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Mechanical Model for Lifespan Analysis of Bridges

Modèles mécaniques pour l'étude de la durée de vie des ponts

Mechanisches Modell für die Lebensdauer von Brücken

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SUMMARY

A computational procedure for the evaluation of material damage under changes of loads, actions and as a result of aggressive chemicals, is presented. The proposed approach is based on a numerical formulation to analyse thermal, hygrometrical and chemical effects, to simulate the ion diffusion into the porous material and then to determine the mechanical behaviour of the damaged material. Structural life span is finally estimated through the effects of chemical and mechanical processes affecting both concrete and steel. Numerical examples are shown.

RÉSUMÉ

Une méthode de calcul pour évaluer les dégâts aux matériaux soumis à des variations de charges, d'actions et d'agents chimiques diffus, est présentée. L'approche est basée sur une formulation numérique des effets thermiques, hygrométriques et chimiques, en simulant la diffusion d'ions dans le matériau poreux et en déterminant le comportement mécanique du matériau endommagé. La durée de vie de l'édifice est évaluée au moyen des effets des procédés chimiques et mécaniques combinés agissant sur le béton et l'acier. Des exemples numériques sont donnés.

ZUSAMMENFASSUNG

Eine Berechnungsmethode zur Bewertung der Schäden an den Materialien, die verschiedenen Belastungen, Einflüssen und weitverbreiteten chemischen Stoffen ausgesetzt sind, wird dargestellt, um schliesslich die Lebensdauer der Brücken und Bauten im allgemeinen zu bewerten. Der vorgeführte Versuch gründet sich auf eine zahlenmässige Formulierung, die aufgestellt wurde um die thermischen, hygrometrischen und chemischen Auswirkungen zu analysieren, indem eine Diffusion von Ionen im porösen Material simuliert wird, um danach das mechanische Verhalten des Materialschadens zu ermitteln. Zuletzt wird die Lebensdauer der Bauten geschätzt, die sich aus den Auswirkungen der Vereinigung von chemischen und mechanischen Vorgängen ergeben, die auf Stahlbeton und Stahl einwirken. Es werden numerische Beispiele gezeigt.

1. INTRODUCTION

The evaluation of mechanical and durability performance of bridges and building structures is a relevant goal in civil engineering. Together with mechanical and thermal actions, main causes of deterioration of concrete structures are steel corrosion, induced by the action of chloride and carbonation, and concrete damage due to its reaction with calcium chloride and sulphates salts. For this purpose, a computational analysis of the stress state in connection with thermal, humidity and chemical species changes, is carried out in this paper with the aim of estimating lifespan extension of structures. The development of suitable algorithms based on the finite element method has been performed in view of producing efficient procedures for the analysis of bridges and structures. The evolutions of humidity, temperature and contaminant concentrations are considered through partially coupled diffusive mechanisms; chemical effects are analyzed studying in particular calcium chloride or sulphate ions diffusion. Then the mechanical effects are evaluated in terms of stresses, strains and material damage.

The temperature and humidity fields are described generalizing a formulation presented in [1,2], to take into account saturated-unsaturated behaviour (see Ref. [3]), within the framework of a purely diffusive model. More complete formulations considering the whole humidity range, together with phase changes, like evaporation is developed in [4].

The evolution of the chemical species, like e.g. chlorides, sulphates, carbon dioxide, etc., into a porous medium exposed to a contaminant environment, is a complex phenomenon involving various factors such as the gas or ion diffusion and the ion flux due to the solution permeation through the material [5]. One of the main new features of this paper is to take into account the dependence of the chemical species diffusivity on the damaging of the material.

As far as the mechanical aspects are concerned, in Ref. [6] viscoelastic models including isotropic damage effects have been considered, substituting in the stress-strain relationship expressed as a Stieltjes integral, different definitions of the standard relation based on the concept of the so called effective stress as in [7], or different definitions of the relaxation or creep functions to take into account material damaging [8]. Here account is taken also of anisotropic damage as in [9] and its coupling with viscosity [10] to better model the time transient behavior of concrete. The mechanical aspect of the problem is strictly linked to the diffusive one since the chemical reaction between cement hydrates and diffusing species modifies the mechanical behaviour of the material as shown in [11]. Moreover both the sulphate and the calcium chloride attacks appear macroscopically through swelling and cracking of the original material.

The space discretization of the model is carried out using the finite element method and solved numerically. The transient numerical simulation allows to analyze the evolution of the temperature, relative humidity, ions concentration, damage parameter, stresses and strains.

