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Estimation of creep strain and creep failure of a glass reinforced plastic by semi-analytical methods and 3D numerical simulations

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ABSTRACT

Glass reinforced plastics based on polyvinyl chloride (PVC) is a material of choice for construction applications, such as pipes. The lifetime of pipes may be limited by creep failure and polymers exhibit a viscoelastic response that depends on the time of loading. In this paper, homogenization methods are designed to upscale the viscoelastic properties of a composite material made of chopped glass fibers with random orientations and PVC. The estimates of the Mori–Tanaka scheme and 3D numerical computations for creep strains and creep failure are compared, validating the Mori–Tanaka model as a practical tool to predict the effect of fiber length and volume fraction of fibers on creep strain and creep failure. In particular, it appears that, for a given creep load, the lifetime of the material is increased if the volume fraction of fibers increases or if the length of fibers decreases, as long as the failure mode is fiber breakage.

1. Introduction

Polyvinyl chloride (PVC) is a material of choice for construction applications, such as pipes for water and gas, house sidings or window frames where long service life is required (Rabinovitch and Summers, 1992). The European demand of PVC was 5000 ktons in 2012 (PlasticsEurope, 2013). Many polymers may be part of composite materials, such as fiber-reinforced materials. For instance, glass fibers may be incorporated into a polymer matrix such as PVC to increase stiffness, creep resistance and dimensional stability (Rahrig, 1985; Kinson and Faber, 1992; O'brien-Bernini et al., 2006). The effect on tensile strength of glass fibers depends on the volume fraction of inclusions, on the fiber length and on fiber orientation. These parameters can be significantly affected by processing operations (Tungjitpornkull and Sombatsompop, 2009; Hohe et al., 2015).

In case of water pipes, different permanent loads coexist. Cooling after extrusion could trigger internal tensile stress in the range 1.5 to 4.8 MPa on the inner diameter, the water pressure induces a permanent hoop stress and additional stresses can occur as a result of non-uniform soil settlement (Breen and in't Veld, 2006). The lifetime of such pipes depends on the operating conditions and on the mechanical properties of the constitutive materials.

Glass reinforced plastic pipes may feature a complex structure, including chopped strand mat layers on the inner side and filament wound layers on the outer side (Guedes et al., 2010; Diniz Melo et al., 2011; Rafiee and Reshadi, 2014). Short-time hydraulic failure occurs on the inner diameter (Diniz Melo et al., 2011). Ring deflection tests may be performed according to standard ISO 9967 to estimate the time-dependent strain of a pipe and study the long term creep failure (AFNOR, 9967;

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Guedes et al., 2010). In this case, failure mode was always the same, fiber breakage, and always localized in the same region, on the inner diameter (Guedes et al., 2010). The strain at failure is almost constant, slightly decreasing with the time elapsed since loading. An internal pressure test is defined by the standard ASTM D2992 to estimate the long term static hydrostatic strength of glass-fiber-reinforced pipes (ASTM, 2012). The time-to-failure is expected to depend on the pressure level, following a power law. Hence, studying the viscoelastic behavior of glass reinforced plastics is required to adjust delayed fracture criterion (Guedes, 2012) and estimate the lifetime and durability of such pipes.

Polymers exhibit a viscoelastic response that depends on the time of loading t'. This phenomenon is described as physical aging. It is well known that the viscoelastic properties of polymer glasses are significantly influenced by a physical aging process (Struik, 1978; Sullivan, 1990; Odegard and Bandyopadhyay, 2011). This is the reason why the standard ISO 9967 specifies both the temperature (23 ± 2 °C) and the age of the samples at loading (21 ± 2 days), measured since quenching. Experimental evidences on creep properties of various polymer materials below the glassy temperature have been gathered by Struik (1978) and further creep tests have been performed on PVC since Read et al. (1992) and Zhou et al. (2012). A PVC quenched from 90 °C to 20 °C at starting time $t_0 = 0$ is considered in the present study.

