

## Designed with Dlubal Software...

### Dlubal Programs Help to Save Stone Monuments in Angkor, Cambodia

Stone monuments in the Angkor archaeological park, registered as a UNESCO World Heritage Site, are considerably deteriorated nowadays and the state of the preserved ones is getting worse quickly.

Thus, international experts are intensely looking into causes of a bad technical condition of these important monuments and try to find suitable solutions for their rescue.

The Czech research team participates in saving these monuments in Angkor as well, with the five-year research project "Thermal Imaging and Structural Analysis of Sandstone Monuments in Angkor".

The main project objective represents an analysis of a stone structures loading by environmental temperature changes and their influence on a static safety of the monuments. Besides the research directly in Angkor, numerical simulations of behavior of stone structures loaded by external actions, focused on an effect of temperature changes also make a part of the project. The program RFEM by the Dlubal company was used to create numerical models and carry out a structural analysis.

The Angkor stone monuments, built between 8<sup>th</sup> and 14<sup>th</sup> century, are mostly ruins in various stages of deterioration at present. Majority of monuments was constructed from stone blocks assembled without any binding material, firebricks were used sometimes. At the temples preserved so far, a continuous development of failures occurs, mainly a disintegration of a stone blockwork, caused by a combination of several different factors.

Besides an improper construction technique, as regarded with today's knowledge, demanding climatic conditions represent one of the main deterioration causes.

The monitoring of deformations and temperatures of selected temples showed that the difference between the maximum and minimum temperature on intensely insulated ex-



Angkor Vat temple in Cambodia

ternal surfaces exceeds 60°C during a year cycle. Large thermal differences exist between night and day as well, the temperature on the internal surface was often about 40°C lower than on the external one. This contributes to an uneven loading and large dilatation motions within the stone structures; combined with other factors, a gradual expansion of joints occurs among the blocks, individual stones drop out from the structure and the entire temple parts disintegrate or collapse.

Numerical simulations of monuments static behavior are carried out with Dlubal's FEA program RFEM, which allows reaching a high correspondence rate between properties of numerical models and real structures of stone temples. The analysis goal is to predict the further development of their technical condition, based on simulation results. Among others, obtained results could also serve to elaborate a project proposing optimal saving procedures for stabilization and rescue of these rare monuments.

Within the research, 3D models of selected typical segments of stone structures were created and tested in the RFEM program so far - a single wall, a tetragonal pyramid, a roofed column gallery and various tower shapes. The numerical models were formed by solids - volume elements representing individual stone blocks. The mutual interaction of the blocks was simulated by contact elements that allow to eliminate tension effects perpendicular to a joint and to work with different friction intensity among block contacts.

A number of simulations was processed for loading of mentioned models by temperature, considering characteristic construction subsoil and various connection types of

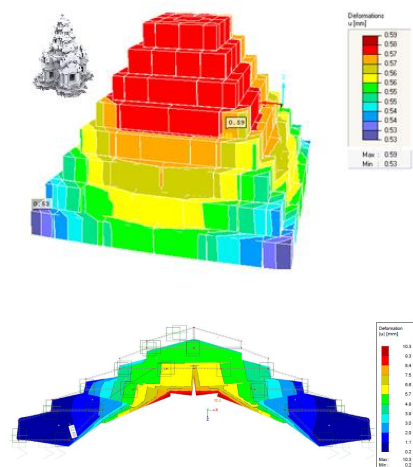
stone blocks. The results of numerical analyses show a considerable correspondence with the stone structures behavior (deformations, failures etc.). The research phase executed so far proved that the temperature loading of Angkor temples reaches significant values and has considerable influence on their technical condition, worsening constantly. In next research phases, the steps performed so far will be further developed in such a way that the influence of temperature changes on the stone monuments behavior in Angkor could be more specified and optimal procedures could be proposed to preserve the monuments for next generations.

### Czech research team in Angkor:

Project director:  
Dr. Karel Kranda  
Academy of Sciences of the Czech Republic  
Nuclear Physics Institute

Head of research:  
Doc. Ing. Jan Pašek, Ph.D.  
Faculty of Civil Engineering of the CTU (Czech Technical University) in Prague  
Department of Building Structures

Team members:  
Ing. Jiří Svoboda  
Ing. Hansley Pravin Gaya  
Otakar Veverka



Analysis results in RFEM

### Software

Ing. Software Dlubal  
www.dlubal.com