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Single-phase and multi-phase modeling of concrete structures

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This paper is dedicated to Prof. Herbert A. Mang on the occasion of his 70th birthday

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ABSTRACT

The paper focuses on recent developments in the fields of advanced 3D constitutive modeling and multi-phase modeling of concrete. In particular, the application of a 3D damage-plasticity model to the large-scale numerical simulation of an ultimate load test, conducted on a model of a concrete arch dam, and the numerical simulation of the impact of drying shrinkage on the behavior of concrete structures strengthened by concrete overlays are presented. In both cases comparisons of the computed response with available experimental data demonstrate the capabilities of the numerical models.

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1. Introduction

For the last five decades extensive research activities were carried out focusing on the development of constitutive models for plain and reinforced concrete and on the development of robust and efficient solution algorithms for nonlinear finite element (FE) analyses of concrete structures. Whereas early research endeavors in constitutive modeling of concrete were mainly devoted to 2D models for panels, slabs and shells, for the last two decades research activities were directed towards the development of advanced constitutive models for 3D stress–strain states, advanced models for the numerical simulation of crack propagation, multi-phase models considering concrete as a porous material, and multi-scale models.

In this contribution some recent developments in the fields of advanced 3D constitutive modeling and multi-phase modeling of concrete are described. As computational mechanics of concrete structures rests on both constitutive modeling and structural analysis, applications to problems in engineering practice will be presented.

In the last two decades several 3D constitutive models for concrete were proposed, e.g., in [1–4]. More recently, a 3D concrete model, based on a combination of plasticity theory and damage theory, was published by Grassl and Jirásek [5]. In [6,7], the latter was modified by enhancing the evolution law of the damage variable, its predictive capabilities were investigated on the basis of experimental data for concrete specimens subjected to different stress paths, and it was validated by comparisons of the experimental and computed structural response of well-known 3D benchmark tests, including tests on beam-shaped specimens, subjected to combined bending and torsional loading [8] and a cyclic loading test of a squat bridge column [9].

In the first part of this paper, the application of the 3D concrete model to problems in engineering practice is demonstrated by the numerical simulation of an ultimate load test, conducted on a model of a concrete arch dam on the scale of 1:200. The numerical simulation of the model test – instead of the real dam – permits a comparison of the predicted structural behavior with the test results up to the ultimate load.

Whereas for structural analyses commonly suitable stress–strain relations are sufficient for representing the material behavior of concrete, also problems in engineering practice are encountered which require considering additional physical phenomena, e.g., thermal, hygral and/or chemical processes, for an appropriate description of the material behavior and of the structural response.

Exemplarily, the second part of the paper focuses on the impact of drying shrinkage of concrete overlays on the behavior of strengthened concrete structures. Drying shrinkage of concrete is characterized by the time-dependent volume decrease due to moisture migration and moisture transfer to the environment caused by a decrease in ambient relative humidity [10]. Due to the variable moisture distribution in a structure, shrinkage of the dryer near-surface regions will be restrained by the moist inner regions. Additional restraint effects are encountered, when a concrete structure is strengthened by adding a concrete overlay, since for the latter shrinkage is restrained at the interface with

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the original concrete [11]. Hence, tensile stresses will be generated, which may attain the tensile strength and, consequently, may cause cracking, resulting in a reduced serviceability and a reduced load carrying capacity of the composite structure [12]. For commonly encountered values of relative humidity the physical origin of drying shrinkage is related to the increase of the capillary pressure in the porous concrete during the drying process [13]. Hence, a physically based model of drying shrinkage relies on a multiphase formulation, in which concrete is considered as a porous material, consisting of a solid skeleton and voids, filled by liquid water and gas [14]. The former consists of bound water and capillary water, the latter consists of dry air and water vapor.

Both an experimental and numerical investigation on the strengthening of an existing concrete structure by a concrete overlay will be presented. In the experimental study brick-shaped concrete specimens were supplemented by concrete overlays, measuring both the time-dependent spatial moisture distribution and the shrinkage strains in the original and the composite specimens. The experimental results provide the basis for validating a multi-phase concrete model for simulating hardening and drying shrinkage of concrete overlays.

2. Numerical versus experimental failure study of a concrete arch dam by a reduced scale model

2.1. Model test

Zillergründl arch dam is one of the highest concrete arch dams in Austria. It is characterized by a height of 186 m and a thickness ranging from 7 m at the crest to 42 m at the base. In the course of the design and construction of the dam, model tests were carried out by the department for tests and measurements of VERBUND – Austrian Hydro Power [15,16]. The reason for choosing the model dam for the numerical simulation instead of the full-scale concrete arch dam is given by the fact, that only for the model test measurement-data up to failure of the dam is available for a comparison with computed results.

