value of individual surface temperatures, air temperature and humidity were exported in the same time interval (fig. 8). The results affirmed the first assumption about the surface temperatures. The interior surface temperatures of the individual structures show a smaller fluctuation than the exterior surfaces. The fluctuation of exterior surface temperatures of individual structures was assessed as significant especially on the west side. For this reason the west wall became a subject of further investigation. A comparison on the west wall was made between the interior and the exterior, along with a comparison between the masonry and the concrete. A very significant fluctuations of surface temperatures was identified throughout the entire year. The exterior surface temperatures of both materials easily reached 40 °C in the summertime and -12 °C during the winter period. This is shown in tab 2.

![Figure 8 Outdoor and indoor surface temperatures of the west wall during a model year](image)

Table 2 Extreme values of surface temperatures of concrete and masonry during a model year

<table>
<thead>
<tr>
<th>Surface Temperature</th>
<th>Max. Concrete (°C)</th>
<th>Max. Masonry (°C)</th>
<th>Min. Concrete (°C)</th>
<th>Min. Masonry (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior Surface</td>
<td>43.01</td>
<td>44.95</td>
<td>-12.95</td>
<td>-12.95</td>
</tr>
<tr>
<td>Interior Surface</td>
<td>29.64</td>
<td>29.7</td>
<td>-4.63</td>
<td>-3.28</td>
</tr>
</tbody>
</table>

c) Results validation

Although the results showed matching temperatures, it was necessary to check the calculated values. In this case, a short time monitoring was performed in the church’s tower. The verification of the model in the Design Builder software was the main aim of this measurement. The measurements were performed in two steps. Firstly, the air temperature and the humidity if the interior and the exterior were monitored for three weeks. Simultaneously, the monitoring of the interior masonry wall's surface temperature was being performed. In the second step, the infiltration of air in the tower was measured using the method of Age of air with concentration decay.

- Temperature monitoring

During the time period from March 10th to March 29th 2015, the air temperature, humidity and interior surface temperature were monitored. Three representative days (March 17th - 19th) were chosen for future exploration. The values were recorded in 5 minute time steps.

After that, a similarity of the dry-bulb temperature between the three representatives monitored days and three other days during the model year was sought. The time step of a monitored value was unified to 30 minutes as the same time values of model years were exported. Two criteria were taken into consideration for the search of the most suitable similarity. Firstly, the lowest mean of individual difference between dry bulb temperatures in the time was sought. Secondly, the lowest standard deviation was sought as well. The temperature values of days from October 29th to October 31st emerged as the most matching with the three monitored days. (as you can see in Fig. 9)
As shown in the chart in Figure 10, there are differences in the indoor air temperature between the measured values and the values from BPS in the course of three days. In both cases, decreases of temperature come in the night. However, during daytime, there are differences in the temperature increase. The measured temperatures indicate an increasing tendency. On the other hand, the values gained from BPS show a rather oscillating character. These trends almost correspond with the values of solar irradiation (Figure 11). In case of measurement the insolation was estimated by insolated/noninsolated temperature sensor values difference. For this reason, the values from BPS can be considered matching.

The last chart (Fig. 12) shows the values of surface temperatures of the masonry wall inside the tower. The curves in the chart show a similar character as the curves of indoor air temperature in Fig. 10. Of course, the curves showing the surface temperature behave much more constantly. The massive wall prevents significant temperature fluctuations. The differences between the values in the surface temperature chart are caused by different solar radiation.

- Measurement of infiltration

The air movement in the interior affects the convection coefficient and the air temperature. For this reason, air exchange is an important calculation parameter which could have impact on the surface temperature results. No permanent ventilation openings are considered in the tower of the church, but there are large, poorly designed and single-glazed windows. For this reason, the air exchange value was determined to be 0.7 /ach. This hypothesis about air infiltration was verified by measuring using the method of the age of air with tracer-gas concentration decrease.

