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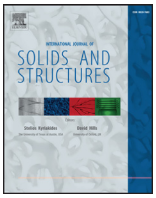

A multiaxial load-induced thermal strain constitutive model for concrete

Giacomo Torelli[a,*], Martin Gillie[a], Parthasarathi Mandal[a], Van-Xuan Tran[b]

[a] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, UK
[b] EDF Energy, R&D UK Centre, SW1×7EN, 40 Grosvenor Place, London, UK

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ABSTRACT

The paper presents a novel thermomechanical 3D Load-Induced Thermal Strain (LITS) model that captures the experimentally demonstrated behavior of concrete in the case of heating under multiaxial mechanical load, for temperatures up to 250 °C. In contrast to the models available in the literature, the new model takes into account the observed dependency of LITS on stress confinement. Such a dependency is introduced through a confinement coefficient which makes LITS directly proportional to the confinement of the stress state. Also, a new practical bilinear LITS model is proposed and proved to be suitable for fitting the general trend of the curves experimentally obtained for different loading conditions. The presented model is embedded in a thermoelastic material constitutive law, and then verified and validated against experiments performed on concrete specimens subjected to transient temperatures up to 250 °C under uniaxial, biaxial and triaxial compressive stress states. Once calibrated and validated, the constitutive model is used to evaluate the effects of LITS on the structural behavior of a Prestressed Concrete Pressure Vessel (PCPV) of a typical Advanced Gas cooled Reactor (AGR) subjected to a heating-cooling cycle simulating a temporary fault in its cooling system. The results of this study indicate that the development of LITS significantly influences the stress redistribution in the structure. Moreover, it is shown that in the case of PCPVs (and by extension similar structures) it is crucial to consider the LITS dependence on the stress confinement.

1. Introduction

Load induced thermal strain, or LITS, is a strain component that develops when concrete is heated while subjected to compressive stress states. Several studies have demonstrated that accurate and robust modeling of this strain component is crucial for reliably assessing the effects of heating-cooling cycles on concrete structures (Law and Gillie, 2008; De Borst and Peeters, 1989; Anderberg and Thelandersson, 1976; Schneider, 1976). Most of the available experimental and theoretical works focus on the development of LITS for uniaxial compressive stress states, providing a good basis for assessing the behavior of concrete framed structures, such as typical offices. However, little attention has been paid to the development of LITS in bulk concrete structures where the stress state is expected to be multiaxial, such Prestressed Concrete Pressure Vessels (PCPV) of nuclear reactors, tunnels and vaults. With this in mind, the present paper presents a novel and robust 3D LITS material model which overcomes some of the shortcomings of the models available in the literature.

When heated in the absence of mechanical load, concrete exhibits a volumetric thermal strain usually referred to as Free Thermal Strain (FTS). Such strain is generally expansive and is due to the interaction of different phenomena affecting the structure of the material, such as shrinkage of the cement paste and thermal expansion of the aggregates. Experimental evidence shows that if heated concrete is subjected to uniaxial compressive stress, a smaller thermal strain occurs in the direction of the load than in the case of free thermal expansion. It is this additional thermal strain component, which is defined as LITS. In other words, LITS may be seen as the difference between the thermal strains developing in the cases of concrete subjected to constant compressive stress and stress-free concrete.

According to this definition, LITS includes several strain components which are due to the development of various coupled mechanisms on heating under compressive load. Specifically, LITS includes an increment in elastic deformation due to the degradation of the elastic modulus with increasing temperature, basic and drying creep strains which develop on heating and an additional strain

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[*] Corresponding author.
E-mail address: giacomo.torelli@manchester.ac.uk (G. Torelli).

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component usually referred to as Transient Thermal Creep (TTC) (Gross, 1975; Anderberg and Thelandersson, 1976; Hager, 2013; Schneider, 1988; Khoury et al., 1985). TTC is the biggest component of LITS (Anderberg and Thelandersson, 1976; Khoury et al., 1985). It is an irrecoverable strain due to the physical disintegration and chemical reactions that take place in the cement paste for temperatures up to 300–400 °C, together with the thermomechanical damage of concrete produced by the thermal incompatibility between cement paste and aggregates for higher temperatures (Schneider, 1976; Mindeguia et al., 2013; Thelandersson, 1974). For these reasons, and based on empirical research, LITS is commonly regarded, and modeled, as a quasi-instantaneous strain component which develops only on first heating under load, i.e. it does not recover on cooling or develop further on reheating unless the first heating temperature is exceeded (Mindeguia et al., 2013; Thelandersson, 1974; Petkovski and Crouch, 2008; Colina and Sercombe, 2004; Illston and Sanders, 1973; Parrott, 1979). For a full description of LITS and survey of previous studies, see the recent review by Torelli et al. (2016).

A common method for modeling LITS in the case of uniaxial loading is to assume its development on first heating depends only on temperature and stress: $\varepsilon_{lits}(\sigma, T)$. LITS is generally assumed to be linear with the stress level, defined as the ratio between the compressive stress σ and the compressive strength σ_{u0} of the material, and strongly nonlinear with temperature (Anderberg and Thelandersson, 1976; Mindeguia et al., 2013; Khoury et al., 1985). Among published models, the evolution of LITS with temperature has been formulated directly, expressing the LITS as a polynomial function of the temperature (Terro, 1998; Pearce et al., 2004; Nielsen et al., 2002; Li and Purkiss, 2005), or indirectly, assuming LITS to be directly proportional to the FTS (Anderberg and Thelandersson, 1976). Whilst it is more practical, an indirect formulation of LITS seems to contrast with some experiments, where the LITS and FTS functions of temperature have been proved not to be proportional for some types of concrete (Petkovski and Crouch, 2008).