The model consisted of the arch dam and the surrounding rock foundation. It was built employing a scaling factor for the geometry of MG = 200. In the model both the concrete and the adjacent rock were substituted by different mixtures of gypsum, siliceous earth, dinatriumphosphat and water, thereby accounting for the different material properties of the dam body and the rock foundation. The plan view of the model is shown in Fig. 1.

The gypsum mixture for the arch dam was characterized by Young's modulus of E_{dam} = 2690 MPa and the cube compressive strength, shear strength and flexural tensile strength were given as 3.52 MPa, 0.54 MPa and 1.01 MPa, respectively [15,16]. Young's moduli $E_{rock,1}$ and $E_{rock,2}$ of the gypsum mixtures, representing the rock foundation, are provided in Fig. 1. After pouring of the rock foundation, the arch dam was cast in one part. Thus, in the model the arch dam is represented by a monolithic structural member, disregarding joints and inspection chambers. The model of the dam body was glued to the rock foundation by means of a synthetic resin.

The scaling factor for the stresses, MS, was defined as the ratio of the shear strength of the dam concrete τ_{dam} = 3.70 MPa over the shear strength of the gypsum mixture τ_{model} = 0.54 MPa, yielding MS = 6.85.

The model was loaded by the scaled dead load of the arch dam and the scaled hydrostatic water pressure acting on the upstream face of the arch dam. The scaled specific weight of the dam model was computed from the specific weight of the dam concrete of 24 kN/m^3 as $\gamma_{dam,model} = 24MG/MS$ = 702 kN/m^3. The scaled dead load was applied to the dam model by 42 steel plates, which were encased in the arch dam at six horizontal levels. The steel plates were connected to vertical steel strings of about 4 mm diameter, which were anchored at a steel grid below the base of the model. In order to minimize interactions of the steel strings with the arch dam during loading, they were surrounded by synthetic cladding tubes. The steel plates were loaded by prestressing the steel strings. Hence, the scaled dead load was approximated by concentrated loads. The scaled hydrostatic water pressure was applied onto the upstream face of the arch dam model by 77 hydraulic jacks and steel plungers (Fig. 2), which were arranged at nine horizontal levels. The scaled specific weight of water was determined from the specific weight of water of 9.81 kN/m^3 as $\gamma_{water,model} = 9.81MG/MS$ = 286 kN/m^3. Hence, the scaled design water pressure at the base of the arch dam model at full reservoir is determined as $p_{model} = 0.286 \cdot h_{model}$ = 0.266 MPa, where $h_{model} = 186/MG$ = 0.93 m is the height of the dam model. The magnitude of the scaled hydrostatic water pressure was increased during the ultimate load test until the model failed at 4.4p_{model}.

In the experiment failure occured due to rupture of the arch dam body, i.e., about 150 mm below the crest a crack was propagating nearly horizontally until it extended almost along the whole

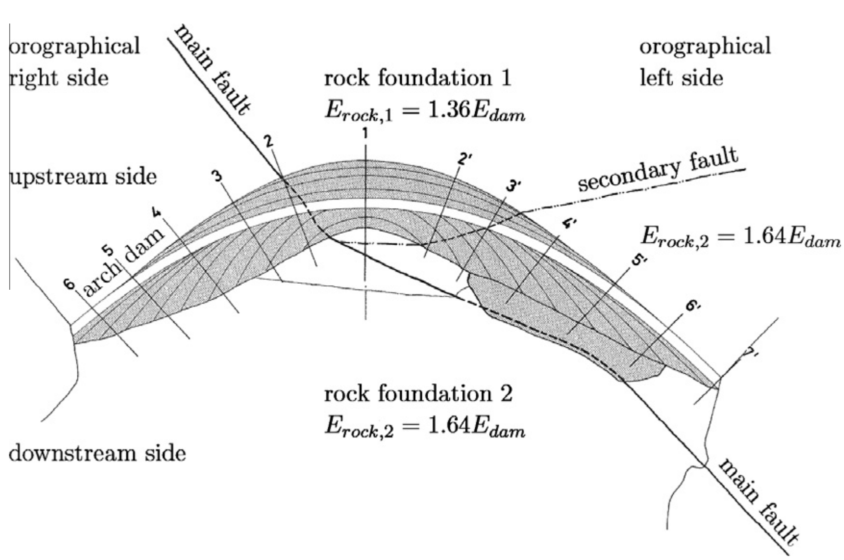

Fig. 1. Plan view of the model test layout [16].

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