With this method the air in the interior is marked with tracer-gas and the decrease of the gas concentration due to the infiltration of unmarked outdoor air into the interior is studied. The local mean age of air is the area under the concentration versus the time curve. [4]

Three sensors measuring air concentration were placed in the solved part next to the large circular windows in the church tower. Two of them were installed in the northern and the southern part of the tower about 1 m from the wall and one sensor was installed in front of one of the large circular windows.
As expected, the most considerable value of air exchange is shown in the area with sensor No. 3. This sensor is situated next to the large, poorly constructed window. On the other hand, both sensors No.1 and No.2 show a similar value of air exchange. These values are lower than the values measured by the sensor next to the large window.

Figure 14 Tracer-gas concentration during the time

The values of air exchange were calculated by the formula (1).[4] Typical plots of the tracer-gas concentration as a function of time as shown in Fig. 14. At the beginning there is a region with a non-exponential decrease, but after a certain period of time, the gas concentration decreases exponentially. The measuring was stopped when the concentration began to decrease exponentially.

The results of infiltration on each sensor are shown in tab 3.

\[ I = \frac{1}{\tau} \cdot \ln \left( \frac{\text{con}(\tau)}{\text{con}(0)} \right) \quad [\text{h}^{-1}] \quad (1) \]

Where:
- \( \tau \): measurement duration [h]
- \( \text{con}(\tau) \): concentration in the end of measurement [ppm]
- \( \text{con}(0) \): concentration on the start of measurement [ppm]  [4]

Tab 3: Results of infiltration on individual sensors

<table>
<thead>
<tr>
<th>TIME</th>
<th>INFILTRATION [ach/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SENSOR No.1</td>
<td>0.74</td>
</tr>
<tr>
<td>SENSOR No.2</td>
<td>0.61</td>
</tr>
<tr>
<td>SENSOR No.3</td>
<td>0.9</td>
</tr>
<tr>
<td>AVERAGE VALUE</td>
<td>0.75</td>
</tr>
</tbody>
</table>

This value of air exchange fully corresponds with the value used in the Design Builder software.

2. THERMO-MECHANICAL ANALYSIS

Preliminary studies on a 2D linear model, subsequently refined with non linear properties and geometrical details, were used to demonstrate that thermal loads in a plausible range could be able to induce such stress in the structure that might result in cracks in the structure. In the final step of the refining process the real thermal load acting upon the tower wall was applied considering the results obtained with the BPS program. Namely the external and internal surface temperature of the concrete, the masonry and the circular window at the clock level were considered. These acquired data were then carefully elaborated in order to find representative intervals of the long and short term behaviour of the wall. Due to the fact that the damage pattern shows numerous cracks on the inside and the outside of the structural elements, long-term thermal phenomena were investigated. The effect of high temperature variations on the wall in the course of time generates cracks, affecting the entire thickness due to the small gradient of temperature through the thickness. For this reason it is possible to evaluate this phenomenon on a 2D model of the structural element.

The model shown in Figure 16 considers the tower from the connection with the church with vertical displacements constrained at the bottom, considering the wall infinitely stiff in vertical direction. On the top of the model a pressure was applied in order to represent the remaining part of the masonry over the concrete floor of the belfry. 2D solid elements were used to model the masonry, the concrete ring and the concrete floor whereas hermitian beam elements were used for the iron profiles. Eight rigid links were considered at the connection between the iron circular profile and the concrete ring where bolts were detected during the visual inspection. Non-linear properties of materials were considered for the masonry and the concrete (tab 4) using the
“concretemodel” of ADINA. This represents the material as a homogeneous isotropic solid. A tensile failure was considered using a smeared crack band model and the compressive nonlinearity is treated by plasticity.

<table>
<thead>
<tr>
<th>Tab 4 Materials properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODULUS OF ELASTICITY [GPa]</td>
</tr>
<tr>
<td>CONCRETE</td>
</tr>
<tr>
<td>MASONRY</td>
</tr>
<tr>
<td>IRON</td>
</tr>
</tbody>
</table>

The thermal load applied to the concrete ring and the masonry, due to the considerations expressed before, was the average of the temperatures through the thickness calculated with a 1D thermal model in Adina. As it was not possible to specify the iron profiles in the DesignBuilder software, the average of the inside and outside temperatures of the window was considered. This value could be considered the most representative considering the small thickness of the iron profile and its high conductivity.

