Compression Deformation of Glass Fibre Reinforcements in Composites Manufacturing Processes

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Abstract

Glass fibre reinforced polymer (GFRP) composites find application in diverse industries such as aerospace, marine, automotive, infrastructure and sport. GFRP composite products can be manufactured by a variety of methods, including the commonly employed Liquid Composite Moulding (LCM) group of techniques. Whatever the method, compression of the fibrous reinforcement is usually necessary in its natural dry state, and depending upon the technique, also after injection of a polymeric resin into a mould containing the reinforcement. A good understanding of the compression deformation behaviour of the reinforcement aids development of better models to describe and predict the manufacturing process, evaluate stresses acting on the mould, mould clamping and tooling forces required, and improvement of finished product quality.

LCM models commonly assume non-linear elastic deformation of the fibre reinforcement network, while some also take into account viscoelastic behaviour. Earlier investigations demonstrated reinforcement stress relaxation under constant compressive strain. Reinforcements under loading (compaction) and unloading (release) follow different paths for the two phases. These phenomena indicate viscoelastic behaviour. Cyclic loading and unloading of reinforcements show a progressive shift of the fibre volume fraction - compression stress curve, signifying non-recoverable strain. This research further investigated these complex compression deformation phenomena which are not normally considered for modelling simulations.

A series of experiments were conducted on glass fibre reinforcements of different architecture to determine and quantify in order of importance, different components of compression deformation. Permanent deformation was found to occur in all cases, and is comparable in magnitude to the elastic deformation of the reinforcement. Permanent deformation of the reinforcement considerably increased after just a few cycles of repeated compression and release. Time-dependent recovery of deformation on release of the compaction strain was found to largely depend on the number of layers of material in Continuous Filament Random Mat and Plain Weave Fabric reinforcements, it being of significant magnitude only with Plain Weave Fabric. A five component Maxwell-based model was developed to help explain and predict stress relaxation in the reinforcements under constant compressive strain.

X-ray micro-computed tomography (micro-CT) scanning and imaging technology was utilised to investigate fibre reinforcement deformation in manufactured composite laminates. It was hypothesised that permanent deformation in Biaxial Stitched Fabric and Plain Weave Fabric reinforcements occurs by means of changes to fibre bundle cross-sections, while time-dependent recovery of deformation on release of the compaction strain is related to the undulations of fibre bundles in the direction of loading, and also to the tow crimp in the case of Plain Weave Fabric reinforcements. Analysis of the micro-CT images proved correct the hypothesis in the case of Continuous Filament Random Mat, while there was support for Plain Weave Fabric. It was also proposed that permanent deformation in Continuous Filament Random Mat reinforcements is via filament bending and displacement, while time-dependent recovery of deformation is based on filament – filament interactions. In this case CT scanning images provide some support towards understanding filament spread but more information is needed to conclusively prove the hypothesis.

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A	Area, area of cross-section, mm^2
CS	Compaction Speed, mm/min
E	Spring stiffness
h	Mould cavity (sample) thickness, mm
h_0	Initial mould cavity (un-compacted sample) thickness, mm
h_1	Final mould cavity (final compacted sample) thickness, mm
h_e	Sample height after elastic spring-back, mm
h_t	Sample height after time-dependent recovery, mm
m	Mass, g
P	Presssure, MPa (kPa)
t	Time, s
V	Volume, mm^3
ν_f	Fibre Volume Fraction
ε	Strain, mm/mm
$\acute{\varepsilon}$	Strain rate
η	Viscosity of dashpot
μ	Absolute viscosity, Pa.s
ρ	Density, g/mm^3 (kg/m^3)
σ	Compressive stress, MPa (kPa)
σ_0, σ_1, σ_2	Stress constants
$\sigma_{(max)}$	Peak stress
$\sigma(t)$	Stress at time t
τ_1, τ_2	Relaxation time constants