The knowledge of the above behaviour allows to draw a durability evaluation in terms of residual actual load capacity of the investigated structure compared with the external applied loads. The proposed tool also allows the forecasting of the expected service-life time of structures in whatever different aggressive environment.

2. GOVERNING EQUATIONS

The governing equation of moisture flow is derived following the lines of References [2,3]. It is assumed that the various phases of water in each pore (vapour, capillary water and adsorbed water) are in thermodynamic equilibrium with each other [2] and with the solid skeleton.

Non isothermal moisture flow is governed by a nonlinear parabolic equation of diffusive type as reported in [1,2,3]. The energy transport through the concrete is governed by a similar nonlinear parabolic equation. Both equations are used here, as explained below, being the complete formulation given in Refs. [3,12].

The flow of chemical species through concrete, coupled with non isothermal moisture one, is described by the following relationship:

$$\frac{\partial C}{\partial t} = \mathrm{div}(D_c \cdot \nabla C) + \frac{C}{\alpha} \cdot \frac{\partial w}{\partial t} \tag{1}$$

where the first term of the R.H.S. represents the diffusion mechanism and the second one takes into account the ions dragged by water flux [5]. In eq.(1) C is the diffusive species concentration (e.g. chloride, sulphate); w is the moisture content, D_c is the actual diffusivity coefficient of the material and α is a binding coefficient. The diffusivity of aggressive species $D_c = \beta \cdot D_{c,ref}$ is assumed to be dependent on pore humidity, temperature and degree of cement hydration through $D_{c,ref}$ described in [5]. To consider the damaging effect of the chemical pollutants, such diffusivity is assumed increasing with the parameter β which is defined as follows:

$$\beta = \chi + (1-\chi) \Big/ \left[1 + \left(2 \cdot C/C_f\right)^4\right] \tag{2}$$

where χ is the ratio between the residual strength corresponding to $C=C_f$ (i.e. the reference concentration of the diffusing species for which the degradation process attains its maximum effect) and the initial strength. χ parameter is related to the material characteristics and the aggressive agent (in particular $\chi=1$ for undamaged material).

The time transient boundary conditions associated to non isothermal, moisture and ion diffusion equations may be either of the following types: prescribed humidities, temperatures, and chemical concentrations or prescribed water vapour flows, heat flows and flux of species concentration. For the ion transport analysis, a more realistic boundary condition able to reproduce the ion deposition rate from the external environment and the natural washing effect of rains, can be used [5].

The equilibrium equations can be written once suitable hypotheses on mechanical behaviour are posed. Here, a formulation based on viscoleasticity coupled with damage is considered. The geometrically nonlinear approach has to be adopted because if anisotropic models are taken into account, the principal directions of damage rotate during the process. Hence the variables which control the evolution of damage (true strains), rotate also and must be referred to evolving geometrical configurations even if strains remain small. Here we consider such situations with small strains, hence the heat and mass transfer formulation stated before within a linearized geometrical framework can be considered sufficiently accurate.

The viscoelastic constitutive relationship taking into account damage effects presented in [6] is written using the second (symmetric) Piola-Kirchhoff stress tensor $\underline{S}$ and the associated Lagrangian strains. Elastic damage at finite strains is incorporated in the procedure, reducing the free energy by the factor $\|(\underline{1} - \underline{d})\|$, where $\underline{d}$ is the damage tensor. In the particular case of isotropic damage behaviour, the process is controlled by a scalar variable $d \in [0,1]$. As in the above paper, the damage model is based here on the maximum strain concept [7].

The diffusion of sulphates salts and calcium chlorides affects the cementitious materials inducing a reduction of their mechanical strengths [11]. Therefore in the numerical algorithm the initial elastic Young modulus of the material is reduced according to the parameter β, eq.(2). Damage tensor is also affected by β parameter as follows: $\underline{d} = \underline{d} + (1-\beta)(\underline{1}-\underline{d})$. The physical justification can be found in [11]. As stated before, the value of parameter χ depends mainly on the material characteristics and the type of chemical attack. Typically the value of the reference concentration C_f varies within the range 4-8% in weight of cement content. For OPC paste specimens with w/c ratio 0.35, immersed in 30% $CaCl_2$ solution, assuming χ=0.25 and C_f=6% a good fitting with the experimental data reported by Collepardi in [11] was achieved, as shown in fig. 1a.