As stated earlier, the long-term temperature fluctuation of the structure was considered dominant. For this reason, the process of these temperatures was simplified, as shown in Fig. 17.

Due to the fact that the cracks were caused by temperature changes, great attention was paid to estimating the reference temperature of the structure. It represents the temperature at which the structure was able to carry the load. According to historical data and photographs it is possible to determine the date of the construction of the church tower in September-October 1930, when the tower was built up above the circular clock. Due to that fact it is possible to take into account two possibilities of the initial temperature: 10 °C and 20 °C (October 14th and September 1st). These reference temperatures (minimum and maximum values) and their dating were applied to the model as load.

Tab.3 and Fig.17 show the considered temperature value which the individual materials reached in the course of the model year.

<table>
<thead>
<tr>
<th>Tab 5 The considered temperature values of the individual materials (time steps is shown in Fig. 17)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONCRETE</td>
</tr>
<tr>
<td>TEMPERATURE [°C]</td>
</tr>
<tr>
<td>-6.27</td>
</tr>
<tr>
<td>-4.59</td>
</tr>
<tr>
<td>29.43</td>
</tr>
</tbody>
</table>

The simulations showed that, due to a different thermal expansion coefficient and a different temperature of individual materials, contractions of the concrete structure are generated during lower temperatures (in comparison to the reference). This leads to the formation of radial cracks in the concrete and partial tearing of the concrete ring from the masonry. (Fig.18). On the contrary, higher temperatures cause expansion of the concrete ring and radial cracks in the masonry.

![Figure 16 Mechanical model [5]](image)

![Figure 17 Average of the temperature trends of the west masonry wall through the thickness during the typical year obtained from an 1D FEM model of the wall section with BSP results as boundary conditions. The data elaboration for the mechanical model shown in this graph considers an initial temperature of 10°C.]

![Figure 17 Cracks generated by lower temperatures in comparison to the reference. Left: r.t. 10 °C, right: r.t. 20 °C. Red... open cracks, blue ... closes cracks [5]](image)
Figure 18 Cracks generated by higher temperatures in comparison to the reference. Left for reference temperature 10 °C, right 20 °C. Red... open cracks, blue ... closed cracks [5]

Figure 19 Real damage [5]

RESULTS ANALYSIS
It is possible to accept some dissimilarities in the results obtained due to the difference between the i.t. and final temperature: the analysis with the reference temperature of 10 °C gave a better representation of the crack pattern in the masonry and the analysis with the r.t. of 20 °C was more precise in the identification of the crack pattern in the concrete ring. This conclusion could be explained by the effect of the accumulation of the damage due to the cyclic opening and closing of the cracks and higher temperature fluctuation of the structure throughout the history of the building than it is possible to get from model year. More detailed information regarding this problem can be found in the diploma thesis by one of the authors.

CONCLUSION
The paper described the synergistic process of damage analyses on a historical heritage. Firstly, an energy performance simulation of the building in macroscale was used. Secondly, a thermo-mechanical analysis of a disrupted structure was used in detail. The results obtained for a typical year in the BPS software were subsequently used on a two-dimensional final element model of the wall. These values resulted in damage in the concrete ring and the masonry wall similar to the damage actually detected during a visual inspection. The tower mode in BPS was verified by short-term monitoring. During this measurement, similar values were obtained to the ones generated by the software for a building's energy performance. The observing of extreme values of surface temperatures on individual structures is a fundamental aspect for the case of effect of long-term temperature changes. Weather data used in the calculation provide rather typical than extreme values. Due to that fact it is possible to expect more significant differences of extreme values in the real course of time of the structure's history. In this aspect, the simulation methods could not fully replace long-term monitoring of the structure. It might be interesting to repeat the simulation with weather data files for a typical hot and a typical cold year to investigate this influence.

Nevertheless, in this case the simulation method suffices to verify the hypothesis of the effect of long-term changes. For this reason the simulation method might be a tool of great importance in other cases in which it is not possible to perform a long-term monitoring of a structure.

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