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CHARACTERIZATION OF EFFECTIVE PERMEABILITY IN CRYOGENIC COMPOSITE LAMINATES

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ABSTRACT

Composites find numerous structural applications in the aerospace industry due to their low weight, high strength and stiffness properties. In recent applications composite materials have been used in the manufacture of cryogenic fuel tanks for reusable launch vehicles. The use of composite materials results in significant reduction of the overall structural weight. Permeability of cryogen through micro cracks in the composite material is a problem of concern. In this study, an analysis regarding the effective permeability of a graphite epoxy system with micro cracking induced damage is carried out. The effective permeability due to diffusion of cryogen through the matrix layer in the presence of cracks with no interconnections is investigated. Further, the study is expanded by considering a single-phase flow model for the permeation of cryogen through interconnected cracks. A continuum model is considered for the fluid flow analysis. The crack irregularities over the thickness of a single ply and the interconnection geometry between cracks from neighboring plies are examined in detail. Macroscopic estimation of the effective permeability of a ply is obtained by a homogenization procedure. Commercial finite volume software is used for the analysis.

Keywords: Permeability, Damage, Crack opening displacement, Crack density.

INTRODUCTION

In single stage reusable launch vehicles, lightweight composite materials find critical application. The structural systems of these vehicles are subjected to severe thermal and mechanical loading, as they contain cryogens such as liquid hydrogen under pressure at cryogenic temperatures. The loading conditions induce transverse micro cracks, running along the length of fiber in the composite due to mismatch in the mechanical and thermal properties of the matrix and the fiber. The micro cracks in different plies of the composite form a network of leakage paths, which assists the leakage of cryogen through the composite laminate. Hence, the study of cryogen flow through these micro cracks and their intersections is required in addressing the leakage problem. The leakage in composites is governed by several factors such as pressure gradients, micro crack density, the composite lay-up, and other damage in the composite due to delamination, connectivity of the cracks, residual stresses from manufacture and service-induced stresses from thermal and mechanical loads. Experiments can be performed mainly for specific designs and service conditions whereas modeling of cryogen flow through micro cracks will facilitate in designing the cryogenic composites subjected to various service conditions for optimum performance.

Under the storage conditions, cryogenic composite fuel tanks are exposed to temperatures ranging from 20 °K to the maximum allowable temperature for the composite of about 450-590 °K. Under the pressurized condition, biaxial stresses develop in the cylindrical tank in a ratio of 2:1[1]. Thermo-mechanical loading during the vehicle launch and due to containment of cryogen in the fuel tank causes the formation of transverse cracks. It is therefore important to obtain a measure of cryogen leakage by estimating the effective permeability of the composite.

Permeability measurements in composite laminates are made experimentally by pressurizing one side the composite specimen and detecting the leak rate on the other side [2,3]. Humpenoder measured the permeation rates of helium, hydrogen and methane through fiber reinforced plastics, thermoplastics and thermosetting plastics at temperatures varying from cryogenic to room temperature [4]. Aoki, Ishikawa and Morino [5] investigated the dependence of permeability on applied load with the help of a biaxial cruciform specimen. The effect of thermo-mechanical loading on the permeability was studied by exposing the composite specimens to thermal and mechanical cyclic loading. Rivers, Sikora and Sankaran examined permeability variation with applied load at cryogenic temperatures in their work [6]. It was also found that the permeability values are affected by the volume fraction of fibers in the composite. Temperature dependence of permeability was studied by measuring leak rates in a composite specimen at temperatures ranging from cryogenic temperature to room temperature [7]. Nishijima, Okada and others found that the permeation rate dependence on temperature could be expressed by the Arhenius equation [8]. The crack density in different plies also influences permeability of a composite. A correlation of permeability with crack density was examined in the work of Kessler et, al [9]. Aoki and others modeled the leakage of cryogen in a composite using a semi-analytical method [10,11]. Certain parameters in the model were obtained experimentally. Behavior of cryogen leak rate through composite to applied load was studied by considering the enlargement of crack opening displacements. Modeling of cryogen leakage through composites with interconnected cracks requires knowledge of fluid flow through cracks [12,13]. The flow through cracks is governed by three-dimensional Stokes equations.