This article is focused on the aging creep and failure of the chopped mat strand layer of the pipe, modeled as a composite material made of E-glass fibers and PVC. Homogenization methods are designed to upscale the viscoelastic behaviors of such materials. Mean-field homogenization schemes such as the one of Mori–Tanaka (Mori and Tanaka, 1973; Wang and Weng, 1992; Li et al., 2006) or coupling the single fiber problem and the rule of mixture (Hohe et al., 2015) produce estimates of these elastic properties while taking account of fiber aspect ratio and distribution of orientations. Complete modeling of the failure of fiber-reinforced plastics, including damage of fibers and matrix, have been performed by Sasayama et al. (2013) and Hashimoto et al. (2012). Some of these micromechanical approaches have recently been able to treat aging linear viscoelastic materials and their accuracy is to be checked by numerical simulations (Ricaud and Masson, 2009; Sanahuja, 2013; Šmilauer and Bažant, 2010).

Mean-field homogenization schemes and 3D numerical simulations of matrix-inclusion materials have been compared in the range of elasticity (Iii and Liang, 1999; Moussaddy, 2013; Ghossein and Lévesque, 2014; Moumen et al., 2015). The case of elongated or flat inclusions has been explored (Iii and Liang, 1999; Moussaddy, 2013; Ghossein and Lévesque, 2014) with the conclusion that Lielen's model (Lielens et al., 1998) was the most accurate one provided that the inclusion is stiffer that the matrix. Such comparisons have also been performed on viscoelastic (Lahellec and Suquet, 2007), plastic (Pierard et al., 2007a) or viscoplastic (Pierard et al., 2007b; Lahellec and Suquet, 2007) matrices to assess the accuracy and performances of different methods. Lahellec and Suquet (2007) have used 2D full finite element simulations to validate a semi-analytical scheme which combines the Hashin–Shtrikman estimate for periodic materials and a time-stepping procedure to compute the in-plane time-dependent strain of aligned circular fibers in a viscoelastic matrix. The range of applications of such models depends on the contrast between phases and volume fraction of inclusions.

The objective of the present article is to estimate the aging viscoelastic behavior and creep failure of a E-glass fiber reinforced PVC. Therefore, the Mori–Tanaka scheme is to be compared to full-field computations. The main features of the model presented in this article are:

1. Both the Mori–Tanaka scheme and the 3D numerical procedure rely on a time-shift procedure to account for the aging creep of PVC.
2. The Mori–Tanaka scheme and a 3D numerical procedure are presented and successfully compared.
3. The influence of volume fraction of fibers and length of fibers are investigated.
4. An estimate of creep failure related to the strength of glass fiber, based on the largest principal stress (Rankine criterion), is proposed.

The behavior of each phase is described and the microstructure is presented in the first section. The methods to obtain the overall property are briefly recalled. The outputs of these methods are compared in the second section and the effect of the length of fibers and of the volume fraction of fibers on the time dependent strain and creep failure are estimated.

2. Microstructure: geometry and mechanical properties

2.1. A short-fiber reinforced plastic

The polymer-based composite that is described in the present article will be a mix of hard PVC and short E-glass fibers. Fig. 1(a) shows the microstructure of the considered material (Rahrig, 1985).

In the considered fiber-reinforced material, elastic inclusions are added to the viscoelastic matrix, their elastic stiffness being the one of E-glass fibers: the Young modulus is $E = 80$ GPa and the Poisson's ratio is $\nu = 0.22$ (Wallenberger et al., 2001; AGY, 2001; Mounier et al., 2012). These inclusions are assumed to be cylindrical chopped fibers, with a diameter of 10 μm and a length of 100 μm. The distribution of their directions is chosen as isotropic and their volume fraction is 15%. The density of E-glass being about 2.55 and the one of PVC being about 1.35, a weight ratio of 34 phr (part per hundred part of resin) corresponds to a volume fraction of 15%. Above 50 phr (or 20% volume fraction), processing difficulties may appear during the extrusion (Rahrig, 1985).

The considered chopped strand mat features shorter fibers than the one used in automotive applications (Haque, 2007) (11–75 mm) or pipes, comparable to fibers used for flooring materials (0.2–1 mm) (Nakano, 2003). The considered microstructure could be similar to the one obtained by the use of chopped strand glass as