Modelling the effect of porosity on the mechanical properties of unidirectional composites. The case of thick-walled pressure vessels

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MODELLING THE EFFECT OF POROSITY ON THE MECHANICAL PROPERTIES OF UNIDIRECTIONAL COMPOSITES. THE CASE OF THICK-WALLED PRESSURE VESSELS

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Abstract
The present article highlights morphological features present in composite pressure vessels. The use of X-ray microtomography provides three-dimensional information about the voids in a large thick-walled type 3 pressure vessel at the mesoscopic scale. The observations show that the porosity structure depends strongly on composite thickness and orientation. A numerical approach is proposed to model realistically the damage phenomena in pressure vessels.

1. Introduction

The increasing popularity of alternative fuels such as compressed natural gas (CNG) or hydrogen has led to a growth in manufacture of composite pressure vessels. Their light weight is a major advantage for on-board applications by increasing efficiency and reducing the environmental footprint.

Low density of hydrogen means that high pressures (usually 700 bar) are necessary to store a sufficient amount of propellant in a typical pressure vessel of approximately 50 litres. This requires thick composite walls able to carry the resultant structural loads.

Efforts have been made to quantify the reliability of composite pressure vessels [7, 2]. However, it is not known to what extent various factors might affect their strength. The parameters of the filament winding process, such as winding tension, speed and time, can significantly influence mechanical properties [11, 4, 12]. Whilst filament winding is a fast and automatized manufacturing process, the resultant composite microstructure is less uniform than in a prepreg-based laminate. Composite pressure vessels are known to exhibit significant porosity [17]. Furthermore, porosity content and fibre volume fraction are not uniform, but rather show a gradient across wall thickness [4]. Therefore, to successfully model the mechanical behaviour of composite pressure vessels, it is desirable to know their morphology on a ply-by-ply basis.

The objective of the present study is to provide a morphological description of thick-walled pressure vessels used for hydrogen vehicles. The necessary information is gathered through X-ray microtomography. This serves as a basis to include the effect of porosity and other morphological features encountered in pressure vessels into the tensile failure model of Bunsell and Thionnet [21]. It allows more realistic modelling, giving more insight into the behaviour of real composite structures.

2. Porosity in fibre-reinforced composite materials

Porosity is commonly observed in fibre-reinforced composites. Temperature and pressure in the curing cycle are known to have an important effect on the final porosity in composite materials [10]. Among the reasons for void formation are the entrapment of air during lay-up and volatiles arising from the resin system inside the composite [14].

Increase in porosity is known to deteriorate the matrix-dominated properties of the composite [19]. Under tension, increased porosity content leads to an earlier onset of matrix cracking in transversely loaded plies [1]. The mechanical properties of a unidirectional composite in the fibre direction are less sensitive to the presence of porosity. Whilst macroscopically important changes in axial properties are not observed, voids could still act as preferential locations for damage initiation. Therefore, apart from overal porosity content, void shape, size and spatial distribution are also a factor, as noticed by some authors [14]. Scott et al. observed a disproportionately high number of fibre breaks adjacent to voids using X-ray microtomography [17]. Olivier et al. observed some decrease in axial strength of a unidirectional composite with increasing void content and suggested it could be caused by local fibre deformation [14]. Porosity has also been reported to reduce the fatigue life of carbon/epoxy laminates [18]. However, this effect remains outside the scope of this article.

3. Morphology of a thick-walled pressure vessel

To obtain 3D information on the morphology of the composite material, a 40-litre type 3 pressure vessel was studied at µ-Vis Centre at the University of Southampton using X-ray microtomography. The scans were done on a custom built dual source 225/450 kV micro-CT system. In recent years, several authors have used microtomography to study porosity in composites and its impact on the mechanical properties [9, 17, 19]. The novelty of the current study is in scanning a large cylinder (330 mm diameter) with thick walls, which poses a significant technical challenge. Two tomography scans were obtained: 1) an overview scan of the complete cylinder at a 97 µm voxel size and 2) a higher-resolution scan (44 µm voxel size) of a region of interest of approximately 100×100 mm. To fit the whole diameter of the cylinder in the first scan, it was further necessary to use a panel shifting acquisition mode.

Composite ply orientation within the cylinder was identified using a modified procedure of Kratmann et al., based on the fast Fourier transform [8]. It shows three hoop plies, with the thickest one located adjacent to the aluminium liner. The helical plies have orientations from 10 to 80 degrees.

The overall porosity content across the cylinder's thickness was calculated from the region-of-interest scan by local thresholding of the voids using Phansalkar method as implemented in ImageJ software [15]. Higher resolution significantly increases the amount of detail that can be obtained from the scans, as can be seen in Figure 1.

