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An anisotropic cyclic plasticity, creep and fatigue predictive tool for unfilled polymers

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ABSTRACT

Resistance to Low Cycle Fatigue (LCF) as well as High Cycle Fatigue (HCF) of polymers and Polymer Matrix Composites (PMC) depends on various loading modes, frequency, temperature, aging, and environmental effects. On the other hand, fatigue, plasticity, and creep deformation mechanisms are history dependent phenomena, and in order to account for their interactions a *coupled* computational platform is required. Cyclic behavior of polymers and PMCs have been extensively explored experimentally, but a rational fatigue failure model that would be anchored in the microstructure and would allow for coupling between fatigue, creep and plasticity through the lifetime is lacking. This work aims at developing an anisotropic coupled cyclic plasticity, creep and fatigue life predictive technique in which a Continuum Damage Mechanics (CDM) framework is utilized to link microscale LCF and HCF damage mechanisms, i.e. microcracking and microvoiding, to the macroscale fatigue failure. This task is accomplished through a *top-down multiscale* CDM approach, in which microscale damage laws are calibrated with respect to the macroscale fatigue failure data. Cyclic plasticity and creep models are also incorporated to capture anisotropic inelastic behaviors of Polymer and PMC systems. The developed framework is implemented into a commercial Finite Element Analysis (FEA) code, viz. ABAQUS, through user-defined coding. The FEA model represents an isotropic polymer or homogenized PMC system in which various factors that affect fatigue behavior are studied. A *cyclic jump* method is also utilized to reduce the computational cost of the proposed coupled computational approach. The performance of the developed computational platform has been examined through numerical studies and comparison to experimental data. The developed fatigue life predictive tool may be utilized by engineers for lifetime prognosis and to improve the performance of Polymer and PMC structures.

1. Introduction

Low Cycle Fatigue (LCF), High Cycle Fatigue (HCF) and Cyclic Creep Rupture (CCR) are major failure mechanisms that limit the lifetime of polymers and Polymer Matrix Composites (PMC) under cyclic loads. Time and temperature dependent damage mechanisms, associated with the viscoelastic and viscoplastic behavior of polymers and PMC, may have a profound effect on the endurance limit (Launay et al., 2013b; Mortazavian and Fatemi, 2015). Fatigue life of polymers and PMC systems also depend on environmental effects, including temperature and moisture effects, aging, load frequency, surface finish, and R-value ($R = \sigma_{min}/\sigma_{max}$). Thus, developing a fatigue life prediction tool for polymers and PMC requires a comprehensive modeling framework that accounts for all abovementioned failure mechanisms. Most current fatigue life assessment methodologies for advanced composite structures rely on empirical stress to number of cycles (S-N data). Anisotropic heterogeneous characteristics, and changes in failure modes over the fatigue life, as well as multiple failure mechanisms that interact with each other, make it challenging to predict damage growth in composite structures. Consequently, most of the current life prediction techniques depend on empirical data for refinement or calibration. Some approaches only discuss failure progression under certain loading configurations, which are often specific to a material system. A successful life prediction tool should be anchored in the microscale failure mechanisms of polymers and PMCs and would allow for coupling between fatigue, creep and plasticity through the material's lifetime. Fatigue damage mechanics in PMC is a multiscale process that originates in molecular level failures, such as polymer chain breakage. Progression of molecular level failure mechanisms lead to initiation and propagation of microscale flaws such as microcracks and mircrovoids (Tvergaard and Needleman, 2011; Shojaei, 2015a). Upon coalescence of these microflaws, a macroscale cracks may form and lead to the final rupture of struc-

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tures (Lemaitre, 1984; Lemaitre and Dufailly, 1987). Continuum Damage Mechanics (CDM) is a multiscale computational methodology that links microscale damage mechanisms to macroscale failures (Lemaitre, 1992; Voyiadjis and Kattan, 2006). One of the most common approaches in mutiscale CDM methods is the so called *top-down approach* in which macroscale fatigue failure experimental data are utilized to calibrate the constitutive laws of microflaw initiation and propagation (Fish, 2013).

To date, two categories of experimental methods have been available to quantify the fatigue life, (i) fracture mechanics, where fatigue crack growth-rate is correlated to the lifetime through crack length, a, versus life, N, curves, i.e. a-N curves (Khan and Paul, 1994; Mars and Fatemi, 2006; Kanters et al., 2015), and (ii) stress-life (S-N) or strain-life (E-N) experiments, where the lifetime is correlated to the applied periodic stress or strain levels (Paris et al., 1961; Manson and Halford, 1967; Voyiadjis and Echle, 1998). Fracture mechanics testing require complex measurement techniques to record crack growth rates. Since a wealth of literature on fatigue modeling and experimental analysis for Polymers and PMC already exists; only a selection of recent pertinent papers is reviewed here. Kanters et al. (2016) argued that both creep and fatigue mechanisms in composites can be distinguished effectively by comparing lifetimes in static and cyclic fatigue. Tensile relaxation tests with various fixed strains, tensile creep tests with various fixed stresses, and stress-controlled cyclic tests were reported by Drozdov (2010) and Drozdov (2011). Rickaby and Scott (2013) investigated stress relaxation, hysteresis and residual strain and combined those effects to the Arruda–Boyce eight-chain model. Fatemi and co-workers have studied the fatigue behavior of short fiber PMC (Fatemi et al., 2015; Mortazavian and Fatemi, 2015; Eftekhari and Fatemi, 2016). Launay et al. conducted an exhaustive experimental study on the tensile fatigue of Polyamide 66 reinforced with short glass fiber (Launay et al., 2010; Launay et al., 2011; Launay et al., 2013a; Launay et al., 2013b).

