# Abstract

Lightweight and durable composite materials have been at the forefront of energy-saving technologies. However, they are not free from defects either induced through the infusion process or during curing in the case of a fibre reinforced polymer composite. Amongst such a wide spectrum of defects, porosity defect plays a pivotal role, which is greatly influenced by each step involved in a composite manufacturing process. One of the primary sources of such defects is an improper infusion of resin, entrapment of cavities, and resin-deficit areas within the composite reinforcement.

In this study, attempts are made to capture the physics behind curing of glass fibre reinforced epoxy composite in presence of porosity defects from micro- to macro-scale; propose an enhanced vacuum infusion technique with proven escalation of inter-laminar shear strength; model residual stress generated during curing and validate the data with XRD and Raman spectroscopy; and experimentally validate the macro-scale model with tensile and flexural test data as per ASTM regulations. A multi-scale modelling framework is proposed to incorporate randomly sized and distributed porosity defects and estimate their effect on cure kinetics and post-cured properties of a thermoset polymer (in this case, epoxy) and glass fibre reinforced polymer (GFRP) composites. A representative volume element-based finite element (FE) model coupled with the thermo-structural periodic boundary condition is developed in Abaqus. This is attained with the help of a user defined constitutive material model (Abaqus type, UMAT) and cure kinetics model (Abaqus type, HETVAL).

Curing simulations are performed for room temperature, oven, and autoclave curing in the case of porous polymers, plain weave GFRP, and unidirectional GFRP composites. The simulated room temperature curing of plain weave and unidirectional glass fibre composites agrees with the experiments with 10% and 5% deviations, respectively. It is found from the model that an increase of porosity by up to 5% decreases the level of numerically obtained residual stress by 35% when compared to a no porosity content in epoxy. In terms of experimental techniques, a comparison is carried out on the manufacturing of GFRP composites with the help of autoclave, oven curing and vacuum infusion processes with a highlight to the degassing time of resin-hardener mix, single or double vacuum bagging, fibre volume fraction and operation of the vacuum pump (VP). The novelty of the experimental study shows that a VP Off and 5 min degassing exhibited 27%, 18% and 27% increase in tensile modulus, tensile strength and interlaminar shear strength compared to the oven and autoclave curing. Further, a study is conducted to determine the level of residual stress through XRD characterisation technique and to validate the numerical residual stress. It is found that the magnitude of simulated residual stress lies within 8% of experimental value of 1.5 MPa. Micro-Raman Spectroscopy is also carried out to determine the residual strain which results in 0.2% at a spectral peak of 1186 $cm^{-1}$. In addition, macroscale tensile and flexural simulations are performed for plain weave and UD composites. It is observed that around 9% and 12% deviation with experimental stiffness are obtained for plain weave composites. Whereas, in the case of the unidirectional composites, around 12% and 10% variation in the stiffness are observed for tensile and flexural simulation when compared to the experiments. A micro-CT scan derived geometry can provide a closer accuracy of the present modelling approach, in terms of precise fibre volume fraction, fibre misalignment and geometric uncertainties. The developed modelling methodology is robust and can be applied to any fibre reinforced polymer composites, given the cure and material parameters of the fibre and the polymer.

**Keywords:** Curing; Porosity; Vacuum infusion; Residual stress; Polymer matrix composites