# The effects of voids in quasi-static indentation of resin-infused reinforced polymers

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# Abstract

The focus of this study is the influence of voids on the damage behaviour in quasi-static loading of resin infused carbon fibre reinforced polymers. Experimental results are presented for quasi-static loading in combination with high resolution tomographic imaging and statistical analysis (homology of pores or voids and induced cracks). Three distinct mechanisms were observed to control delamination growth in the presence of sharp and blunt voids. Delamination cracks interact with the supporting yarns, especially in combination with air pockets trapped in the resin in the form of long, sharp voids. This resulted in crack growth that coalesces with delamination cracks from neighbouring yarn-voids during increased out-of-plane load-displacement, with almost no presence of intralaminar transverse cracks. This highlights the benefits and drawbacks of the supporting yarn during out-of-plane loading.

**Keywords:** E. Resin transfer moulding; D. CT analysis; B. Porosity; C. Damage mechanics.

# Introduction

Applications of composite materials requiring the highest levels of structural performance have traditionally relied upon the autoclave-curing of prepreg materials to manufacture high-performance components due to the high degree of consolidation and microstructural homogeneity achieved compared to other manufacturing processes. Resin transfer moulding (RTM) is an infusion-based process which is currently widely considered as a lower-cost alternative to the prepreg-autoclave route for producing high-performance composites. The response to loading and matrix-dominated properties of such laminates made via RTM must be studied with regards to the effect of pores / voids on such behaviour due to the entrapment of bubbles during infusion. These voids are generally thought to act as crack initiation sites and to facilitate crack propagation, causing damage to form at lower loads than in materials without voids [1-4].

Whether in the presence of voids or not, a key concern regarding composite structures has been their susceptibility to damage and strength reduction from impact loading. Their damage resistance has commonly been investigated through out-of-plane loading, either dynamically by low velocity impact (LVI) testing [5-7] or through quasi-static indentation (QSI) [8-10]. The benefits of QSI over LVI are that damage evolution in the same specimen can be characterised as a function of load or displacement [10,11] and it avoids the issue of interpreting oscillations and other dynamic artefacts on force-displacement curves, allowing more accurate detection of specific damage events [12]. There have been many studies that report similar load-displacement and damage behaviour between the two test methods [13-16]. Some differences have, however, also been reported between the two test methods [7,11,17,18] which suggest that caution should be exercised in using QSI to interpret impact behaviour.

Characterization of the mechanics behind such damage requires micro-level analysis due to the small dimensions of the micro- and meso-scale architecture of composite materials. Microfocus X-ray computed tomography(µCT) is becoming established as a powerful technique by which to investigate damage in composite materials [19-22]. This method has enabled damage mechanisms to be studied in three-dimensions (3D) [13]. It avoids artefacts associated with cutting and polishing, and the limitations associated with only looking at surfaces or 2D images generated by other techniques such as serial microscopy [2], and offers a higher resolution than non-destructive techniques such as ultrasonic C-scan [1, 25-28]. The main disadvantages of µCT are the long imaging times required for such high resolution from laboratory radiation sources, and the relatively small sample sizes allowable leading to a non-trivial selection of the region of interest (ROI) from a composite part [25]. Perhaps the most significant advantage of µCT for damage assessment is the ability to evaluate the effects of time- and load-dependency on crack initiation and growth by non-destructively scanning at intervals during crack development generated by the application of incremental load steps [10,20,21,24].This allows a better assessment of damage development than has been achieved with other imaging methods, and allows more accurate analysis of the role of defects such as voids on damage growth.

The in-plane pressure gradient of an infusion process such as resin transfer moulding (RTM) results in a greater variation in void morphology, distribution, and clustering than a prepreg-based process [29-33]. Thus the advantages of µCT are particularly useful for the characterisation of infusion-based voids, yet little work has been presented to date exploiting this combination, with the exceptions of Schell et. al. [33] and Sisodia et. al. [34]. Using such characterisation methods, an increasing void content has been linked with decreases in several mechanical properties and some work has already been performed to establish the mechanisms governing these relationships [1,4,26,35,36]. Such work may inform strategies to suppress damage growth and increase the mechanical performance. Potentially, mechanism-based models could also be used to decrease the amount of required testing.