The present work focuses first on permeation of cryogen in the composite by diffusion through a matrix layer in adjacent but not connected cracks. A parametric study is carried out to investigate the possibility of permeation by diffusion above a critical allowable value. Further, flow through interconnected cracks in adjacent plies of a composite is investigated. Information about the crack geometry and crack density in each ply obtained by optical inspection through a metallographic microscope is utilized in order to determine the crack opening under different loading conditions. The problem is approached in two stages. First, the effect of applied mechanical loading conditions on the effective permeability of a ply in the composite is considered. The crack geometry, crack opening displacements and crack density information are used in the estimation of effective permeability of single ply of a cryogenic composite laminate. Both the actual crack geometries and different approximations involving straight and tapered channels with straight walls are used to compute the permeability values for the composite numerically. These straight-walled approximations significantly simplify the computational process and are subsequently used in the second phase of the study involving three-dimensional modeling of a two-layer crack network. The three-dimensional study focuses on the effect the crack junction area has on the effective permeability of two adjacent plies.

The numerical studies in the subsequent sections all consider hydrogen as the cryogen since it is widely used in reusable launch vehicles fuel tanks and there is available experimental data for hydrogen leakage through cryogenic laminate composites.

The paper is organized as follows. First the case of hydrogen diffusion is considered for cracks in adjacent plies in the absence of interconnections. This is followed by study of the effects the applied load has on the flow of hydrogen trough a single crack. Finally, a connected, two-crack network is considered two adjacent plies in three-dimensional settings.

NUMERICAL MODELING OF PEREMABILITY IN CRYOGENIC COMPOSITES

The cryogenic composite specimen, considered for the analysis is IM7/5250-4 with IM7 carbon fibers and epoxy matrix (5250-4) and was provided by the Marshall Space Flight Center. The lay-up of the cryogenic composite specimen is $[90/45/0/-45]_s$. The specimen has been mechanically cycled and then tested for gaseous hydrogen permeability at 32 °K. Due to the applied load micro cracks develop in each of the plies and assist the permeation of hydrogen. The cracks in each ply run along the direction of the fibers and span the thickness of each ply. As different plies have different orientation with respect to each other, cracks from adjacent plies only meet in localized regions of the ply interfaces.

The structure of these crack junctions is not well established and therefore the numerical study covered both the possibilities of the cracks being separated by a small layer of matrix and being fully connected. In the next section, the first case of permeation of hydrogen by diffusion through matrix layer between non-intersecting cracks in adjacent plies of a composite is studied.

Diffusion of cryogen in a two-ply composite

The two representative cracks in two adjacent plies of the composite shown on Figure 1a are used as the Representative Volume Element (RVE) for the hydrogen diffusion studies. The micrograph taken through a metallographic microscope of the two adjacent plies shows the cross-sectional area where the cracks come close to each other. Due to the different orientation of the plies it is difficult to tell if they actually intersect or not. For the following parametric study it is assumed that they do not intersect and the cracks are taken in a two-dimensional setup, that is, both of them run parallel to the depth of the specimen. This two-dimensional setting will provide an upper estimate of the permeability since most of the diffusion takes place near the crack tips. When the cracks are assumed parallel, this area runs through the depth of the specimen, while in reality is it localized to a small are of the RVE.

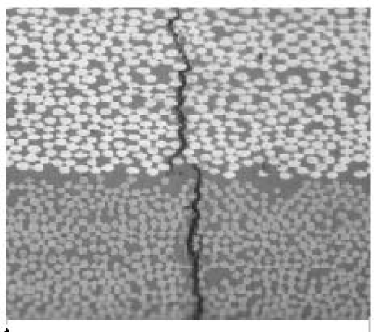

Figure 1a. Micrograph of representative cracks in adjacent plies of IM7/5250-4 composite specimen.

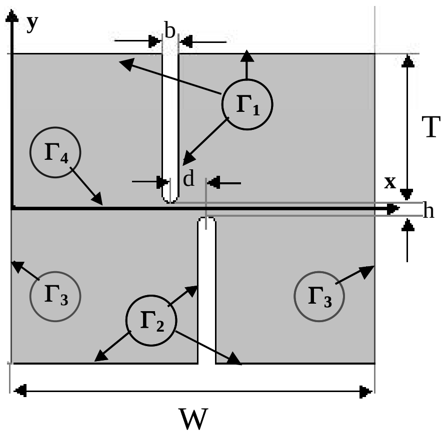

Figure 1b. Schematic of the Representative Volume Element (RVE) for hydrogen diffusion through matrix layer of a composite with no interconnected cracks.