Normally, 3D LITS models are obtained from uniaxial models by assuming that if concrete is heated while compressed in one direction, it develops expansive LITS in the two directions perpendicular to the compression (Mindeguia et al., 2013; Petkovski and Crouch, 2008; Kordina et al., 1986). This leads to a constitutive formulation where the proportionality between the stress tensor and LITS increment tensor depends on an additional material coefficient, ν_{LITS}. This is defined as the negative ratio of transverse to axial LITS strain (De Borst and Peeters, 1989; Pearce et al., 2004; Gawin et al., 2004; Khennane and Baker, 1992; Thelandersson, 1987; Gernay et al., 2013). Such models rely on the superposition principle, i.e., the state of LITS caused by a multiaxial compressive stress state is assumed to be equal to the sum of the states of LITS which would have been caused by each stress component individually.

In fact, a critical analysis of the few multiaxial LITS tests available in the literature reveals that the development of LITS does not follow the superposition principle exactly. Specifically, for multiaxial stress states, LITS strains are significantly bigger than those predicted by superimposing the LITS produced by each stress component individually (Petkovski and Crouch, 2008; Kordina et al., 1986; Thienel and Rostásy, 1996; Ehm and Schneider, 1985). In other words, the triaxial development of LITS depends on the confinement of the stress state. In the light of this, this paper presents a novel 3D LITS constitutive model which captures the experimentally observed confinement-dependency of LITS and its numerical implementation. Experimental results for multiaxial LITS currently exist for temperatures up to 250 °C and these results are incorporated in the model. For temperatures higher than 250 °C, assumptions must be made about multi-axial LITS behavior. However, the method for extending uniaxial LITS curved to 3D is formulated so future results can be added to it. Following the presentation of the LITS model, it is applied to an indicative problem – that of a nuclear PCPV vessel under heating due to fault conditions. It is shown that failing to use an accurate multiaxial-LITS model for such problems, may lead to non-conservative estimates of the stress and strain states.

2. LITS model

2.1. Confinement-based modeling approach

This section aims to present a novel approach for a 3D implementation of uniaxial temperature-LITS functions.

2.1.1. Traditional approach

Uniaxial LITS curves are commonly extended to 3D by assuming that the behavior of concrete heated under mechanical load does not depend on the confinement of the stress state (De Borst and Peeters, 1989; Pearce et al., 2004; Gawin et al., 2004; Khennane and Baker, 1992; Thelandersson, 1987; Gernay et al., 2013):

$$\dot{\varepsilon}_{ij}^{lits} = \frac{\beta(T)}{\sigma_{u0}}\left(-\upsilon_{lits}\sigma_{kk}^{-}\delta_{ij} + (1+\upsilon_{lits})\sigma_{ij}^{-}\right)\dot{T} \tag{2.1}$$

where $\dot{\varepsilon}_{ij}^{lits}$ is the ith jth component of the time derivative of the LITS tensor; $\beta(T)$ is the LITS derivative function, i.e. a function of temperature which describes the derivative of LITS with respect to temperature for a given stress level; σ_{u0} the concrete uniaxial compressive strength; σ_{ij}^{-} the ith jth component of the negative projection of the stress tensor; υ_{lits} a material parameter defined as the negative ratio of transverse to axial LITS strain, analogous to the elastic Poisson's modulus υ; and $\dot{T}$, the time derivative of temperature. Considering the negative projection of the stress tensor in Eq. (2.1) ensures LITS is produced by only the compressive stress components, as required. The total number of material parameters involved in a 3D LITS model is given by the sum of the parameters included in the LITS derivative function $\beta(T)$ and the ones needed in its 3D implementation. As evident from Eq. (2.1), two material parameters are introduced when a uniaxial LITS curve is extended to 3D through the traditional approach: the concrete compressive strength σ_{u0} and the LITS Poisson's modulus υ_{lits}.

2.1.2. LITS dependency on the stress confinement

The traditional formulation described in (2-1) is based on the assumption that the LITS state produced by a multiaxial compressive stress states is the sum of the LITS states produced by uniaxial loads individually. However, this assumption contrasts with the experimentally observed concrete behavior in the case of multiaxial stress states, which show that the degree of LITS depends on the stress confinement (Petkovski and Crouch, 2008; Kordina et al., 1986; Thienel and Rostásy, 1996; Ehm and Schneider, 1985). This is exemplified by Fig. 1, which shows that the LITS obtained in Petkovski and Crouch (2008) for equal biaxial and hydrostatic compression in the loaded and unloaded directions is significantly greater than the one predicted through the superposition principle. Specifically, the underestimation of LITS obtained through the superposition principle is greater for hydrostatic than for equal biaxial compression, suggesting that LITS state grows with the stress confinement.

To date, the precise mechanisms behind the confinement dependency of LITS are not fully understood. Based on experimental evidence, such a phenomenon could be explained by postulating the confinement-dependency of two of the mechanisms underlying LITS: micro cracking effect and micro diffusion.

Micro cracking effect is commonly considered to be a source of drying creep (Bazant, 1994; Bazant and Chern, 1985; Bažant and Raftshol, 1982; Cohen et al., 1990), i.e. the excess in creep