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Damage and permeability in tape-laid thermoplastic composite cryogenic tanks

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ABSTRACT

This work presents a combined experimental and numerical approach to the design and analysis of tape-laid thermoplastic composite cryogenic tanks. A detailed material and defect characterisation of automated tape-laid CF/PEEK is undertaken using optical micrography and 3D X-ray CT (computed tomography) as well as cryogenic testing to investigate damage formation. Resulting material data is used as input for a novel XFEM (extended finite element method)–cohesive zone methodology which is used to predict intra- and inter-ply damage in an internally pressurised cryogenic tank. An optimised tank lay-up is presented and analysed using the numerical method to ensure resistance to microcrack formation and fuel leakage through the tank walls under operating loads.

1. Introduction

Due to their high specific strength and stiffness amongst other properties, carbon-fibre reinforced polymers (CFRP) are seen as candidate materials for the fuel tanks of next generation reusable launch vehicles (RLVs). These fuel tanks will be exposed to cryogenic temperatures as low as −250 °C and to internal pressurisation as high as 1 MPa. This extreme thermo-mechanical loading can lead to microcracking and delamination formation within the CFRP, which, in severe cases, can result in permeation of the cryogen through the fuel tank walls. A precise understanding, therefore, of the methods of damage accumulation in the material and how the various damage modes interact underpins the potential use of CFRP for RLVs.

While numerous works have been published on the design and testing of composite overwrapped pressure vessels (COPVs) [1–4], the unique challenges posed by cryogenic fuel storage have yet to be fully addressed. Work on the design and analysis of composite cryo-tanks has intensified since the failure of the NASA/Lockheed X-33 RLV fuel tank [5], where fuel leakage occurred due to cryogenically induced damage in the composite tank wall. Subsequent experimental and theoretical analyses of cryo-tanks [6,7] have found that, unlike traditional COPVs, the thermal stresses induced by cryogenic loading are the main design consideration and play a critical role in damage formation. In addition, the role of material quality and processing conditions on damage initiation remain understudied [8,9], particularly for advanced thermoplastic composites such as CF/PEEK, which are increasingly used in conjunction with novel processing techniques such as automated tape laying (ATL) for the manufacturing of large structures.

Thermoplastic composites offer several advantages over thermosets in terms of their improved range of properties and processing techniques available. CF/PEEK is a high-performance thermoplastic carbon-composite material, which is increasingly being used in the aerospace industry for weight sensitive designs and is also known to offer increased resistance to damage propagation compared to epoxy based materials [10,11]. Importantly, thermoplastics allow the use of out-of-autoclave processing techniques such as automated tape laying (ATL), a relatively new processing method based on the in-situ consolidation of plies. This is carried out by a computer controlled robot which typically applies prepreg tape to a heated mould placed on a revolving mandrel, using a heat source such as a laser which is focused on the ply lay-down area. Unlike autoclave processing, consolidation occurs at the point where the robotic head first heats, then melts and finally consolidates and cools the incoming tape, as opposed to processing the entire laminate simultaneously. This facilitates the manufacture

Abbreviations: SFT, stress free temperature; TTS, transverse tensile strength; TCS, transverse compressive strength; IPSS, in-plane shear strength; ILSS, interlaminar shear strength; SHC, specific heat capacity; UD, unidirectional specimen; QI, quasi-isotropic specimen; COD, crack opening displacement.

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of large structures without the investment required for a large autoclave of several metres diameter. Thus the technique is well suited to producing components such as cryo-tanks. The main drawbacks of this technique include the potential for poor ply adhesion due to insufficient melting and adhesion and the presence of significant residual stress gradients due to non-uniform cooling [8,12,13]. The tape-laying process itself can also result in gaps due to overlapping plies which can result in high void contents. These issues can often lead to composite laminates of a lower general quality than those produced in an autoclave [9,14].

CF/PEEK, due to its high processing temperature and semi-crystalline nature, exhibits significant property variation with temperature. Residual stress build-up for CF/PEEK laminates begins below the stress free temperature (SFT), which is approximately 315 °C [15]. This is far above the glass transition temperature of 143 °C, which usually marks the point of residual stress formation for amorphous polymeric composites. Thus, using this material for cryogenic applications can involve having to design for thermal residual stresses due to temperature changes in excess of 500 °C. The difficulty in accurately characterising material properties, including fracture strength and toughness, over such a wide temperature range means that little experimental data is available from the literature, particularly for relatively novel materials such as tape-laid CF/PEEK.