A schematic of the RVE comprising of two cracks in adjacent plies is shown in Figure 1b. Since the diffusion takes place inside the composite and near the crack tips it is not necessary to reproduce the crack profile exactly. Therefore, the cracks considered are straight channels with semi circular tips. As shown in Figure 1b, region Γ_1 is the top surface of RVE and the surface of the top crack; region Γ_2 is the bottom surface of RVE and the surface of the bottom crack, region Γ_3 includes the walls of the RVE, and Γ_4 is the mid-section of RVE. The RVE is repeated periodically by consecutive reflections about the lateral surfaces Γ_3.

The diffusion process in the matrix starts by the adsorption of the cryogen onto the surface of the composite followed by dissociation into individual atoms, their chemical absorption into the surface of the composite followed by Fickian diffusion through the matrix. The diffusion of hydrogen through the matrix is well approximated by Ficks law [14]:

$$\mathbf{J} = -\mathbf{D}\,\nabla C \tag{1}$$

where C is the volume concentration of hydrogen, $\mathbf{J}$ is the volumetric hydrogen flux and $\mathbf{D}$ is the isotropic second order diffusivity tensor. The conservation of mass equation is given by

$$\nabla\bullet(\rho\mathbf{J}) = 0 \tag{2}$$

where ρ is the density of hydrogen diffusing through RVE. Combining equations (1) and (2) leads to the following field equation:

$$\nabla\bullet(\rho\mathbf{D}\,\nabla C) = 0 \tag{3}$$

Concentration boundary conditions are specified on the top and bottom surface of the RVE (see Figure 1)

$$C|_{\Gamma_1} = C_0 \quad , \quad C|_{\Gamma_2} = 0 \tag{4}$$

The concentration C_0 on Γ_1 is obtained from the partial pressure p_0 of hydrogen on the boundary by the expression

$$C_0 = k\ p_0 \tag{5}$$

where k is the solubility coefficient of hydrogen. Finally, due to the assumed periodicity of the RVE in the x-direction, the solution to equation (4) must also be periodic. Therefore the normal component of the flux $\mathbf{J}$ must vanish on the two lateral surfaces, that is

$$\mathbf{J}\bullet\mathbf{n}|_{\Gamma_3} = 0 \tag{6}$$

where $\mathbf{n}$ is the normal vector to Γ_3.

The numerical experiments were performed on a specimen with $\mathrm{T} = 100\mu\mathrm{m}$, and $\mathrm{W} = 100\mu\mathrm{m}$. The width of the crack is 10μm. The permeability coefficient of hydrogen diffusing through matrix is $D_{xx} = D_{yy} = 7.169\mathrm{x}10^{-9}$ (cm^2/s.atm) and is obtained based on the information in [3]. Three different cases are studied for offset distance between cracks, d equal to 0, 20, 40μm (see Figure 1). The longitudinal distance between the cracks h is 0.5μm for all the three cases. This value of h is less than a fiber diameter in the composite and is a worst-case scenario for cracks with no interconnections.

Due to the boundary conditions given by equations 4 and 6, the averaged flux in the x direction, $\langle J_x \rangle$ is zero. The averaged values of the y component of the flux, $\langle J_y \rangle$ over the whole RVE obtained in the numerical simulations are given in Table 2. The average flux is defined as:

$$\left\langle J_y \right\rangle = \frac{\int J_y dA}{A} \tag{7}$$

where the integral is taken over the whole RVE. As can be seen from the table the average value of flux component J_y *i.e.*, $\left\langle J_y \right\rangle$ decreases gradually as the offset distance between the crack is increased. The pointwise values of J_y along the midsection of the RVE, Γ_4 for the case d = 0 (the two cracks are aligned vertically) are plotted in Figure 2. The flux value, J_y is high near the crack tips and decreases gradually away from the crack tip.

