Ultrasound characterisation of features and defects in 2D and 3D woven composite materials

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Woven composites are expected to be widely used in the automotive industry to achieve improved strength-to-weight ratios and reduce CO₂ emissions. Woven composites are susceptible to various types of defects, which can considerably alter mechanical properties whilst only subtly changing the response to ultrasound excitation. However, use of the analytic signal in a way originally explored for non-woven composites has proven that these features can be detected and characterised using the instantaneous amplitude, phase and frequency (1). The presented study compares experimental results for real woven specimens with different stitching weaves with both analytical and 3D time-domain finite-element (FE) models to understand the response of these materials in the presence of defects such as broken yarns, missed stitches, porosity, draping distortions and changes of warp and weft spacings.

First, an ultrasound immersion test was carried out to acquire data from real specimens with different weave types such as Orthogonal, Plain and Multilayer stitching. The results obtained for the Orthogonal weave particularly depict two alternating regions of interest (ROI) with different characteristics in terms of number of yarns and Fibre Volume Fraction (FVF). The first ROI named as “61616” (see Fig.1a, 1c and 1e) is located along the binding yarn. For this region, the impinging ultrasound wave travels through either 6 horizontal yarns or 1 vertical yarn. No back-wall signal was observed for the 1-vertical yarn location. The second ROI named as “94949” is located in-between two binding-yarn regions. For this region, the impinging ultrasound wave travels through either 9 or 4 horizontal yarns. A hexagonal pattern was observed on the instantaneous-frequency C-scan results for this specimen. The nodes for this pattern are observed to appear where the binding yarns are horizontal. At this stage it is difficult to know whether it is the part where the binding yarn goes beneath or above the weft yarns. The differences in the FVF for these ROIs are demonstrated to be responsible for a variation in the time of arrival to the back-wall echo. The direct consequence of this variation is undulations that appear to intensify with the depth in the woven structure (2).

Next, a simple 1D analytical model was built using a mixture-rule approach for the yarns embedded in the resin (Fig. 1c). This model assumes normal-incidence plane-wave propagation and was initially validated against experiment and other models. The reflected signal was convolved with a realistic input pulse to apply the method to the woven composite. The results show that the instantaneous frequency increases when yarns are squashed. For this model, alternating regions of high and low instantaneous frequency are also observed as depicted in the real data. Although the analytical model does not account for either a focused ultrasound beam or the anisotropy of the yarns, it has proven to be useful in revealing the instantaneous parameters’ sensitivity to the resin-layer thickness, yarn spacing, centre frequency and bandwidth used. This model is used to determine the optimum centre frequency to excite all the different yarn spacings within the woven structure. This supports the use of a 5 MHz probe centre frequency throughout the study, as used for Fig. 1b.
Finally, a 3D refined FE model was built to explore realistic features such as the anisotropy and squashing of the yarns due to the compaction. TexGen software was used to create the geometry of the sample studied. This geometry was then exported to PZFlex using a Matlab built GUI to simulate the ultrasound propagation. For the FE model, a probe of square cross-section with natural focusing was considered. An orthotropic stiffness matrix is orientated to account for the local yarn orientation. To ensure a good stability and accuracy for the results, the choice of 20-elements per wavelength was made. The model is run for the probe locations covering all unique yarn formations and a tessellation algorithm is applied to extend the results to larger dimensions of the modelled sample. The results obtained for the “61616” region particularly show that the wave impinging on the 1-vertical yarn is trapped in the binding yarn where it propagates as a guided wave at a higher velocity due to the higher longitudinal than transverse fibre stiffness, such that only a very small leakage out of the yarn occurs. The pulse-echo response from this vertical-yarn location is negligible.
A parametric study carried out on both the analytical and FE models shows that a small change in the yarn spacing due to compaction often results in a considerable change in the instantaneous parameters, particularly the instantaneous frequency. This latter parameter is thus considered to be suitable for detecting errors in the stitching of the binding yarn, whilst the instantaneous phase will reveal information about resin-layer locations, which have been shown to correspond to a particular instantaneous phase angle. Good agreement is observed between the experimental and predicted results as depicted in Fig.1b, 1d and 1f (for the 61616 ROI) and Fig.2a, 2b and 2c (for the 94949 ROI) for the instantaneous amplitude. The results obtained for the orthogonal weave type can be extended to the other types to characterise common features and defects such as missed stitches, distorted yarns and the presence of porosity.

The yarn compaction has been shown to play an important role in material performance and instantaneous parameters are very sensitive the compaction so this work suggests that a parametric study should be carried out for different compactions.

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