Taking into account the constitutive relation, a new form of the equation of motion is obtained, as shown in [12]. The space discretization by means of finite element technique is reported in the same Reference. After solving the resulting system of algebraic equations, the strains can be calculated. The stresses are then obtained by the standard procedure for viscoelasticity with damage [13]. The procedures were implemented in the finite element code DAMVIS.

3 - NUMERICAL COMPUTATIONS

The numerical simulation of a typical bridge cross-section was performed to check the evolution of the humidity, thermal, chloride, stress, strain and damage fields during construction. The building up time was divided into 75 time steps of variable size (maximum time = 6 years). Since the procedure takes into account construction phases, it was assumed as completely built-up at time t = 180 days from the beginning of the simulation. The boundary conditions for humidity and temperature were assumed constant during all the period, respectively $R.H.$ = 50% and T = 20 °C. As far as the chloride diffusion is concerned, the effect of calcium chloride in reducing the mechanical characteristics of the concrete was considered. After 200 days from the beginning of the simulation, a chloride deposition rate on upper surface of bridge, with a sinusoidal trend during the winter period (maximum value 10 g/mq/day), constantly equal to zero during the summer period, was used. A constant washing away effect and the contribution of a upper bituminous layer 2 cm thick in reducing the chloride penetration was also considered. The typical chloride concentration curves along a vertical section of the bridge slab are drawn in fig. 1b. The maximum surface concentration is reached at the end of the winter period when the external deposition stops; the washing away effect produces the drop of the surface concentration that reaches its minimum at the end of the summer period. The chosen value of the parameters for chemical analysis can be found in [5].

With the finite element mesh shown in fig. 2a the time transients of relative humidities, temperatures (including generation of heat of hydration), diffusion of chemical species, and the corresponding stresses and strains in the viscoelastic damaging material were found. In figs. 2b,c,d,e,f are shown at time 6 years the relative humidities, max. principal stresses without chloride, damage without chlorides, max. principal stresses with chlorides and damage with chlorides. The complex stress state found is the result of competing effects of contractive (like shrinkage) or expansive (thermal and chemical) types. Damage is concentrated where chemical attack occurs and shrinkage (although smoothed by creep effects) gives rise to high local strains.

4. CONCLUSIONS

The presented model allows a realistic evaluation of the stress-strain states in multiphase materials like concrete in several engineering situations. The model incorporates diffusive thermal, hygral and ionic species fields, coupled with the mechanical one. The latter is strictly connected to the previous ones and embodies viscoelasticity coupled with damage to simulate a typical time transient behaviour of concrete accounting for material degradation. The feasibility of the finite element formulation here adopted has been shown in complex structures such as a bridge section, giving a picture of the stresses and strains developed in the domain of interest during an assigned time transient. Further efforts are under development in improving the damage model including itself the chemical attacks action and moreover to better justfy experimentally the parameters used in the numerical analysis.

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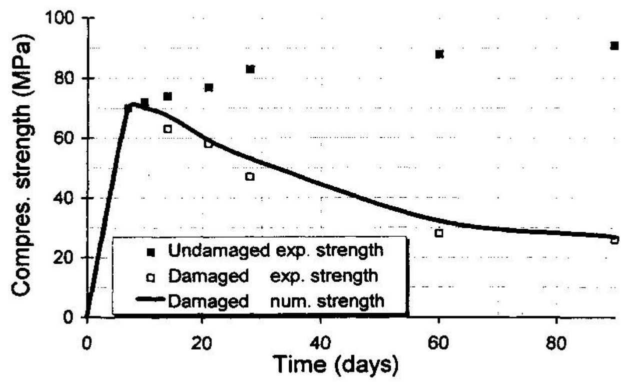

Fig. 1a: numerical simulation of strength decrease of OPC cement paste specimens immersed in a 10% $CaCl_2$ solution (experimental data by Collepardi [11]).

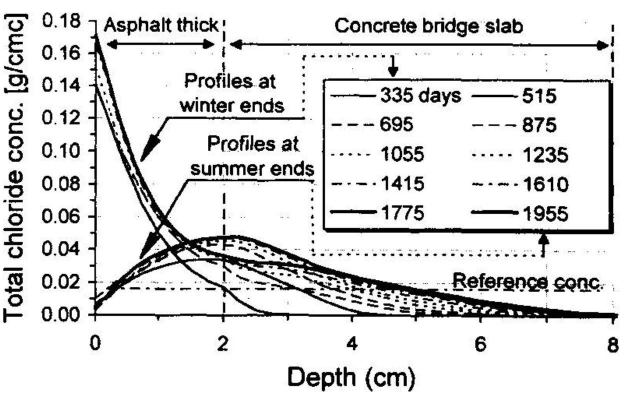

Fig. 1b: chloride concentration profiles along a vertical section of the bridge slab at various time.