This work aims to advance the design and analysis of linerless composite cryo-tanks by combining the extensive material characterisation of a tape-laid composite with a novel numerical methodology capable of predicting composite laminate damage and permeability. This approach represents a significant departure from existing analysis methods such as unit cell, first-ply-failure and continuum analyses [6,16–21] by allowing the discrete damage modelling of large structures using detailed material data inputs. An optimised cryo-tank design is also presented, which accounts for the thermo-mechanical stresses resulting from processing, fuelling and internal pressurisation. A sub-model meso-scale damage analysis shows that the optimised tank design is capable of preventing fuel leakage after exposure to cryogenic temperatures and internal pressurisation.

2. Material characterisation

2.1. Overview of material properties

Measurements of temperature-dependant mechanical, thermal and fracture properties of CF/PEEK materials have been collated from several sources in Tables 1 and 2. Using the properties of the tape laid Suprem IM7 [22] at 25 °C from Table 1 as a base, temperature-dependant data is generated by interpolation and normalisation using fitting functions across a range of temperatures for available material data. Table 3 presents the resulting interpolated temperature dependant data which is used in subsequent modelling work, described in Section 3. Linear interpolation has been used to complete the material data set where possible. Material strength and fracture toughness data are not available above the glass transition temperature of the material.

When compared with previously published material data for a similar grade of CF/PEEK processed using an autoclave [26], the tape-laid material exhibits lower strength values, particularly in the matrix-dominated directions. Transverse tensile strength alone was found to reduce by a third for the tape laid material. The increased presence of manufacturing defects resulting from the tape-laying process contributes to this property degradation.

2.2. Defect characterisation

The void and inclusion content for several types of tape-laid CF/PEEK laminates were measured using 3D X-ray computed tomography (CT). This non-destructive testing technique allows full internal characterisation of a specimen based on the varying densities of its constitutive material phases. The specimens (see Table 4) were manufactured from a Suprem T/60%/IM7/PEEK/150 material with 0.14 mm ply thickness and included:

- Two unidirectional coupons, named UD1 and UD2 from a flat plate (16 ply, 34 mm × 27 mm).
- Two $[45°/-45°/90°/0°/90°/0°/90°/0°/90°]_S$ coupons QI1 and QI2, from a flat plate (18-ply, 34 mm × 27 mm).
- One unidirectional hoop wound section (16-ply, 100 mm wide, 500 mm diameter).

A KUKA KR 180 R2900 robot with a laser-line diode laser module (LDM) 3000 W system operated by the Irish Centre for Composites Research (ICOMP) and based at the University of Limerick [14], Ireland, was used to manufacture the specimens. The nominal process parameters included a lay-down speed of 6 m/min, a target temperature of 420 °C, a tool temperature of 280 °C, a roller pressure supply of 4.5 bar. and a laser power of 500 W. Due to the nature of the ply-by-ply lay-up process, material inhomogeneity in the form of through-thickness crystallinity gradients is expected in the specimens. While there was no specific thermal post-treatment applied to the specimens, a relatively high tool temperature of 280 °C was used. This would help to offset the high cooling rates typically associated with the lay-up of the initial plies, with the effect of bringing their crystallinity levels closer to those in the centre of the laminate [28]. In addition, given that the lay-up process for the samples spanned several hours, the majority of the laminate would be kept above the glass transition temperature of the material. This would facilitate relatively uniform cool rates and thus crystallisation levels, at least for a portion of the thermal profile. Although it was not possible to measure the exact crystallinity gradient through the samples, work from collaborators has shown that the average crystallinity of samples increased from

Table 1
Measured temperature-dependant mechanical and fracture properties of CF/PEEK materials.

Temp. (°C)	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	TTS (MPa)	TCS (MPa)	IPSS (MPa)	ILSS (MPa)	G_{IC} (J/m^2)	G_{IIC} (J/m^2)
−196	141[a]	–	–	51[a]	–	81[a]	106[a]	–	–
−70	–	–	–	63[a]	–	104[a]	116[a]	–	–
−55	172[b]	11[b]	5.9[b]	–	–	–	–	1600[b]	2100[b]
25	155.0[c]	8.6[c]	4.00[c]	41[c]	163[c]	80[c]	98[c]	1910[c]	1355[d]
125	–	–	–	48[a]	–	75[a]	–	–	–

E and *G* are the elastic and shear moduli, TTS and TCS are the transverse tensile and compressive strengths, IPSS and ILSS are the in-plane and inter-laminar shear strengths, G_{IC} and G_{IIC} are Mode I and Mode II fracture toughness. The subscripts 1 and 2 refer to the longitudinal and transverse directions.

[a] Suprem Victrex AS4 [23].
[b] Cytec APC-2/IM7 [24].
[c] Suprem Victrex IM7 [22].
[d] Suprem Victrex IM7 [23].