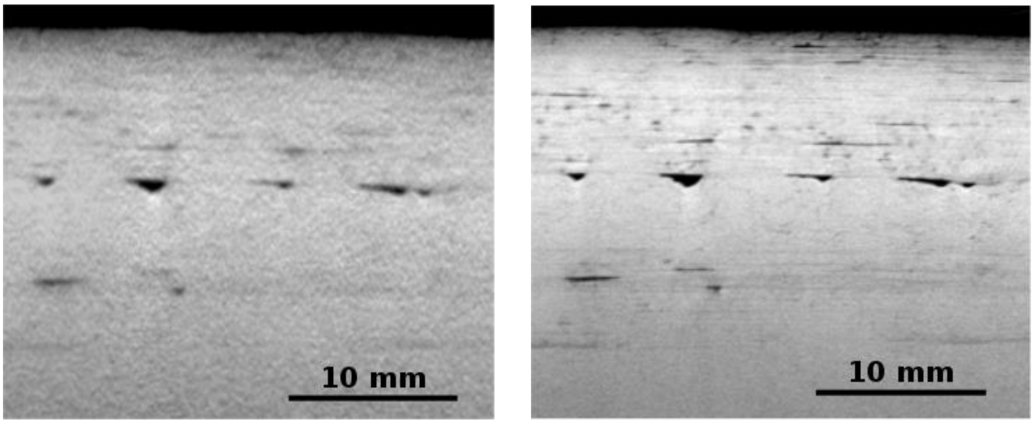

Figure 1. Comparison of the tomography scans: a) overview scan (97 µm voxel size), b) region of interest scan (44 µm voxel size).

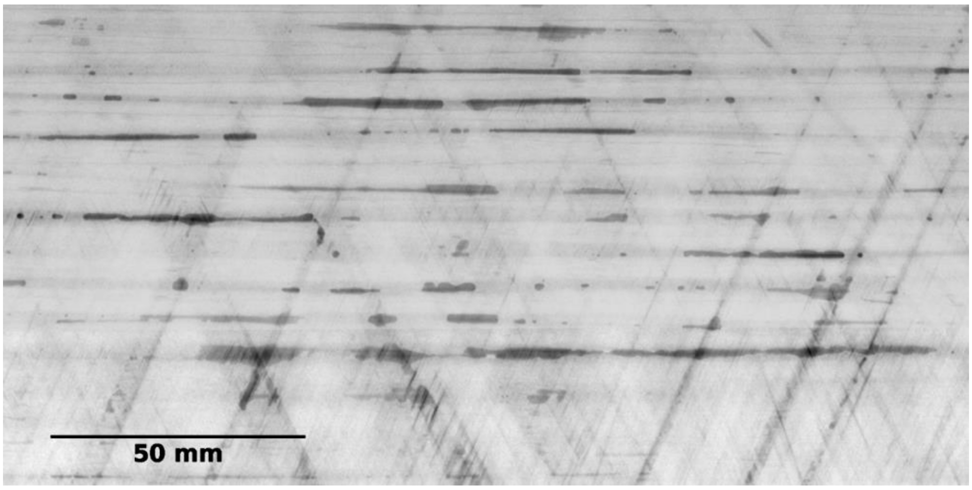

Figure 2. Large voids located at an interface between two plies. Sum projection across 30 slices (approximately 3 mm).

The scans showed a significant number of voids of various sizes. Usually the voids were strongly elongated along fibre direction, with much smaller dimensions in the transverse direction. Figure 2 shows an example of this morphology.

The results reveal some general features of porosity. Firstly, the void content is much higher in the helical plies. This can be explained by their weaker compaction during the filament winding process. Secondly, the porosity content increases towards the outside of the cylinder. This is in agreement with the observations of Cohen [4]. Figure 3 shows the relationship between through-thickness position, ply orientation and porosity content.

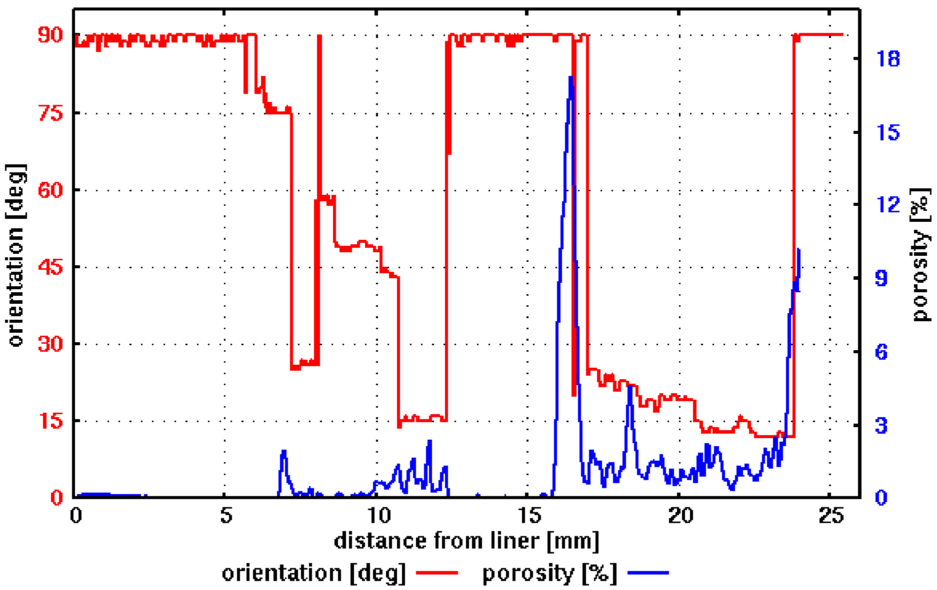

Figure 3. Fibre orientation and void percentage across wall thickness obtained from tomography. Orientation is given with resepct to cylinder axis.

