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Multi-Physics Analyses of Selected Civil Engineering Concrete Structures

J. Kruis*, T. Koudelka and T. Krejčí

Department of Mechanics, Faculty of Civil Engineering, Czech Technical University, Thákurova 7, Prague, 166 29, Czech Republic.

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Abstract. This paper summarizes suitable material models for creep and damage of concrete which are coupled with heat and moisture transfer. The fully coupled approach or the staggered coupling is assumed. Governing equations are spatially discretized by the finite element method and the temporal discretization is done by the generalized trapezoidal method. Systems of non-linear algebraic equations are solved by the Newton method. Development of an efficient and extensible computer code based on the C++ programming language is described. Finally, successful analyses of two real engineering problems are described.

AMS subject classifications: 74C10, 74F05, 74F10, 74R05, 74S05, 76R50, 80A20, 80M10

Key words: Coupled problems, heat and moisture transfer, creep, damage mechanics, hydro-thermo-mechanical analysis, efficient solvers, analysis of containment, watertightness of foundation slabs.

1 Introduction

Analyses of many engineering and scientific problems become more complicated in the course of time because the multiphysics approach is required in branches where the single physics was satisfactory several years ago. Civil engineering is not an exception which can be documented on coupled analyses used for very important and monumental structures. Usually the mechanical analysis coupled with heat and moisture transfer is considered. The multiphysics approach can be used because of large achievements in numerical methods and significant development of computers, especially the parallel computers.

*Corresponding author. *Email addresses:* `jk@cml.fsv.cvut.cz` (J. Kruis), `koudelka@cml.fsv.cvut.cz` (T. Koudelka), `krejci@cml.fsv.cvut.cz` (T. Krejčí)

From many multiphysics problems of civil engineering, this paper concentrates only on the coupled hydro-thermo-mechanical analysis of concrete structures. The paper describes selected material models for mechanical and transport processes, balance and governing equations, their approximation by the finite element method, efficient methods for time discretization and solvers of algebraic equations. Special attention is devoted to development of a computer code which has to be easily extensible and very efficient. At the end, some real world engineering problems solved by the authors during past five years are described.

Concrete represents a very specific material which requires multiphysics analysis because the mechanical behaviour depends strongly on distribution of moisture and temperature. In the past, moisture and temperature were assumed time independent or they were not taken into account at all. The coupled hydro-thermo-mechanical approach enables description of real conditions and the material and structural response is in accordance with experiments.

The classical mechanical analysis based on the finite element method defines two or three unknown displacements in nodes of the mesh with respect to the dimension of problem solved. Heat and moisture transfer can be described by models which define two or three unknown nodal values. The unknowns represent nodal temperature, moisture content, relative humidity or partial pressures. In the general three-dimensional case, the coupled analysis deals with six unknowns in each node of the mesh. It is clear that the requirements on computers grow rapidly with the growing number of nodes in the mesh.

The classical single processor implementation of coupled problems gives severe limits on finite element mesh. Unfortunately, the mesh has to take into account the shape of the structure solved as well as possible steep gradients of all unknown variables. Only two-dimensional or very simple three-dimensional problems can be treated on a single processor computer. On the other hand, parallel computers with several processors together with domain decomposition methods represent a very efficient tool which is able to deal with significantly larger problems and reasonably fine meshes. The domain decomposition methods were successfully applied in various problems in past twenty years [9,19–21,31,34,40].

Another possibility of efficient solution of complicated multiphysics problems is application of adaptive methods. It is known, that there are basically three types of adaptive methods connected with the finite element approach. The h-version changes the meshes while the degree of polynomials used for approximation on finite elements is constant. On the other hand, the p-version changes the degree of polynomials used while the finite element mesh is fixed. Finally, the most efficient hp-version combines the previous approaches, i.e. the mesh and the degree of polynomials are changed simultaneously [36]. Clearly, the hp-version is the most difficult version in the perspective of computer implementation but it saves significant number of degrees of freedom which leads to shorter computational time and smaller demands on computer memory [37].

The paper is organized as follows. Section 2 summarizes useful mechanical material