Table 1. Average volumetric flux of hydrogen through the RVE for different offset distances d (see Figure 1b) between cracks.

Transverse offset distance, d (μm)	Average diffusing flux, $\left\langle J_y \right\rangle$ (m/s).
0	3.38x10-5
20	8.80x10-6
40	5.67x10-6

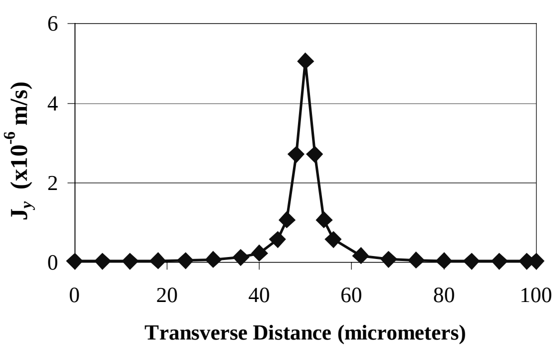

Figure 2. Volumetric flux of hydrogen across the mid-section of RVE for d=0μm and h=0.5μm.

The values for $\left\langle J_y \right\rangle$ are compared with the allowable flux values specified for reusable launch vehicle fuel tanks of the X-33 vehicle. The allowable flux value during ascent and for an inside tank pressure of 3.40×10^5 N/m^2 is 3.58×10^{-6} m/s. Comparison of the average values of J_y computed for different case studies that are given in Table 1, it is concluded that the average value of flux for hydrogen diffusing through epoxy layer is an order of magnitude less than the allowable value specified for X-33 fuel tank for all studied cases. Therefore, a matrix layer of thickness 0.5μm is sufficient to prevent the leakage of hydrogen by diffusion.

Cryogen flow through cracks and their intersections

In this section the leakage of cryogen through networks of cracks with respect to typical crack geometry and possible junction configurations is investigated in two model problems. The first model problem described next considers the effects of irregular crack geometry and applied load on the effective permeability of a ply in the composite in a two-dimensional setting. The effects of irregularities in the geometry of actual crack are studied by different straight and tapered channel approximations. The second model problem discussed later focuses on the three-dimensional effects of crack junction area on the effective permeability of two-ply network of cracks. Change in the junction area is achieved by changing the ply orientations.

Effects of crack irregularities on the effective permeability of a ply in a composite. Straight and tapered approximations of the cracks with irregular geometry in a ply are considered for the study. These approximations reduce the computational effort in subsequent three-dimensional modeling of the network of cracks. The composite specimen under consideration, IM7/5250-4, is mechanically loaded from 47 MPa to 101 MPa and optically inspected for damage at the Air Force Research Laboratory (AFRL). Micrographs of actual crack in the 90-degree ply at different loads and the crack density information are provided by AFRL. Figure 3 illustrates the micrograph of a representative crack and the corresponding RVE in the 90-degree ply of the composite.

The initial step in computing the effective permeability of the ply is analyzing hydrogen flow through the representative crack. The effective permeability of the ply is then obtained by averaging the computed gas velocity over the RVE. In the analysis, the matrix is assumed to be rigid and impermeable to the gaseous hydrogen flow. Due to the small width of the crack, steady-state flow at low Reynolds numbers is assumed. Therefore the velocity $\mathbf{v}$ and pressure p satisfy the Stokes equations which together with the incompressibility constraint read:

$$-\nabla p + \mu \Delta \mathbf{v} = 0 \tag{8}$$

$$\nabla \bullet \mathbf{v} = 0 \tag{9}$$

where, μ is the viscosity of hydrogen. The velocity satisfies no slip boundary conditions at the fluid-crack interface, S:

$$\mathbf{v}\big|_S = 0 \tag{10}$$

In order to obtain the effective permeability, the natural boundary condition at the inlet A and outlet B is a pressure differential:

$$p\big|_{inlet} = p_1 \quad , \quad p\big|_{outlet} = p_2 \tag{11}$$

where p_1 and p_2 are two arbitrarily chosen constants.

