Composite Structures 132 (2015) 527–535

Contents lists available at ScienceDirect

Composite Structures

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

Non-linear material modeling of fiber-reinforced polymers based on coupled viscoelasticity–viscoplasticity with anisotropic continuous damage mechanics

D. Vasiukov [a,*], S. Panier [a], A. Hachemi [b,c]

[a] TPCIM, Ecole des Mines de Douai, 941 rue Charles Bourseul, 59508 Douai, France
[b] IAM-RWTH Aachen University, Templergraben 64, 52056 Aachen, Germany
[c] GUtech, Athaibah PC 130, Muscat, Oman

ARTICLE INFO

Article history:
Available online 15 May 2015

Keywords:
Progressive damage
Viscoelasticity
Viscoplasticity
Non-linear behavior
Polymer-matrix composites (PMCs)

ABSTRACT

A meso-scale material modeling of the fiber-reinforced polymer composites is presented. This model is based on coupled anisotropic viscoelasticity–viscoplasticity with anisotropic continuous damage mechanics. The constitutive equations are derived for three-dimensional statement and integrated implicitly by using return-mapping algorithm. Viscoelasticity model implies time dependent material properties. Viscoplasticity model is based on modified Hoffman criterion with combination of the Perzyna model. Anisotropic damage model is based on extended three-dimensional damage model. Developed material model is implemented in ABAQUS/Standard and is applied for modeling glass and carbon fiber laminate composite plates with various stacking sequences. Obtained results are in high agreement with already published experimental data.

1. Introduction

The fiber-reinforced polymers (FRP) composite materials have many applications in industry and have been extensively investigated thanks to aeronautical developments in last few decades. Nowadays FRP is gaining their place for those applications for which lightweight design is required. Thus it is important to be able to predict material response for new developed composite structures. Due to anisotropy and heterogeneity of material properties as well as complex non-linear behaviour during loading, the material modeling of FRP composite is still a challenging task.

There exist many material models for non-linear constitutive behavior of FRP. Here, we will focus on modeling which is based on continuous damage mechanics (CDM) framework thus it can be classified as phenomenological (so-called meso-scale material modeling). This type of modeling considers composite ply as homogeneous material and damage effects are accounted by introducing effective properties (effective stiffness/compliance tensor) along with damage kinematics rules. These damage mechanisms stand for different degradation effects at the microscopic level. This type of methods is widely applicable in the majority of commercial and scientific software. Main idea is to define specific energy potentials for a ply and interface which depend on damage mechanisms [1]. The thermodynamic forces conjugated with damage could be defined as partial derivatives of the strain energy with respect to damage variables. One of the first model was developed by Ladeveze and Dantec [2] in which the damage mechanisms were described by three scalar variables and the accumulation of inelastic strain was accounted for in-plane shear response. Modeling of material non-linearity can involve the plasticity framework [3,4], continuous damage mechanics (CDM) [1,5,6] or coupled plasticity with CDM [2,7–9,4]. In Matzenmiller et al. [7], Maiméet al. [10], Schuecker and Pettermann [11] and Flatscher and Pettermann [12] brittle damage models with strain softening behavior were developed. Many efforts have been given to define, represent and describe correlation between micro- and meso-damage phenomena [13,14] using homogenisation of the damaged composites.

The strength prediction arises more challenges for FRP material modeling. Numerous efforts have been dedicated to these issues. One of the clearest way to put on evidence related difficulties is World Wide Failure Exercise (WWFE) [15]. First exercise is focused on two dimensional test cases and considered models which are based on very different assumption thus the predicted results were so scattered, however some theories have been chosen as preferable among the others. The further investigations of the material response and generalization to the three-dimensional case have

* Corresponding author.
E-mail addresses: dmytro.vasiukov@mines-douai.fr (D. Vasiukov), stephane.panier@mines-douai.fr (S. Panier), hachemi@iam.rwth-aachen.de (A. Hachemi).

http://dx.doi.org/10.1016/j.compstruct.2015.05.027
0263-8223/

brought the WWFE II and III. The results are discussed in Kaddour and Hinton [16] where the top theories were chosen whose prediction provide least error with experiments. These discussions and analysis are of particular interest for current development especially for plasticity and damage part of the model as well as general statement of the problem.

This work introduces development of the constitutive model for FRP composites based on viscoelasticity–viscoplasticity coupled with anisotropic continuous damage mechanics. Subsequently viscoelastic model is adopted to describe time-dependent material behaviour. Then viscoplasticity framework is applied if yield condition is satisfied that allows to consider non-linear material response and irreversible strain as function of strain rate. Finally, anisotropic damage theory of the FRP composite materials has been used to model softening effect due to meso-cracking. Constitutive model is derived for three dimensional problem statement within implicit time integration scheme. Developed model is implemented in ABAQUS/Standard via UMAT subroutine. Composite laminate materials made of E-glass/MY750 and T300/1034-C carbon/epoxy were chosen for numerical simulations which were carried out for single finite element and for multidirectional composite plate with a central hole. The results of simulations have been compared with already published numerical results and experimental data.