Another feature observed in the pressure vessel is the presence of matrix cracks in the innermost hoop ply, running around the circumference of the cylinder. One of the cracks was captured in the high-resolution scan and is shown in Figure 4. Matrix cracking is probably a result of high autofrettage stresses. However, its nature is not completely clear and further investigation is necessary to get a better understanding of the underlying process.

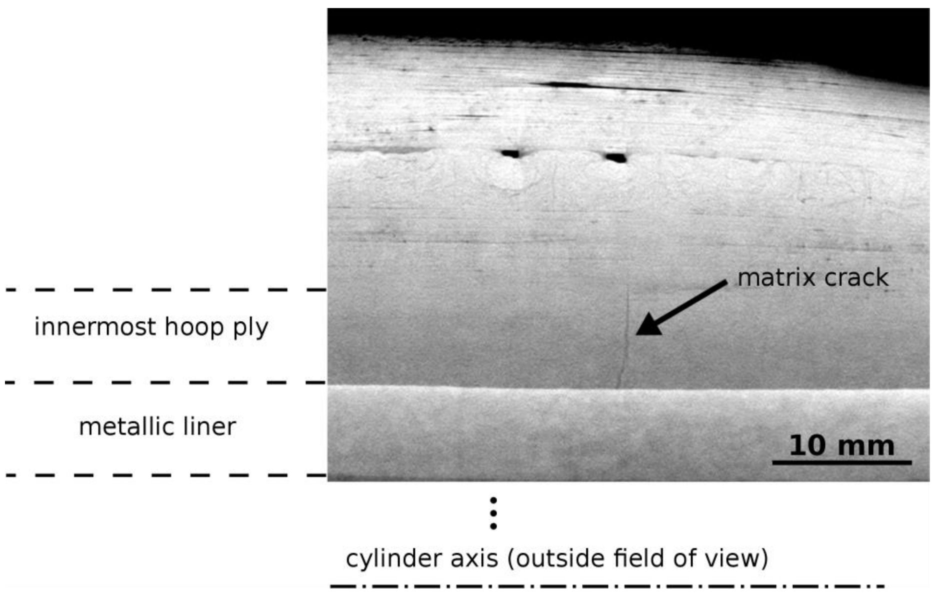

Figure 4. One of the transverse cracks in the innermost hoop ply.

4. Modelling approach

Whilst in the long term it is desirable to directly study the effect of porosity at the microscale, the lack of reliable input data and computational limitations dictate that the first approach be at the mesoscopic (laminate) scale.

Porosity is taken into account by appropriately modifying the material properties at the ply level. A two-step generalized self-consistent scheme (GSCS) [3] is chosen to calculate the stiffness matrix of the homogenized material. Firstly, equivalent properties are calculated for the fibre-matrix system. Secondly, this equivalent material is again homogenized, this time including a given volume fraction of porosity.

We assume that the failure of pressure vessels is driven by the accumulation of fibre breaks in the hoop plies. Since the tensile stress in the helical plies is significantly lower, fibre breakage is disregarded there. This allows a significant reduction in the computational cost of the calculations, since the multiscale procedure only needs to be applied in approximately half of the structure.

The second element of the modelling scheme is to take into account the appearance of matrix cracking and its influence on the properties of the laminae. This is done using the model developed by Thionnet [20]. This damage-based approach takes into account the progression of microcracking in the matrix. It is highly versatile, allowing an arbitrary load type and sequence (e.g. transition from tension to compression). The negative effect of increased ply thickness is taken into account, based on earlier research [16].

A limitation of the approach introduced above is that it does not take into account some microscopic phenomena. For instance, at the point where a crack tip meets a neighbouring longitudinal ply, the fibres in that ply are locally overstressed. Whilst this does not appear to influence significantly the strength of the longitudinal ply in thin composites [13], it could be more critical in thick laminates, such as those used in hydrogen pressure vessels.

5. Conclusions

Composite pressure vessels exhibit a significant amount of porosity due to the character of the filament winding process. This is confirmed by X-ray microtomography observations of a carbon fibre thick-walled pressure vessel. Largest porosity is observed in the areas between the plies. Void content exhibits a clear through-thickness gradient. Furthermore, helical plies show significantly higher porosity than the hoop plies.

A three-dimensional finite element model of a pressure vessel takes into account the observed features and simulates the damage propagation in the structure. High pressure results in a presence of a non-negligible radial compressive load. Little is known of the damage propagation in composites under such complex loading. There is evidence that transverse compression has a deleterious effect on the tensile strength of the composite in fibre direction [5, 6]. Numerical modelling can provide predictions that are helpful in understanding the damage processes taking place.

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