The pressure and velocity values inside the crack are obtained by solving equations (8)-(11). The permeability component, K_{yy} of the ply is then given by:

$$K_{yy} = \frac{\mu \langle v_y \rangle \mathrm{H}}{(p_1 - p_2)} \quad (12)$$

where H is the height of the crack, and $\langle v_y \rangle$ is the area-averaged y-component of the velocity field in the RVE (the velocity is taken to be zero in the area occupied by the matrix). The remaining permeability components K_{xx}, K_{xy} and K_{yx} are identically equal to 0 since there is no net flow in the x direction.

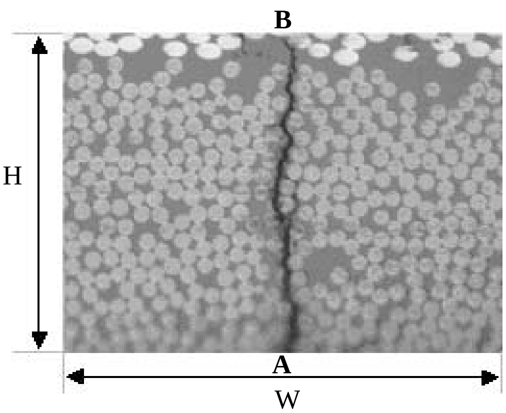

Figure 3. Micrograph of representative crack in 90-degree ply of IM7/5250-4 composite specimen at 101 MPa load.

The cracks in a single ply are not connected to each other hence the total flow rate is simply the sum of the flow rates through individual cracks therefore the width W of the RVE (Figure 3) is equal to the average distance between the cracks in the ply. The crack density values in all the plies of the composite at the end of applied mechanical load are given in Table 2. Based on this the RVE dimensions are H = 73μm and W = 1909μm. Crack opening displacements for the actual crack at the inlet A, outlet B and the average opening at different loads are given in Table 3. The average crack opening is obtained by integrating the opening of the actual crack along the height of the crack dividing by the crack height. The ply under consideration is an outermost ply in the composite and the difference in the opening of actual crack in the ply at inlet and outlet is due to redistribution of stress on the free surface of the composite. It should be noted that the actual crack opening at 93 MPa applied load is approximately equal to that for 47MPa load and is smaller than for 62 and 78 MPa. This is caused by the formation of new cracks as the load is increased from 78 to 93 MPa.

Table 2. Crack density in different plies of IM7/5250-4 composite specimen.

Ply Orientation (degrees)	Crack Density (Cracks per mm)
90	0.523
45	0.187
0	0.009
-45	0.026

Table 3. Crack opening displacement values at different loads in 90-degree ply of IM7/5250-4 composite specimen.

Load (MPa)	47	62	78	93	101
Actual crack opening at outlet B(μm)	1.06	1.18	1.38	1.10	1.34
Actual crack opening at inlet A (μm)	2.79	1.73	3.63	2.54	4.26
Average crack opening (μm)	1.71	1.80	2.13	1.94	2.58

The effect of the irregular geometry of the actual crack on the effective permeability is studied by different straight and tapered channel approximations. In the straight channel approximation, the width of the channel is taken to be the inlet opening at A, outlet opening at B, and the average opening of actual crack. The tapered channel approximation has width at the inlet and outlet equal to the opening of the actual crack at inlet and outlet respectively, connected by straight walls.

The effective permeability of ply for tapered channels and for the actual cracks is obtained from equation (12) after solving numerically equations (8)-(11). The viscosity μ of hydrogen used in the analysis $8.411\mathrm{x}10^{-6}$ Kg/m.s. For each load case the crack geometry is obtained by digitizing the available

Table 4. Effective permeability of 90-degree ply in IM7/5250-4 composite specimen at different loads.

Load (MPa)	Actual crack ($\mathrm{x}10^{-15}\mathrm{m}^2$)	Tapered crack ($\mathrm{x}10^{-15}\mathrm{m}^2$)	Straight crack with width equal to inlet opening ($\mathrm{x}10^{-15}\mathrm{m}^2$)	Straight crack with width equal to outlet opening ($\mathrm{x}10^{-15}\mathrm{m}^2$)	Straight crack with width equal to average opening ($\mathrm{x}10^{-15}\mathrm{m}^2$)
47	0.09	0.19	0.95	0.05	0.21
62	0.16	0.12	0.22	0.07	0.25
78	0.20	0.43	2.09	0.11	0.42
93	0.17	0.19	0.71	0.05	0.31
101	0.42	0.51	3.37	0.10	0.74

micrographs. The effective permeability of ply with straight channel is obtained by the well-known formula [15]:

$$K_{yy} = \frac{b^3}{12W} \tag{13}$$

where b is the width of the channel.

