Coupling of phase-field based fracture propagation with healing in self-healing materials

Harini Subramanian *, Chethana P. Rao, Shantanu S. Mulay, Chandrasekhar Annavarapu

Indian Institute of Technology Madras, Chennai-600036, Tamilnadu, India

Self-healing materials exhibit damage tolerance as they can recover from mechanical damage either due to their natural ability or by certain material constituents acting as healing agents. Experimental investigations on self-healing material has been an active area of research over the last few decades with the development of extrinsic self-healing mechanisms, such as micro-capsules, vascular structures, and shape memory alloys/polymers [1]. Various models for prediction of mechanical behaviour, capturing the damage and healing, have been developed based on the continuum damage mechanics, micromechanics, and cohesive zone modelling [2, 3].

Damage mechanics based damage-healing models are developed at the macroscopic continuum scale, which track the evolution of damage and healing as internal state variables and correspondingly evaluate the degradation and recovery in the material integrity. Damage (D_g) and healing (h_l) variables are defined as fraction of the total area that has undergone damage, and the fraction of the damaged area that has undergone healing, respectively [2]. The collective influence of damage and healing on the material's constitutive response is given by the effective damage variable defined as $\phi_{eff} = D_g\,(1 - h_l)$ [2]. Phase-field based damage modelling is a diffusive damage approach which, unlike damage mechanics, enables tracking individual cracks while also avoiding an explicit representation of kinematic discontinuities.

The objective of present work is to develop a coupled phase-field-based damage - healing model for the analysis of crack propagation in self-healing material. An elastic self-healing material, undergoing small deformation with a pre-existing crack (not necessary requirement), is considered in the present work. The minimization of total potential energy of system (bulk elastic and crack surface energies) provides the governing equations for the phase-field damage model [4]. A quadratic energy degradation function is considered, and tension-compression split of elastic strain energy is performed such that damage variable evolution is driven by tensile elastic energy (no damage in compression). The healing evolution is proposed accounting for both, stress-based and stress-free, cases.

The primary focus of present work is on development of staggered solution scheme to estimate damage-healing evolution and track fracture path for each loading increment. The phase-field equation is firstly solved based on the initial definitions of displacement, phase-field, and history variables. The equilibrium equation, coupled with the healing evolution equation, is secondly solved based on the updated phase-field parameter for the current loading increment. The numerical implementation is performed by meshless local differential quadrature method, and various boundary value problems are solved illustrating the healing of multiple cracks, non-local healing evolution, fracture propagation coupling the damage and healing, and stress-free healing.

References

[1] S. K. Ghosh, Self-healing materials: fundamentals, design strategies, and applications, John Wiley & Sons, 2009.

[2] H. Subramanian, S. S. Mulay, On the constitutive modelling of elasto-plastic self-healing materials, International Journal of Solids and Structures 234 (2022) 111289.

[3] S. A. Ponnusami, J. Krishnasamy, S. Turteltaub, S. van der Zwaag, A cohesive-zone crack healing model for self-healing materials, International Journal of Solids and Structures 134 (2018) 249–263.

[4] C. Miehe, M. Hofacker, F. Welschinger, A phase field model for rate-independent crack propagation: Robust algorithmic implementation based on operator splits, Computer Methods in Applied Mechanics and Engineering 199 (45-48) (2010) 2765–2778.