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# Concrete creep modelling for structural applications: non-linearity, multi-axiality, hydration, temperature and drying effects

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ABSTRACT

Concrete creep models have to consider several important phenomena (non-linearity, multi-axiality, hydration, and thermal and drying effects) to be relevant in structural applications. A selection of experimental results of creep tests found in the scientific literature are used to highlight these phenomena. Firstly, regarding the creep rate in different directions of a specimen under various loads, it is shown that creep rate under moderate loading can derive from elastic strains. Secondly, the reason why a Drucker Prager criterion can be chosen to model non-linear creep is discussed. Thirdly the interest of resorting to a creep theory able to decouple ageing (or hydration) effects and consolidation effects is explained. Moreover, interest using a poro-mechanical formulation, in which Biot coefficient depends on stress state, to model drying creep and shrinkage is discussed in the light of short meso-scopic analysis. The effect of temperature on creep is also addressed. The numerical implementation of the proposed modelling is briefly exposed and the model responses are confronted with experimental results.

## 1. Introduction

Long-term management of major civil engineering concrete structures such as dams, nuclear power plants, nuclear waste storage tunnels, and large bridge elements needs finite element models able to demonstrate the reliability of these structures over a long period. However, concrete is well-known to present delayed strains which control its long-term mechanical behaviour [1–3]. To consider this phenomenon, it is usual to split the total delayed strain into autogeneous shrinkage, drying shrinkage, basic creep and drying creep. The fundamental cause of delayed strains lies in the constitutive properties of hydrates [4]. The viscous property at this scale is due to instability of the bond between C–S–H sheets [5]. At larger scale, other additive non-linear phenomena could play an important role, among other effects, micro cracking of anhydrous phases and water content variation are important [1,6–9]. To model these different phenomena, a poro-mechanical framework is useful [10]; In fact poro-mechanics allows the role of water forces (capillary or disjoining) and the constitutive behaviour of solid phases to be distinguished. The objective during the model finalization was to obtain the simplest possible formulation, that was easy to implement in any structural finite element code, and able to consider the non-linearity of creep amplitude versus loading, the possible multi-axial stress states, the effects of temperature, and the effects of water, in terms of creep velocity, shrinkage and drying creep. Another requirement was to decouple the model from other non-linear aspects such as damage or plasticity, so that this formulation could be coupled with any type of non-linear model already used for structural analysis. A further preoccupation was to obtain a differential formulation able to consider the time-variation of mechanical loading or hydro-thermal conditions, while, despite this versatility, also providing an analytical solution in cases of simple loading. In a first part, the model principles are explained with reference to the physical origins of each phenomenon, then various creep tests are simulated and the numerical results are compared to experimental results. These tests concern multi-axial basic creep, uni-axial basic creep at various loading levels, drying creep and basic creep at various temperatures and at early age. Selected in the literature for their interest and complementary, these tests can also be used for benchmarking other structural creep models or to validate their numerical implementation.

## 2. Constitutive equations

### 2.1. Model principles

The global scheme of the poro-mechanical model is summarized in Fig. 1. It contains two branches: the left one represents the solid behaviour, with an elastic part to model instantaneous behaviour, a Kelvin module to model the reversible creep and a non-linear Maxwell module to model permanent strains. The right branch represents the effects of hydric forces (capillary pressure and variation of disjoining forces). The non-linearity of the Maxwell module means that its viscosity

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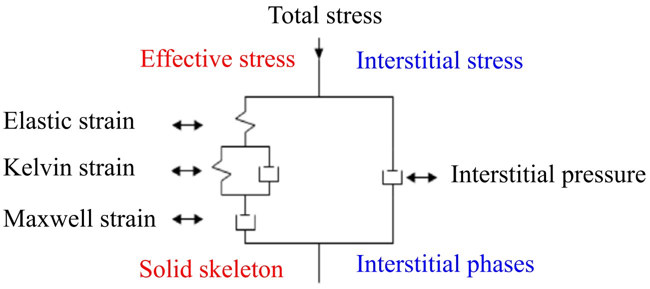

**Fig. 1.** Idealized rheological scheme for poro-mechanical creep model.

depends on the creep strain, corresponding to a consolidation phenomenon [11].

The model is formulated to be usable in finite element codes so as to handle the modelling of large structures. Thus, the concrete microstructure is not explicitly modelled, but the constitutive equations reflect several important underlying phenomena induced by concrete heterogeneity. First, the viscous phenomena are assumed to take place in the C–S–H inter-layer (idealized in stage 1 of Fig. 2), while other hydrates and aggregates are taken to be non-viscous.