2. Material modeling

In this section the following key points in the material modeling for FRP composites are discussed:

- The anisotropy of time-dependency effects which is modeled within anisotropic three-dimensional viscoelasticity theory.
- The anisotropy of irreversible strain accumulation, in its turn involved the visco-plasticity theory with kinematic hardening. It takes place for matrix driven material response.
- Damage mechanisms and material degradation which is defined within continuous damage mechanics.
- Development of the constitutive model in order to take into account hydrostatic pressure sensitivity of the FRP composites which cannot be ignored.

Number of the material models presented in literature, despite of their great development within meso-scale constitutive modeling for FRP composites, do not consider general stress state and were limited to the plane stress statement with reduced definition of the yield surface, damage criterion and material response itself. Moreover, non-linear effects due to viscoelasticity, viscoplasticity and/or damage mechanisms are often ignored.

The proposed material model is developed with accordance to the arguments mentioned above. Generally three characteristic responses are distinguished for plane stress case as shown on Fig. 1. These responses are extended for three dimensional stress state. It is assumed the elastic-brittle damage in fiber direction, i.e. no inelastic strain and no time-dependency effects can be developed (Fig. 1(a)). In contrast to fiber direction, transverse and shear responses are non-linear (Fig. 1(b) and (c)) with anisotropy of viscoelastic, viscoplastic and damage mechanisms. The general stress state leads to more complex definition of viscoelastic, viscoplastic and damage potentials. For the sake of simplicity in the explanations, the initial one dimensional material model is presented on Fig. 2 where three main blocks are organized in series. The VE block is defined in form of the generalized standard linear solid of Kelvin–Voigt type. Therefore the total strain rate is decomposed into three terms:

$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}^{e} + \dot{\boldsymbol{\varepsilon}}^{v} + \dot{\boldsymbol{\varepsilon}}^{vp} = \dot{\boldsymbol{\varepsilon}}^{ve} + \dot{\boldsymbol{\varepsilon}}^{vp}, \tag{1}$$

where dot on top of the symbols denotes time derivative, $\boldsymbol{\varepsilon}^{ve}$ and $\boldsymbol{\varepsilon}^{vp}$ stand for viscoelastic (or reversible) and viscoplastic (or irreversible) strain tensor, respectively. Thus considering FRP materials, the Gibbs free energy potential is decomposed into two parts: one is associated with damage and other with inelastic dissipation:

$$\mathcal{G}(\boldsymbol{\sigma}, \mathbf{d}, \boldsymbol{\alpha}) = \mathcal{G}^{ve}(\boldsymbol{\sigma}, \mathbf{d}) + \mathcal{G}^{vp}(\boldsymbol{\alpha}), \tag{2}$$

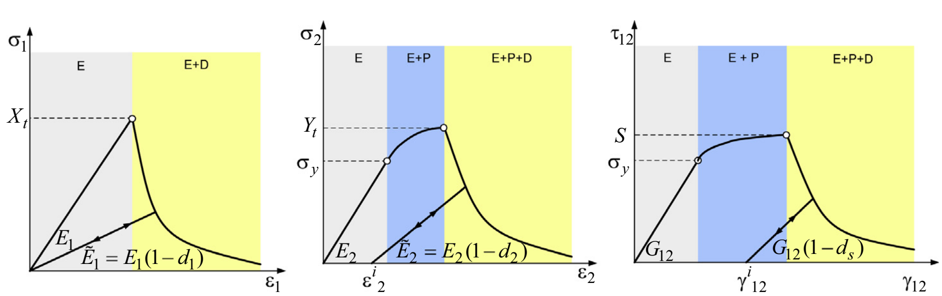
where $\{\boldsymbol{\sigma}, \mathbf{d}, \boldsymbol{\alpha}\}$ are internal second-order tensor variables denoting stress, damage and kinematic hardening, respectively; thermodynamic associated variables: $\{\boldsymbol{\varepsilon}^{vp}, \mathbf{Y}, \mathbf{X}\}$ stand for plastic strain, thermodynamical forces conjugated with damage and back-stress tensor, respectively.

2.1. Anisotropic viscoelasticity

Development of the meso-scale constitutive model is started from the viscoelastic anisotropic constitutive model. The viscoelastic block (VE on Fig. 2) is included for description of the time-dependent properties of the polymer matrices which are clearly observed in creep or relaxation tests. The developed viscoelastic model will focus on prediction of short-time creep loading cases (only 750 h data were considered). If a longer-term description is required then the model has to be extended. No temperature effects were included in the modeling, therefore the model can be applied for material at temperature which is less than glass transition temperature (T_g) of polymer matrix of the composite. An efficient integral form of general non-linear viscoelastic material has been proposed by [17] according to which the viscoelastic strain is defined as:

$$\boldsymbol{\varepsilon}^{ve}(t) = g_0 \mathbb{S}_0 : \boldsymbol{\sigma} + g_1 \int_0^t \mathbb{S}^{ve}(\Psi^t - \Psi^\tau) : \frac{\mathrm{d}(g_2 \boldsymbol{\sigma})}{\mathrm{d}\tau} \mathrm{d}\tau, \tag{3}$$

where $\mathbb{S}_0$ and $\mathbb{S}^{ve}$stand for instantaneous and transient compliance respectively, g_0, g_1 and g_2 are non-linear material parameters, Ψ^t



(a) (b) (c)

Fig. 1. FRP composite material characterization: (a) fiber direction, (b) transverse direction, (c) in-plane shear.