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Can we achieve controlled localised grading of continuous fibre polymer composite properties using out-of-autoclave process?

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Grading, *i.e.* the spatial variations of properties, of composites has a great potential for improving mechanical performance in critical locations. Advantages of grading have been exploited in many materials as it allows for release in stress concentration, reduced thermal stresses and optimising load flow. For example, a theoretical study on spatially graded distribution of carbon nanotubes (CNT) in nanocomposites have shown to significantly enhance the toughness of epoxy nanocomposites [1], [2]. Grading in continuous fibre reinforced composites is limited by available composites manufacturing technologies. The closest concept to material grading for these composites is fibre steering using automatic fibre deposition however even the minimum achievable steering radius is still much greater than characteristic variation of stresses around a feature (hole, bolted joint) and hence, much greater than the required scale of grading.

Recent studies have demonstrated that grading can be achieved through application of Liquid Resin Printing (LRP) [3]. This technique can precisely integrate functionalised resins in-plane and through-thickness of textile preforms. The injected/printed resin can then be loaded with high fraction of additives and the printing process avoids problem with elevated viscosity of injected suspension and cake filtration of particles known for conventional composites manufacturing processes. This technique, utilising a CNT enhanced resin as injection solution around stress concentrators have shown to improve composite performance [4]. The present study is focused on developing further processing strategies that allow morphology of the printed patch and the distribution of material properties within it to be controlled.

The main challenge in local incorporation of additive-rich resin suspensions is that the print process is not vacuum assisted which may lead to significant void entrapment due to the unsaturated resin flow. A pragmatic solution is to develop a viscosity-tailored consolidation process where the resin is thermally treated prior to consolidation. If the resin is conditioned to reach appropriate viscosity by advancing the degree of cure (DOC) then flow length is reduced. Further, the resin would be capable of bearing a substantial part of the pressure along with the fibre network and porosity can be reduced or fully suppressed. To explore this concept experimentally, a series of instrumented manufacturing trials with snap curing DGEBA based epoxy resin system were conducted using a bespoke consolidation setup as shown in Figure 1(a). This resin system presents a particular interest as changes in material state can be achieved in minutes/seconds time scales. Therefore to tailor the consolidation programmes to the actuation DOC, a model-based sensor was developed to solve the differential cure kinetics equations in real time based on the data flow from thermal sensors. A range of experiments with consolidation programmes with varying actuation DOC were conducted. A chemo-rheological study of the resin was then conducted to estimate the exact viscosity at which the consolidation is applied.

The key observations from this study are: a) significant qualitative reduction in porosity by actuating the consolidation pressure at a higher viscosity as shown in the micrographs and flow visualisation images in Figure 1(b) and (b) change in dominant flow mode from inter-tow to intra-tow was observed with increased actuation viscosity. An unsaturated bleeding flow through the preform was observed at lower actuation viscosity. While a fibre suspension flow similar to squeeze flow was observed at higher actuation viscosity. In order to understand the dominant flow mechanisms for various experimental consolidation programmes, a series of analytical models addressing these mechanisms were constructed.

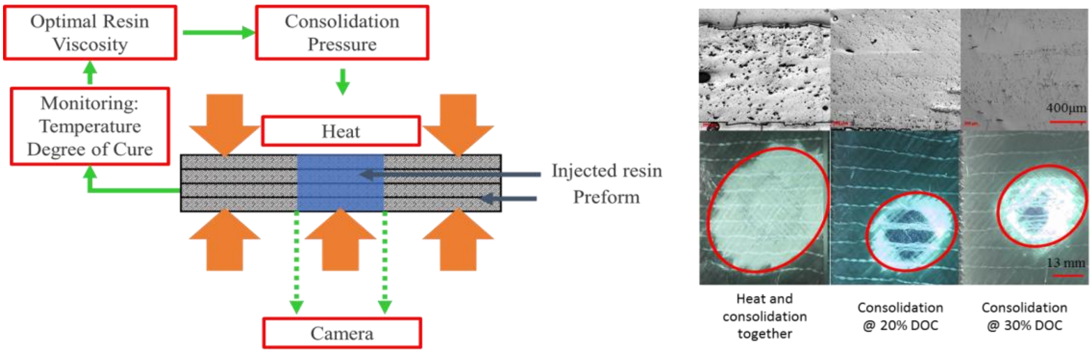

Figure 1: (a) Schematic of bespoke consolidation setup (b) (Top) Micrographs & (Bottom) flow visualisations of resin patches for various consolidation programmes.

Further studies are being conducted using CNT-enhanced resin in combination with predictive tools to showcase the capability of achieving controlled grading of composite properties to improve mechanical and functional performance. The preliminary investigation showcases the scope of an optimised set of processing parameters to achieve controlled patch morphologies. Hence, the current study opens further routes for controlled grading and optimisation of continuous fibre polymer composite properties through OOA processing with local high precision management of local composite architecture.

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