When a stress is applied to the material, as symbolized by red arrows in stage (2) of Fig. 2, an instantaneous elastic response occurs. It is modelled by the elastic level in Fig. 1. However, if the stress lasts for a long time, a viscous sliding of C–S–H sheets occurs (stage (3) in Fig. 2). This sliding includes a reversible creep corresponding to the reversible arrangement of inter-layer water molecules [12]; corresponding to the Kelvin module in Fig. 1. It is also assumed that some inter-layer bonds can break and repair to form a new configuration (as in plasticity theory), leading to irreversible basic creep. This last strain corresponds to the non-linear Maxwell module in Fig. 1. When concrete is loaded, the stress in the solid skeleton transits in C–S–H and rigid inclusions (non-viscous phase in Fig. 2), but, during creep, the part of the stress supported by C–S–H inter-layer is relaxed due to its viscous behaviour, leading to a stress concentration in non-viscous phases. So, the stress increases on the non-viscous phases while it decreases by the same magnitude in C–S–H. As the creep velocity is proportional to the micro-stress applied to the C–S–H, this phenomenon leads to a creep velocity reduction assimilable to a consolidation process. This phenomenon can be modelled by the Kelvin module as long as the redistribution is reversible, However, as the C–S–H matrix surrounds all the other non-viscous phases, a purely viscous creep component is also possible, it is why a Maxwell module must be used to consider irreversible creep strain. Moreover, during the C–S–H matrix creep, a material rearrangement occurs, and a configuration that blocks the viscous flow can be reached (schematized by stage (4) in Fig. 2), where it is qualified as an interlocking phenomenon. Once the viscous flow is blocked, the stresses concentrate on the non-viscous inclusions and, if the loading level is sufficient, induce a micro structural damage (stage (5) in Fig. 2). This damage has been revealed experimentally by acoustic emission [8] but seems to have only negligible effects on elastic properties as illustrated in the experimental results provided in [13]. So the damage induced by creep takes place at a micro-level, it modifies the creep strain without changing the elastic modulus. When this damage occurs, as schematized in stage (6) of Fig. 2, it allows a new viscous flow until the next interlocking occurs on another site where non-viscous phases are not yet damaged. The relative importance of reversible creep and permanent creep depend on the proportion of elastic inclusions per unit volume of material as shown in homogenization creep

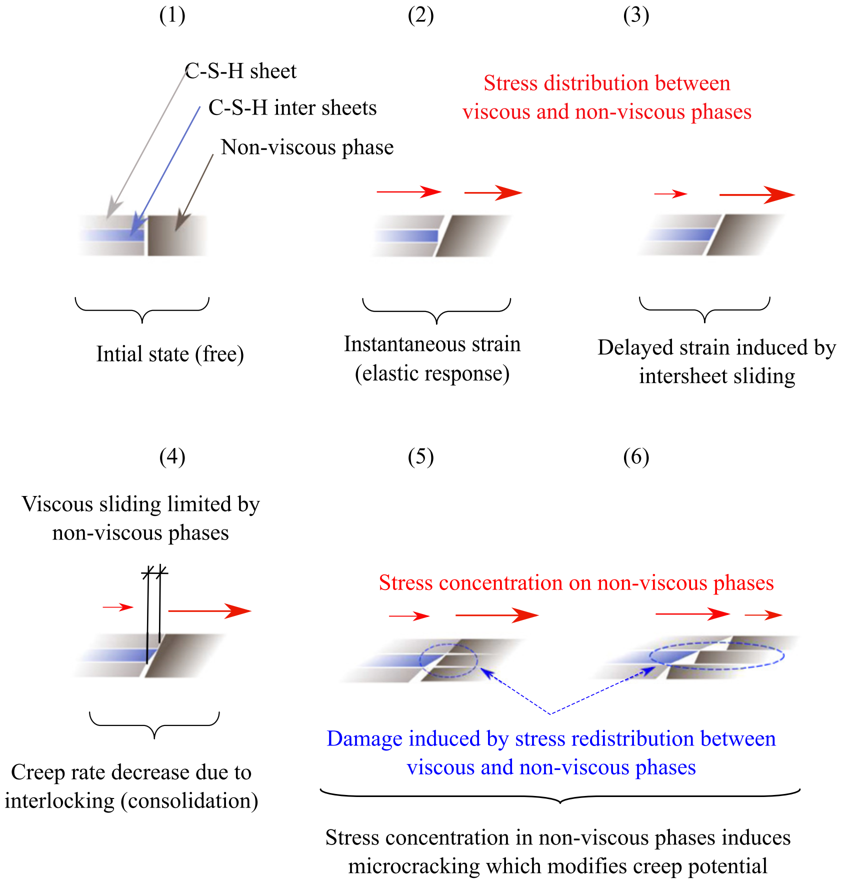

**Fig. 2.** Idealized underlining phenomena of basic creep.