The numerical simulations are performed using FLUENT, a commercial finite volume software. The results from the numerical simulations for the effective permeability of the 90-degree ply for the actual cracks geometry and for the different straight-walled approximations at different applied loads are given in Table 4. A typical velocity profile is illustrated in Figure 4. The straight channel approximations have significant difference in the estimated permeability values when compared to the one for the actual cracks. The use of tapered channel allows to estimate the effective permeability values more accurately than the corresponding straight channel approximations. The relative error in the estimated permeability value for tapered channel is around 20% for 62, 93 and 101 MPa loads. At 47 and 78 MPa loads however the tapered channel approximation results in two-fold error in the effective ply-permeability estimation.

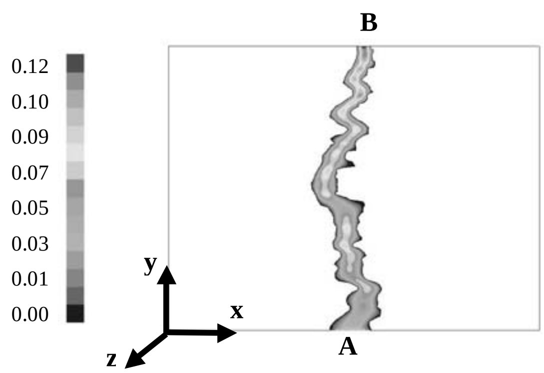

Figure 4. Contour plot of fluid velocity v_y (m/s) inside the representative crack in the 90-degree ply of IM7/5250-4 at 101 MPa load.
(figure not drawn to scale: horizontal scale is exaggerated)

The variation of effective permeability of the 90-degree ply for actual crack as a function of applied mechanical load is illustrated in Figure 5. The permeability value increases as the applied load increased from 47 MPa to 78 MPa. The value then decreases as the load is increased to 93 MPa and finally the effective permeability value increases when the load is further increased to 101 MPa. The decrease in the permeability value at 93 MPa is expected because the effective permeability depends on the crack opening and a decrease in the opening of cracks at 93 MPa is observed due to formation of new cracks.

From the two-dimensional analysis it is concluded that the variation of effective permeability of a ply in a composite as a function of applied load is similar to the behavior of crack opening of a representative crack in the ply to the load due to the dependence of permeability on the crack opening. The tapered channel approximation of actual cracks estimated the effective permeability values more accurately than other straight channel approximations at certain applied loads. For other loads the tapered channel approximation of the actual crack is found to estimate the permeability values with a significant error. The approximation of cracks with irregular geometry made from their permeability values is considered in the next section.

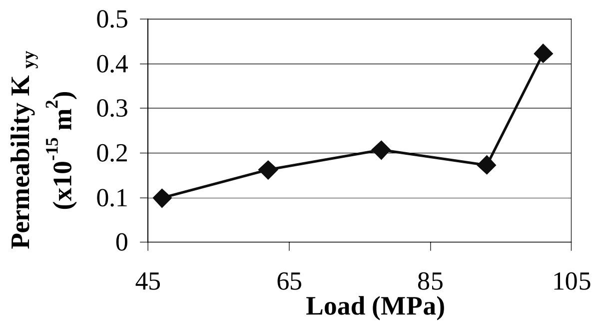

Figure 5. Variation of effective permeability of 90-degree ply as function of applied load.

<u>Three-dimensional analysis of flow through a crack network</u>. A more realistic approach to modeling the permeability of the cryogen composite is considering actual three-dimensional leakage paths through interconnected crack networks. A critical element of a successful approach to solving this problem is understanding the effect crack junction area has on the effective permeability of a composite. The actual junction configuration of cracks from adjacent plies is difficult to obtain experimentally or deduce analytically. In this section a permeability study is performed on a crack network in a two-ply composite and the intersection area is assumed to be the simple cross-section of the cracks. The relative orientation of the two plies is varied thus changing the junction area and therefore the effective permeability of the composite. The delamination effects due to stress concentrations near the junction, which can significantly alter the junction geometry, are not considered at this stage.

