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On a unique fracture micromechanism for highly cross-linked epoxy resins

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Abstract

Micromechanics-based fracture criteria for highly cross-linked thermosets are heavily needed in the context of multiscale composite failure analysis. Fracture in an epoxy resin under quasi-static loadings was previously addressed using a two-parameter model, formulated in terms of the attainment of a critical tensile stress at the tip of internal defects. This model requires the identification of the aspect ratio of the defect and of the critical stress. Here, we unravel the physics underlying this fracture criterion and extend its validity to high temperature test conditions, to fatigue and to fracture toughness in an application to the RTM6 epoxy resin system. The accurate prediction of the fracture strain at high temperatures supports the stress-based nature of the criterion. Fractographic analyses justify the relevance of the attainment of a critical stress in fatigue as well. Indeed, the similitude between fracture surfaces under quasi-static and fatigue loading conditions indicates an identical failure scenario which is found to consist of crack nucleation near a defect, a crack arrest step and a re-initiation process including crack tip blunting. Finally, a combination of finite element analyses and experiments allows linking the fracture in pre-cracked specimens to the identified fracture criterion. The success of this approach encompassing such a wide range of conditions was unexpected and leads to a much simpler treatment of fracture in this class of thermoset materials compared to other existing approaches. It opens new avenues for improving failure analysis of composites based on highly cross-linked epoxy resins for conditions where matrix cracking is dominant.

Keywords: Fracture criterion, maximum principal stress, fatigue, finite element method, unreinforced resin

1. Introduction

The prediction of the mechanical response of fiber reinforced polymers (FRP), such as for any composite or hybrid material, is intimately tied to a physically sound description of their constituents' behaviour. In terms of failure analysis, the most advanced fracture criteria (Puck and Schurmann, 2002; Camanho et al., 2015) predict matrix-dominated failure modes without direct connection to intrinsic matrix fracture properties, hence opting for a description of failure properties at the scale of the ply. Considering that under several loading conditions, the resin is the locus of first damage, particularly in the presence of high void content (Llorca et al., 2011; Carraro and Quaresimin, 2014), the assessment of these engineering criteria against detailed micromechanical models of plies and even laminates requires properly identified, accurate constitutive models and fracture criteria for the resin itself.

Epoxy resins are materials of choice to serve as a matrix for high performance composites. In general, highly cross-linked epoxy resins display significant strain rate, temperature and pressure dependencies in their mechanical response (Boyce et al., 1988; Morelle et al., 2017). Moreover, despite cracking in a quasi-brittle manner under all loading conditions, stress triaxiality has a considerable impact on the fracture strain, displaying a much larger ductility under compression than under tension, where fracture occurs after only a few percents of deformation (Fiedler et al.,

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