International Journal of Plasticity 63 (2014) 152–169

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

Negative through-the-thickness Poisson's ratio of elastic–viscoplastic angle-ply carbon fiber-reinforced plastic laminates: Homogenization analysis

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ARTICLE INFO

Article history:
Received 4 October 2013
Received in final revised form 24 February 2014
Available online 9 June 2014

Keywords:
A. Microstructures
B. Fibre-reinforced composite
B. Elastic-viscoplastic material
C. Finite elements
Negative Poisson's ratio

ABSTRACT

Negative through-the-thickness Poisson's ratios are investigated macroscopically and microscopically in the elastic–viscoplastic behavior of angle-ply carbon fiber-reinforced plastic (CFRP) laminates. For this purpose, an analysis method is proposed based on a homogenization theory for nonlinear time-dependent composites with point-symmetric internal structures. This method is able to efficiently analyze both the macroscopic and microscopic elastic–viscoplastic properties of angle-ply CFRP laminates fully modeled with microstructures consisting of fibers and a matrix. Using the proposed method, the elastic–viscoplastic analysis of angle-ply carbon fiber/epoxy laminates with various laminate configurations is performed to investigate their Poisson's ratios in the viscoplastic region. It is revealed that, for a range of laminate configurations, the through-the-thickness Poisson's ratios exhibit negative values which become increasingly negative as the viscoplastic deformation progresses in the laminates. The effect of strain rate on this increasing negativity is also demonstrated, and microscopic mechanisms are investigated to explain this trend. It is further shown that the increasing negativity significantly affects microscopic interlaminar stress distributions.

1. Introduction

Composites consisting of reinforcements and matrix materials have become indispensable in modern engineering. They can be designed to achieve desirable properties by reinforcing matrix materials, mainly polymers, metals or ceramics, with a variety of long fibers, short fibers, particles or nanomaterials. Their excellent properties, such as high specific stiffness and strength, enable high-end engineering products, including aircraft, spacecraft, transportation equipment, to be lighter and stronger, resulting in higher energy-efficiency. Such advanced uses of composites expose them to severe conditions such as high temperature and high stress. Modeling of the inelastic behavior of composites has thus become increasingly important (e.g. Kawai et al., 2010; Vyas et al., 2011; Chen and Ghosh, 2012; Guo et al., 2013; Lahellec and Suquet, 2013; Prabhakar and Waas, 2013a,b).

Among the various types available, carbon fiber-reinforced plastic (CFRP) laminates manufactured by stacking laminae reinforced unidirectionally by long carbon fibers are regarded as one of the most successful composites. Accordingly, a

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http://dx.doi.org/10.1016/j.ijplas.2014.05.007
0749-6419/

significant body of research exists for inelastic analysis of CFRP laminates (e.g. Mishnaevsky and Brøndsted, 2009; Liu and Zheng, 2010). Many of these studies demonstrated the strongly anisotropic behavior of CFRP laminates due to their microstructures, which is one of their most typical characteristics and is entirely dissimilar to conventional homogeneous materials. Strong anisotropy of CFRP laminates is also observed through the Poisson's effect. In general, their in-plane and out-of-plane (through-the-thickness) Poisson's ratios are significantly different. A more interesting point is that they exhibit not only anisotropy but also negativity depending on the laminate configuration (Herakovich, 1984; Clarke et al., 1994; Harkati et al., 2007). This phenomenon, called 'auxeticity', is an important issue in material design as well as from a mechanical perspective (Almgren, 1985; Lakes, 1987; Evans et al., 1991; Milton, 1992).

Negative Poisson's ratios of CFRP laminates were found in the early work by Herakovich (1984), in which the Poisson's ratios of angle-ply T300/5208 carbon fiber/epoxy laminates were analyzed using the two-dimensional lamination theory combined with a three-dimensional anisotropic constitutive equation. It was thereby shown that the through-the-thickness Poisson's ratios of the laminates strongly depended on the laminate configuration; the maximum value was over 0.4, whereas the minimum value reached about -0.2. Clarke et al. (1994) also analyzed the through-the-thickness Poisson's ratios of angle-ply T300/913 carbon fiber/epoxy laminates, experimentally confirming the negative Poisson's ratios of the laminates and showing that the negativity depended on the laminate configuration. More recent research by Harkati et al. (2007) has been devoted to evaluating the through-the-thickness Poisson's ratios of three kinds of composite laminates including glass and Kevlar fiber-reinforced plastic laminates as well as a CFRP laminate. According to their results, the carbon and Kevlar reinforced laminates exhibited negative Poisson's ratios, whereas the glass reinforced laminate did not.