Since the cracks in each ply are parallel to the ply orientation and perpendicular to the ply-to-ply interface, an RVE for two-crack network is of the type shown on Figure 6. The base of the parallelopiped is a rhombus and the lateral surfaces are perpendicular to the base. The two plies have the same height H and the other two dimensions of the parallelepiped on Figure 6 are determined based on the crack density information in each of the plies. For this study, W and L are taken equal (note, that W and L represent the *distance* between the respective lateral surfaces, *not* the length of the parallelogram's edges). The Stokes equation (8) and incompressibility equation (9) are solved for with a pressure differential imposed at the inlet and outlet. The remaining boundary conditions are no-slip at the crack walls and periodic boundary conditions on the lateral sides of the parallelepiped.

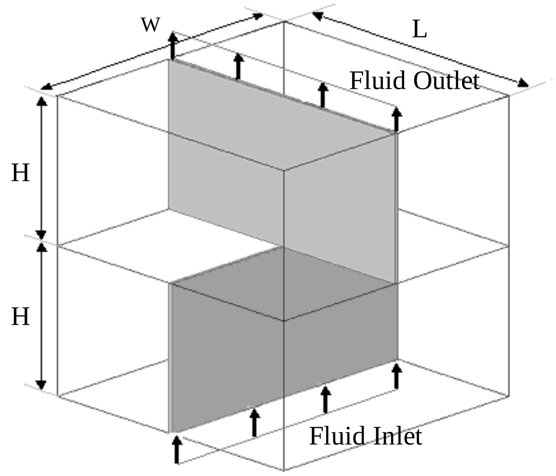

Figure 6. RVE for straight cracks intersecting at a 90 degrees angle. (Not drawn to scale).

The parametric study is performed for two different crack densities (taken equal in both of the plies), one corresponding to W = L = 1909μm which is the average spacing between the cracks form the 90-degree ply from the previous section, and one which is assumed much smaller with W = L = 73μm. For the first case (1909 μm) it is computationally prohibitive to solve the BVP problem with the irregular crack geometries of the previous section. Therefore, a straight-channel crack approximation is made with effective permeability (for a single ply) equal to that of the actual crack at 101MPa load. This is achieved by inverting equation (13) and setting the opening of the straight channel equal to (for W = *L*):

$$b_m = \left(12\mu W K_{yy}^{irr}\right)^{1/3} \tag{14}$$

where K_{yy}^{irr} is the permeability of the actual crack (see Table 4). For the low spacing case of 73μm it is possible to use both a straight channel approximation as well as actual crack profile. To summarize, three geometries were considered: a straight channel and average crack spacing 1909μm; straight channel and average crack spacing 73μm; actual crack profile and 73μm average crack spacing. The numerical computations were performed on all three cases for included angles between the cracks of 15, 30, 45, 60 and 90 degrees.

The results from the numerical simulations are summarized on table (5). For comparisons, the profile of the vertical component of the velocities for perpendicular cracks at 1909 and 73μm spacing are shown on Figures 7 and 8. The first observation regards the realistic, 1909μm crack spacing. It can be seen that the permeability of the composite for all ply orientations is two orders of magnitude (~ 80 times) smaller than the corresponding 2-D case. This can also be seen by comparing the second and third columns of Table (5), which give the permeability values for actual crack and a corresponding straight channel (73μm spacing). The maximum difference is at 60 degrees and is about 60%. This difference can also be explained by noting that the actual crack has a tapered profile, which leads to approx. 20% difference in the junction area compared to corresponding straight-channel approximation. Therefore, the crack junction area in a fully 3-D setting has far greater impact on the composite permeability compared to taking into account the actual profile of the crack.