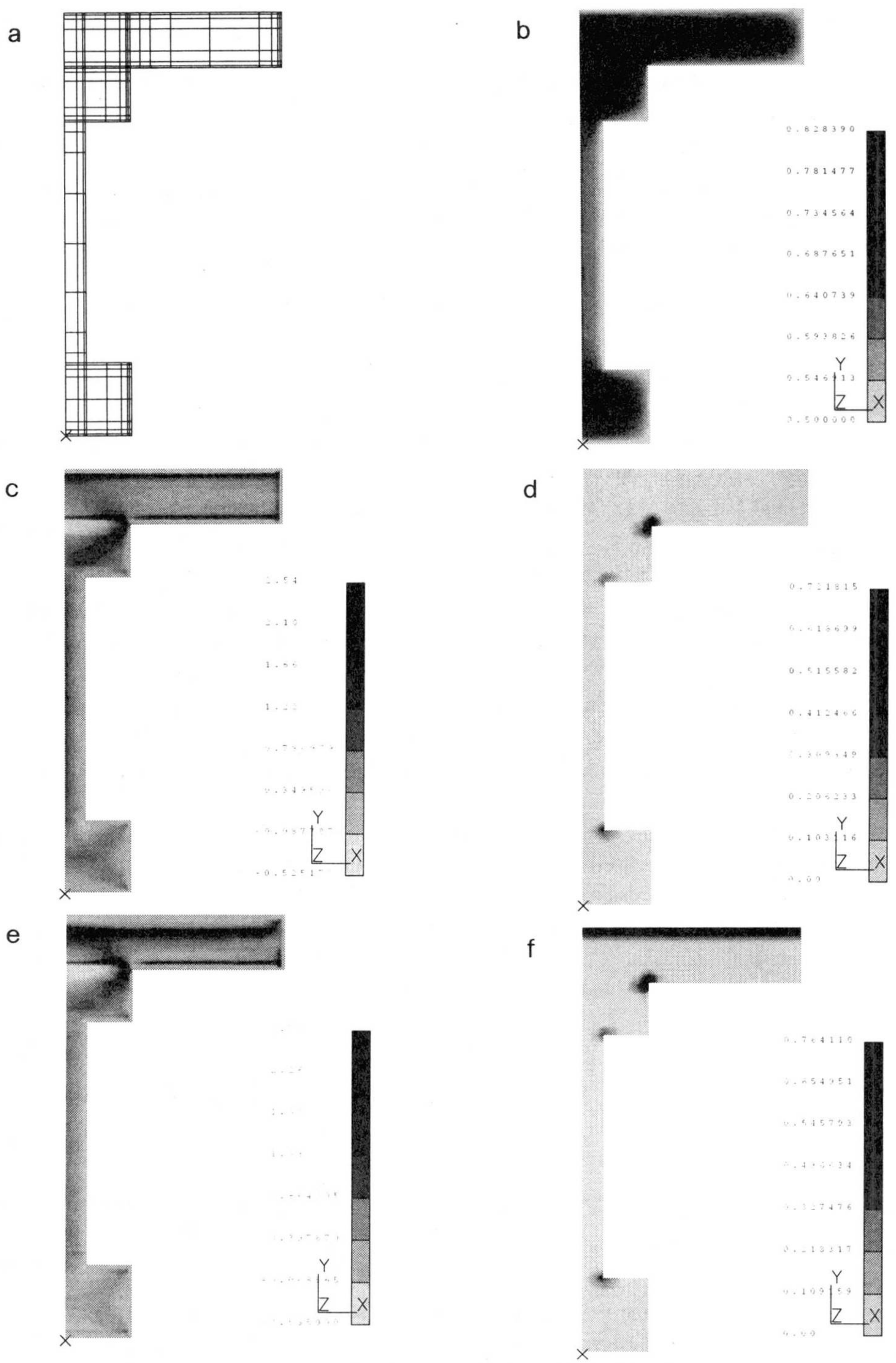

Fig. 2: a)half bridge cross-section used in the numerical analysis; b) relative humidities at time 6 years; c) max. principal stresses without chlorides at time 6 y.; d) damage without chlorides at time 6 y.; e) max. principal stresses with chlorides at time 6 y.; f) damage with chlorides at time 6 y.