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Doctoral Thesis

Abstract

Analysis of early-age thermal–shrinkage stresses in reinforced concrete walls

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The character of early-age stresses is well-recognised in massive concrete elements such as slabs, blocks or water dams. In such elements stresses are induced mainly by significant temperature differences developing between the interior and the surface of the element. However, the impact of the early-age thermal–shrinkage effects is usually underestimated in elements with thinner sections but in which the ability of free deformation is limited. These externally-restrained elements are subjected to restraint stresses caused by potential contraction limited by the restraint along one or more edges of the element; if not restrained, they would not be subjected to such stresses.

There is a very wide range of externally-restrained reinforced concrete elements, such as walls, with different massivity and restraint conditions in which similar character of cracking is observed. The aim of the research presented in this thesis was to analyse the character and magnitude of early-age stresses occurring in reinforced concrete walls due to thermal–shrinkage effects and to investigate the influence of various factors on these stresses, especially the influence of restraint conditions including the founding subsoil. Because of a large scale of the elements in question the analysis was performed in a "virtual laboratory" with use the of computational models.

Firstly, the simplified analytic models were reviewed and evaluated. The stress analysis in these approached is based on the *compensation plane method*. The method takes into account the fact that the early-age stresses in externally-restrained elements result from a coupled action of the internal and external restraints. The external restraint acts against axial deformation and flexural deformation. The concept of the restraint factor is used to represent the degree of restraint of the element by the restraining body. In the most complete form the restraint factor takes into account the geometry of the early-age element and the restraining body, the relative stiffness of the restraining body and the influence of cracking on the change of restraint.

Then, the thermo–physical and mechanical phenomena which govern the early-age behaviour of reinforced concrete walls were defined. A thorough review was made of the proposals for phenomenological description of the thermo–physical and mechanical behaviour of early-age concrete and soil. Based on this review a mathematical model was formulated for simulation of the behaviour of early-age reinforced concrete walls including structure–subsoil interaction. A FEM-based numerical model was developed which was implemented in a form of modular software. The main modules were TEMWIL for thermal–moisture analysis and MAFEM for stress and damage analysis. The main goal of the model was to estimate the thermal–shrinkage stresses in early-age concrete elements without the necessity to perform a series of experimental tests to determine the values of the subsequent parameters. The model was verified on a real

benchmark wall (NPP wall for CEOS.fr benchmark); this aim was successfully achieved. The model was used for a series of analyses of early-age walls. Three-dimensional numerical analysis allowed to explain the important phenomena observed in early-age elements, impossible to explain with the use of simplified models. The numerical approach allowed to describe the time evolution of various phenomena as concrete maturity developed. The results of the analyses confirmed a typical, two-phase character of stresses in the wall. The spatial analysis showed the influence of the self-induced stresses which are responsible for the variation of the total stresses in the cross-section of the wall. Taking into account the subsoil the real temperature distribution in the concrete element was obtained and real values of the degree of restraint were obtained.

Both analytic and numerical models were used for the analysis of the influence of the restraint conditions on the early-age stresses in walls. It was shown that the restraint stresses play predominant role and the effect of the external restraint can be well described by the restraint factor. The value of the restraint factor varies throughout the volume of the wall and is the greatest at the joint between the wall and the restraining body decreasing towards the free edges. The value of the restraint factor depends on the degree of translational restraint (length and height of the wall and their ratio and relative stiffness of the restraining body), rotational restraint, possibility of slip at the joint as well as the properties of the founding soil (friction, cohesion and stiffness); all these characteristics must be taken into account for proper determination of the degree of restraint.

Finally, a discussion was made on the influence of other factors on the magnitude and character of stresses in early-age walls. The factors which influence the early-age stresses relate to the concrete composition, environmental and technological conditions during casting and curing of the element. The most common way of mitigation of the early-age effects is optimum concrete mix design, however, special attention must be paid in externally-restrained elements to the relationship between the hydration heat development rate and the mechanical properties development rate. Development of the early-age stresses is highly dependent on the environmental conditions during curing of concrete. It is advised to realise concreting in moderate ambient temperature with additional pre-cooling of the concrete mix. Appropriate curing technology can be applied when curing is realised in unfavourable conditions. To mitigate early-age cracking in walls insulation should be applied and the moment of the formwork removal should be delayed; at that moment it must be assured that the tensile strength of the concrete element able to withstand the cooling tensile stresses.