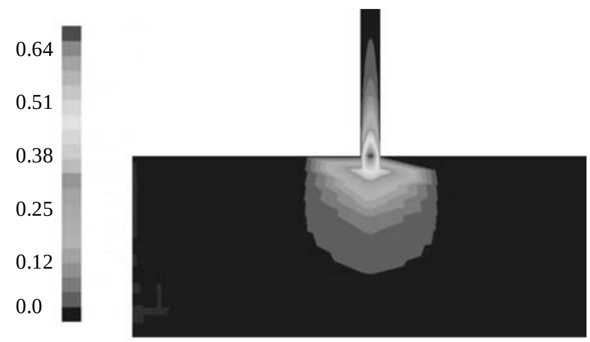

Figure 7. Contour plot of vertical velocity component v_y (m/s) for straight, perpendicular cracks. The crack spacing is W = L = 1909μm.

Table 5. Effective permeability of two-crack network at different angles between the cracks.

Angle (degrees)	Permeability, straight channel W = L = 1909μm ($\times10^{-15}m^2$).	Permeability, actual crack W = L = 73μm ($\times10^{-15}m^2$).	Permeability, straight channel W = L = 73μm ($\times10^{-15}m^2$).
15	0.0031	3.31	2.13
30	0.0042	4.52	2.74
45	0.0051	5.16	3.08
60	0.0054	5.57	3.22
90	0.0064	5.44	4.00

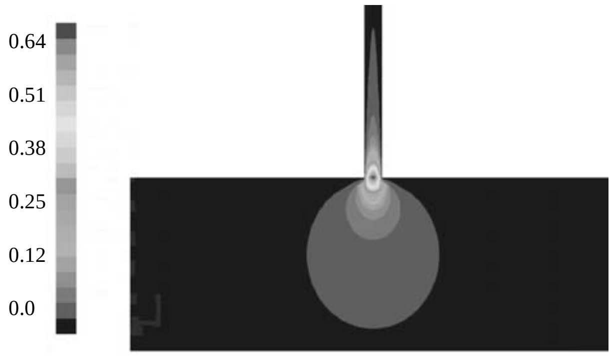

Figure 8. Contour plot of vertical velocity component v_y (m/s) for straight, perpendicular cracks. The crack spacing is W = L = 73μm.

The second observation is that the effective permeability decreases as the angle decreases. The actual flow rate for the RVE does increase when the angle is decreased (and the cross-sectional are is correspondingly increases). However, the volume of the RVE also increases with decreasing angle (because the crack spacing is kept fixed) at a higher rate compared to the increase of the flow rate and as a result the effective permeability decreases.

CONCLUSIONS AND FUTURE WORK

Cryogen leakage and effective permeability of composite laminates used in reusable launch vehicles fuel tanks have been studied numerically. Experimental data have been utilized to reconstruct crack density information and representative crack profiles. Both permeability due to cryogen diffusion through the matrix and cryogen transport though connected crack networks have been estimated. It is found that the permeability due to diffusion is an order of magnitude less than the allowable values specified for the X-33 vehicle fuel tanks. The main mode of transport is determined to be the leakage trough connected crack networks. Upper bounds for the permeability at different load levels have been obtained by modeling cracks in a single ply of the composite. It is also determined that the permeability correlates directly with the crack opening at different applied loads. Experimental observations however have shown that crack opening are not directly correlated to the applied loads.

Further, attempts to approximate the actual transverse crack profile have shown that a straight-walled tapered channel utilizing only crack opening displacements at two ends provides good results for some loading conditions. In some cases however the difference is up to two times. These approximations are then used in a three-dimensional parametric study of leakage in a two-crack network. The three-dimensional study demonstrated that the crack junction area is the most significant factor for the permeation of cryogen and can lead to several orders of magnitude difference compared to the effects of actual crack profile.

Currently, only very simple junction geometry is used. Future work should focus on obtaining better estimates for the junction geometry. These will include both experimental observations and numerical simulations. Finite element analysis can be used to determine the stress concentrations near the junction location and the corresponding delamination in the composite, which significantly impacts the junction area. Representative crack networks in several plies of the composite will be considered compared to the current one or two plies. The effort to use simplified crack profiles will be extended to cracks in internal plies, which generally do not have the tapered profile of the cracks as in the surface layers. It is also important to consider the effects of relative position of crack junctions in several composite plies. The crack openings and density in different plies can also be estimated using numerical tools and will the help of a comprehensive permeability analysis of realistic crack networks will help deduce a relationship between the type of applied load on the overall permeability of a composite. These studies will help optimize the lay-up of cryogen composites in order to minimize the leakage of cryogen.

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