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Modelling of the post yield response of amorphous polymers under different stress states

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ABSTRACT

In this contribution, an elasto-viscoplastic constitutive model based on the single mode EGP (Eindhoven Glassy Polymer) model is proposed to describe the deformation behaviour of solid polymers subjected to finite deformations under different stress states. The polymeric material examined in this work is a specific commercial grade of Bisphenol, a polycarbonate called Makrolon 2607, for which there were experimental results available in the open literature for: uniaxial compression, plane strain compression and tensile test on a dumbbell shape specimen. The material properties of the original model are determined and calibrated from a uniaxial compression-loading test. Then, several numerical examples under different stress states are presented to illustrate the limitations of the single mode EGP model. A more general elasto-viscoplastic model is proposed, which preserves the isotropy of the original model, using the lode angle parameter to distinguish shear-dominated stress states and capture the material post yield response. The numerical treatment of the model, including the state update procedure and also the consistent tangent operator, required for the finite implementation of the model within an implicit finite element scheme, is presented. A comprehensive set of numerical examples is employed to compare the predictions of the original and new models against experimental results and to investigate the effect of the proposed modifications. The numerical results show that the proposed model provides a closer agreement with experimental evidence and opens the possibility for computational simulations of amorphous polymers under different stress states.

1. Introduction

Polymers have become very important materials in structural applications due to their interesting properties such as being good thermal and electrical insulators, and exhibiting lower density and higher yield strains when compared to metals. In addition, one of the most interesting characteristics of polymers is that complicated shapes can be easily fabricated using processes such as extrusion, injection molding and thermoforming. Some of the areas for the application of polymers are

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electronic products (e.g. sensors), automotive industry (e.g. side view mirrors), healthcare (e.g. heart valve prosthesis), and civil and buildings engineering (e.g. pipes) (Mackerle, 2003).

Over the last century, a considerable effort has been devoted to the development of material models capable of reproducing the experimentally observed data. It can be said that the initiation of the efforts to determine the behaviour of polymers dates back to 1930s. Eyring (1936) proposed a molecular theory for the yield stress of amorphous polymers, considering the yield behaviour as a thermally activated process. Temperature and strain rate effects are accounted for, in the theory. Mooney (1940) proposed a strain energy function for rubber elastic materials. Haward and Thackray (1968) developed a one dimensional constitutive model for glassy polymers. The work could be considered as the initial constitutive model proposed for predicting the deformation behaviour of glassy polymers. According to this work, the post yield behaviour of glassy polymers includes two different phases: first, a rate dependent plastic flow, modelled by an Eyring dashpot, and second, a rate independent contribution of the entanglement, modelled by a Langevin spring. The three dimensional version of Haward and Tackray model was proposed by Boyce et al. (1988). An alternative constitutive model that is able to predict the typical deformation behaviour of polymeric materials is the generalized compressible Leonov model, which has been proposed by Baaijens (1991) and extended by Tervoort et al. (1998) and Govaert et al. (2000). Over the last decades, a wide range of constitutive models incorporating linear and non-linear visco-elastic and visco-plastic material behaviour have been developed to capture different aspects of the behaviour of polymers including molecular orientation, strain rate effects, failure, thermo-mechanical effects, among others (Mulliken and Boyce, 2006; Richeton et al., 2007; Miehe et al., 2009; Anand et al., 2009; Ames et al., 2009; Li and Buckley, 2010; Bouvard et al., 2013; Zhang and To, 2016; Srivastava et al., 2010).

It is known that classical yield criteria are not able to characterize yielding of polymers properly (Ghorbel, 2008). Several researchers have devoted their research to develop modified versions of classical plasticity theories in order to adequately describe the yield behaviour of polymers. Modified versions of von-Mises, Tresca and Drucker-Prager yield criteria are used by different authors, e.g. (Ghorbel, 2008; Bowden and Jukes, 1972; Raghava et al., 1973; Fasce et al., 2008; Epee et al., 2011), in order to describe the yield behaviour of different polymers. For a detailed discussion, the reader is referred to (Ghorbel, 2008). Nevertheless, constitutive models capable of characterizing the post-yield response of polymers under different loading conditions are still lacking. In contrast to metallic materials, which show hardening after the yield point, some polymers show pronounced post yield softening and then hardening. After the yield point, the true stress decreases while increasing the strain. The phenomenon is called strain softening. During strain softening, the deformation proceeds at decreasing true stress levels. The physical justification for the softening behaviour is not yet perfectly understood but it seems to be related to physical aging process (Govaert et al., 2000). Plastic localization phenomenon in deformation of glassy polymers is known to be mainly caused by the strain softening behaviour (Govaert et al., 2000) and thus, it is very important to capture it properly. Besides, if the softening regime is not characterized well, the final hardening regime might not be captured properly either.

One of the important issues raised in material constitutive modelling and material parameter identification is that the material properties obtained from one specific stress state (e.g. uniaxial compression or tension) do not provide good estimation of the material behaviour in other stress states. In other words, in order to have good estimation of material behaviour under different stress states, one set of material properties may, most likely, not suffice. Typically, there are three approaches to overcome the issue as follows. First, introducing additional material parameters; second, calibrating the material properties from one stress state to the other and third, developing a constitutive model capable of predicting the deformation behaviour under different loading conditions properly with a specific set of material properties. The objective of this work is to extend the constitutive equations of the EGP based model presented by Mirkhalaf et al. (2016) using the third deviatoric stress invariant (or lode angle parameter) in order to capture the post-yield behaviour of polymeric materials, namely post-yield softening and hardening regimes under different stress states.

Experimental results for a polycarbonate with trade name Makrolon 2607, under three different stress states: uniaxial compression, plane strain compression and tensile test on a dumbbell shape specimen, are taken from (Diez, 2010). Material properties of the elasto-viscoplastic model presented by Mirkhalaf et al. (2016) are quantified and calibrated for uniaxial compression. The material parameters are used for plane strain compression and the tensile test on the dumbbell shape specimen and it is shown that the prediction of the model (using properties obtained for uniaxial compression) for the later stress states is not in agreement with experimental evidence. Based on the observations in the comparisons, some modifications are proposed to improve the predictions of the model.

This paper is structured as follows. Section 2 presents the main equations of the original constitutive model which is used in this study. Section 3 describes how to quantify the material parameters required by the constitutive model. In addition, some simulations, uniaxial compression, plane strain compression and tensile test on a dumbbell shape specimen, are performed using the properties. In Section 4, the propositions to modify the predictions of the model for softening and hardening are provided. Section 5 provides the integration algorithm and finite element implementation of the enhanced model. Evaluation of the predictions of the improved model is given in section 6. Finally, some concluding remarks are provided in section 7.

2. Original model

In this section, the hyper-elastic based finite strain elasto-viscoplastic constitutive model which is used and modified in this study is briefly presented. The main features of this approach, particularized for the developed model, include the