Constitutive models for the viscoplasticity and damage of thermoplastic polymers

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Habilittion thesis

Abstract

This thesis presents a summary of the author's main scientific contributions between 2012 (the date of the author's PhD defence) and 2020, in the field of experimental analysis and simulation of the mechanical behaviour of advanced materials. The focus of the Habilitation is represented by the numerical modelling approaches used for thermoplastic polymers. Results from other research topics that the author was concern with will also be briefly presented.

The Habilitation thesis is divided in three sections. The first section consists of a short introduction, where the author's scientific and academic backgrounds are briefly presented, along with an outline of the thesis.

The second section of the thesis, which encompasses the main topic of the Disertation, is composed of two chapters: *Viscoplasticity of thermoplastic polymers* and *Damage and failure of polymers*.

The first of the two chapters begins with a brief presentation of the experimental results on various polymeric compounds. The main focus was the showcasing of the viscoplastic behaviour of this class of materials through both monotone and cyclic tests. Two parameters were identified as major factors for the non-linear behaviour: temperature and time (through the effects of the strain rate and long-term loading). Apart from the significant effect on stiffness and strength (which increase proportionally with the strain rate and decrease with temperature), a peculiarity of thermoplastic polymers is that, at different temperatures, the same compound can exhibit either brittle or ductile characteristics.

In the second part of this chapter, three formulations were evaluated for their accuracy in modelling the stress-strain response of thermoplastic polymers at different strain rates and temperatures: the viscoelastic formulation, the elastic-plastic formulation and the viscoplastic formulation. For the viscoelastic formulation, the Wiechert model showed the best results, when compared to the other investigated rheological models. For the elastic-plastic formulations, three

models were presented: the Zerilli-Armstrong model, the Johnson-Cook model and the Multi-linear hardening model, with the latter exhibiting the optimal response. Two viscoplastic models were investigated: the Bingham-Maxwell model and the Two-layer viscoplastic model. Even though the TLV model can yield the best results in modelling the viscoplastic effects, its calibration is rather cumbersome. In consequence, for simpler applications, the MLH model is recommended in the case of monotone loadings and the Wiechert model for the case of cyclic loadings at low strains.

The chapter entitled *Damage and failure of polymers* is concerned with the experimental determination and numerical approximation of the failure of thermoplastic polymers when subjected to various loading conditions. The considered failure model was initially developed for metals and it assumes that the failure in ductile materials is caused by the nucleation and subsequent growth of voids in the material during straining (phenomenon also observed in polymers). From a mathematical standpoint, this formulation considers that the critical plastic strain (responsible for the void nucleation) is a function of three tensor invariants: the first invariant of the total stress tensor (the hydrostatic pressure) and the second (through the von Mises equivalent stress) and third (through the Lode angle) invariants of the stress deviator tensor.

For the calibration of the model, several experimental procedures were considered: tensile tests on flat notched specimens, compression tests on round notch specimens and Arcan tests. Numerical analyses were performed with identical test conditions in order to determine the critical plastic strain, stress triaxiality and Lode angle parameter. The results were combined into a damage model that accounts for a wide range of stress triaxiality variation and it was evaluated using simulations that replicate the compression of a metamaterial structure with open Kelvin cells, yielding accurate results.

The third section of the thesis presents the scientific achievements (complete list of publications and research Grants), the scientific development plan and results from other research topics, which are divided in three categories: polymeric foams, metamaterial structures and geopolymer composites.

The research into polymeric foams was mainly centred on un-reinforced and long fibre reinforced polyurethane rigid foams and was concern with the static and dynamic characterization, morphology and microstructural analyses and damage/fracture. For the topic of metamaterial structures, various types of periodic geometries were analysed, manufactured and tested, with the goal of determining optimal configurations. Concerning the geopolymer composites topic, wood fibre reinforced fly ash composites were investigated experimentally and concrete damage plasticity models were calibrated with good results.

The scientific development plan contains a brief presentation of the future research topics. The first topic represents a continuation of the current research into the viscosity, plasticity and fatigue of polymers. The focus will be on the development of yield surfaces and yield potentials specific for polymers and the investigation of the ductile failure hypothesis for a wider range of materials. Another topic of interest is related to metamaterial structures and the continued search for structure optimization in terms of mechanical properties as well as manufacturing. The multi-scale modelling of woven fibre reinforced polymers will also be a priority, with the aim of developing macro-scale constitutive models for elasticity, plasticity and damage based on limited data provided by pre-impregnate manufacturers