The studies mentioned above, however, were limited to elastic analysis. Thus, so far, there has been no report on the effect of matrix plasticity/viscoplasticity on the negative through-the-thickness Poisson's ratios of CFRP laminates, although some studies on the negative Poisson's ratios of elastic–plastic cellular solids have been performed (Dirrenberger et al., 2012; Gilat and Aboudi, 2013). In addition, the previously mentioned studies were based on the lamination theory in which each lamina in the laminates was regarded as a homogeneous elastic material, although laminae are intrinsically heterogeneous materials composed of fibers and a matrix. If this approach is applied to the analysis of Poisson's ratios of CFRP laminates in plastic/viscoplastic regions, the following two problems will arise: (1) a macroscopic elastic–plastic/viscoplastic constitutive equation for each lamina must be constructed three-dimensionally, which is not straightforward because of its remarkably anisotropic and nonlinear behavior; and (2) the approach cannot deal with the microscopic behavior of fibers and a matrix in the laminae, resulting in insufficient understanding of the microscopic mechanisms that determine the negative Poisson's ratios of CFRP laminates.

The mathematical homogenization theory based on unit cell analysis (Bensoussan et al., 1978; Sanchez-Palencia, 1980; Suquet, 1987) is one of the most powerful methods for the multiscale nonlinear analysis of heterogeneous materials. This is because the theory enables the rigorous analysis of the nonlinear constitutive properties of heterogeneous materials directly from their microscopic information, such as the arrangement of their constituents, their material constants and internal variables. This theory has already been applied for a wide range of heterogeneous materials including cellar solids (Ohno et al., 2002; Okumura et al., 2004; Asada et al., 2009), metallic materials (Watanabe et al., 2008; Okumura et al., 2011; Paquet et al., 2011), polymer materials (Tomita and Lu, 2002; Uchida and Tada, 2013) and composites (Ghosh et al., 1996; Takano et al., 2000; Terada and Kikuchi, 2001; Carvelli and Poggi, 2001; Tsalis et al., 2013).

We also developed a homogenization theory for nonlinear time-dependent composites (Wu and Ohno, 1999; Ohno et al., 2000) and reconstructed the theory to be applicable to composites with point-symmetric internal structures (Ohno et al., 2001). The reconstructed theory was able to reduce the volume of analysis domains (unit cells) by half, providing a significant improvement of computational efficiency in the homogenization analysis. The nonlinear time-dependent homogenization theory was then applied to several inelastic analyses of composite laminates including CFRP laminates (Matsuda et al., 2002, 2003; Matsuda and Fukuta, 2010; Kaku et al., 2010) and woven laminates (Matsuda et al., 2007a, 2011). For CFRP laminates, we proposed an elastic–viscoplastic analysis method by combining the homogenization theory with the lamination theory, and analyzed the elastic–viscoplastic behavior of unidirectional, cross-ply and quasi-isotropic CFRP laminates (Matsuda et al., 2002, 2003). The method was further applied to the elastic-creep analysis of unidirectional and angle-ply CFRP laminates (Matsuda and Fukuta, 2010). Comparison between the calculated and experimental results proved the validity of the proposed method. However, these studies did not deal at all with the Poisson's ratios of the laminates.

We also developed an analysis method to investigate the microscopic interlaminar stress distribution of cross-ply CFRP laminates based on the homogenization theory for elasticity (Matsuda et al., 2007b). This method fully modeled cross-ply CFRP laminates as heterogeneous materials composed of fibers and a matrix, allowing both the macroscopic elastic properties and microscopic behavior to be analyzed simultaneously. We succeeded in analyzing the microscopic stress distribution at all locations in the laminates including interlaminar areas, and found that considerably high interlaminar shear stress was brought about by off-axis loading. The method, however, was limited to elastic situations, and was applied to only one laminate configuration (cross-ply showing no negative Poisson's ratio). Therefore, for multiscale analysis of the negative through-the-thickness Poisson's ratios of CFRP laminates in the viscoplastic region, it is worthwhile to combine the nonlinear time-dependent homogenization theory described earlier and the full modeling approach.

In this study, the negative through-the-thickness Poisson's ratios of angle-ply CFRP laminates in the viscoplastic region are investigated macroscopically and microscopically. First, a multiscale elastic–viscoplastic analysis method for angle-ply laminates is proposed based on the homogenization theory for nonlinear time-dependent composites with point-symmetric internal structures (Ohno et al., 2001). The substructure method (Zienkiewicz and Taylor, 2000) is used to enhance