In terms of mathematical modeling, different approaches are followed to simulate progressive failure in composites, including Extended Finite Element Method (X-FEM) (Giner et al., 2008; Xu and Yuan, 2009; Fries and Belytschko, 2010; Giner et al., 2011; Curiel Sosa and Karapurath, 2012; Pourmodheji and Mashayekhi, 2012; Sharafisafa and Nazem, 2014; Ferté et al., 2016; Sadeghirad et al., 2016), Discrete Element Method (DEM) (Borg et al., 2001), Cohesive Zone Models (CZM) (Chaboche et al., 1997; Li and Chandra, 2003; Zhang and Paulino, 2005; Bouvard et al., 2009), phase-field models (Paranjape et al., 2016), and CDM models (Murakami, 1990; Abu Al-Rub and Voyiadjis, 2003; Pirondi et al., 2006; Ding et al., 2007; Moreo et al., 2007; Kang et al., 2009; Voyiadjis et al., 2011; Voyiadjis et al., 2012a; Shojaei and Li, 2014a; Hazeli et al., 2015; Shojaei, 2015a; Shojaei et al., 2015c). Most of the failure simulation methods based upon X-FEM, DEM, and CZM, face numerical difficulties associated with them, including the need to utilize re-meshing techniques, identify the crack front after each crack ‘pop-up’ and prescribe the crack path. An alternative life prediction approach is to rely solely on cyclic plasticity models to predict *shakedown* and *ratcheting* behaviors under different loading scenarios (Chaboche, 1991; Chaboche, 2008; Shojaei et al., 2010; Chaboche et al., 2012; Mahbadi et al., 2014). The main drawbacks for cyclic plasticity models are associated with their high computational costs. Furthermore, cyclic plasticity models are usually calibrated with respect to uniaxial cyclic tests and may fail in predicting cyclic responses in more general loading cases, i.e. 2D and 3D stress states (Bari and Hassan 2000; Bari and Hassan, 2001; Bari and Hassan, 2002). It has been shown that combined CDM and cyclic plasticity models result in more reliable life predictions. In combined CDM-plasticity models the information from both S-N (or E-N) curves and cyclic plasticity behavior are incorporated into the life prediction, resulting in more accurate predictions (Bonnand et al., 2011; Chaboche et al., 2012). CDM approaches provide a high fidelity and computationally efficient tool to predict progressive failure in mechanical systems (Pirondi et al., 2006). Gomez and Basaran (2005) developed a viscoplastic constitutive model unified with a thermodynamics based damage evolution model in order to simulate low cycle fatigue response coupled to size effects. Richard et al. (2011) presented a constitutive model for quasi-brittle materials subjected to cyclic loadings based on CDM. A fatigue prediction model was developed by Jiang et al. that utilizes the plastic strain energy as the major contributor to the fatigue damage (Jiang et al., 2009). Naderi et al. studied experimental fatigue damage in various grades of aluminum and simulated the fatigue damage to determine the scatter lifespans (Naderi et al., 2013). The effects of interactions between various microstructure attributes on the high cycle fatigue life of a Ni-base super-alloy was discussed by Przybyla and McDowell (2010) and Przybyla and McDowell (2011). Statistical methods have been incorporated in either approach to account for degree of uncertainties in prediction results (Pyttel et al., 2016; Paolino et al., 2015; Haidyrah et al., 2016; Wang et al., 2016). Ovalle Rodas et al. developed a thermo-visco-hyperelastic constitutive model to describe the self-heating effect in elastomeric materials under cyclic loading (Ovalle Rodas et al., 2014). Verrona and Andriyana studied fatigue crack nucleation in rubber based upon the framework of *configurational mechanics* (Verron and Andriyana, 2008). Slaughter and Fleck investigated the performance of the Mroz plasticity and the Armstrong and Frederick ratchetting laws in capturing compression-compression fatigue failure mechanisms including microbuckling phenomenon (Slaughter and Fleck, 1993). A thermodynamically consistent coupled damage-plasticity model for the cyclic behavior of shear-loaded interfaces was developed by Carrara and De Lorenzis (2015). Bao and McMeeking proposed a thermomechanical fatigue model for fiber reinforced metal-matrix composites in which interfacial debonding under thermomechanical cyclic loads is considered (Bao and McMeeking, 1995). A multiscale fatigue life analysis approach was presented by Le and Bažant in which a probabilistic theory is utilized to predict the lifetime distribution of quasibrittle materials (Le and Bažant, 2011). Sweeney et al. investigated the role of elastic anisotropy, length scale and crystallographic slip in fatigue crack nucleation of polycrystalline ferritic steel (Sweeney et al., 2013). Bažant and Hubler investigated the cyclic creep of concretes and they proposed a cyclic creep model based upon microstructural information (Bazant and Hubler, 2014). Tvergaard studied the mesh sensitivity effects on fatigue crack growth of ductile materials in which crack-tip blunting under tensile loads and re-sharpening of the crack-tip during unloading were considered (Tvergaard, 2007). Poncelet et al. developed a probabilistic modeling of microplasticity at the scale of slip-planes to study the effect of self-heating at HCF (Poncelet et al., 2010). Sangid et al., developed a model based on the energy of a persistent slip bands in which the stability of bands with respect to dislocation motion was linked to fatigue crack initiation (Sangid et al., 2011).

When dealing with fatigue analysis in structural components, the Finite Element Analysis (FEA) software is incorporated to calculate the stress distribution in all material points. The stress/strain information is then used to find the critical sections in a design and calculate the component's fatigue life. Three common fatigue design methods are used in structural analysis,

- The first class is called “*classical hand calculation*” in which FEA model calculates the stress history at all material points for the first duty cycle. The location of maximum stress is identified manually and the stress/strain data in those critical sections are utilized to calculate the life from S-N or E-N curves. The main