Correlation of voids and mechanical properties such as damage susceptibility requires a high resolution regarding characterisation of void size, shape, and position relative to damage, other inclusions, and reinforcement microstructural features [37]. While previous studies have mainly focused separately on development of the imaging methods, void characterisation, and fabric microstructural effects on damage mechanisms, there has been very little work combining all of these parameters to study mechanistically the role of voids in damage progression caused by out-of-plane loading [22,38,39]. One of the challenges has been the complexity, compared to 2D studies, in obtaining and correlating quantitative data in 3D [26,40,41].

The focus of the present study is the influence of voids on the damage behaviour in quasi-static loading of resin infused carbon fibre reinforced polymers. The present study uses a time-series investigation of µCT experiments, scanning coupons after incrementally applied QSI displacements. The µCT results contribute, partly towards non-destructive 3D evaluation of the damage development within the same coupon [10,41], and partly towards obtaining novel [34,44] statistical data on the homology of voids and damage, with the overarching aim of examining damage interactions in QSI loading. Such understanding can aid in the development of RTM material systems, by (i) combining with flow simulation to improve the manufacturing process in the case of effects of fabric structure on void formation, and by (ii) informing finite element models for indentation tests to capture the correct failure mechanisms in order to predict critical failure loads better.

# Materials and method

# Materials

Test coupons measuring 100 × 150 mm × 4 mm were cut from a rectangular laminated composite plate of 800 mm × 400 mm × 4 mm that was manufactured by resin transfer moulding (RTM) with unidirectional flow parallel to the longer dimension using a constant pressure difference of 200 kPa. The stacking sequence of the plate was [0/-45/90/+45]2s. An oven-cured epoxy (HexcelTM RTM 6) was used with a proprietary aerospace-grade unidirectional (UD) carbon fibre weave. Resin cure was performed according to the manufacturer’s guidelines. The fabric architecture, shown in Fig. 1, consists of UD carbon fibre tows held together by supporting biaxial woven glass fibre yarns in both warp and weft directions. This structure is also known as an “orthogonal interlock weave;” the glass yarns help to mitigate tow waviness from either handling or infusion [42]. The primary flow direction during infusion was parallel to the 0° axis. Analysis of the µCT images showed that the fibre volume fraction was ~53%, with the carbon fibres comprising approximately 93% of the fibre volume and glass yarns comprising the remaining 7%. The areal weight for each layer consists of 242.5 g/m2 of carbon fibre and 13.5 g/m2 of glass fibre. As the resin was degassed and the mould leak-tested per usual industrial standards, the void content in this composite material is suspected to predominately arise from mechanical bubble formation [43].



**Figure 1.** Photograph (A) and schematic (B) of the reinforcement fabric and voids, and reference coordinate system for principal orientations of the carbon fibre layers.

# Quasi-static indentation test

QSI experiments were performed at room temperature under ambient conditions using an Instron universal testing machine with a 50 kN rated load cell featuring a 16 mm diameter hemispherical tup and a base plate with a 75 mm 125 mm rectangular window [8]. Force-displacement data were recorded for the loading portion of the QSI test with a cross-head displacement rate of 1 mm per minute. Incremental displacement steps of 1, 2, 3, 4, and 5 mm were applied sequentially. The range of incremental steps was selected to capture damage initiation and damage growth with 5 mm displacement chosen to match the peak out-of-plane displacement of a 30 J impact event [23] in accordance to the ASTM D7136M standard [5].

# Imaging by X-ray computed tomography

QSI coupons were scanned ex-situ after application of each loading increment using a Nikon Metrology XT H225 LTM micro-focus CT system. The scans were acquired using a micro-focus 225 kV source fitted with a tungsten reflection target together with a Perkin Elmer XRD 1621 CN14 HS detector. The scan settings are provided in Table 1. Scanning was performed non-destructively, with no cutting of the samples and no penetrative dyes added. The scans were reconstructed using a filtered back projection algorithm to form an 8-bit volume with grey scale intensities in the range 0 to 255. Image analysis was performed using VG studio Max v2.1TM (Volume Graphics GmbH, Germany). The carbon fibres, biaxial yarns, voids, and damage consisting of cracks and delamination were all discernible throughout the sample’s volume, as shown in Fig. 2. These features were segmented through a combination of global thresholding and use of a seed-growing algorithm (ISO-50%), by taking the mean value between the peaks of the air distribution and material distribution [44]. The segmented data was then quantified using ImageJTM [45,46] and Avizo Fire 9.0TM (FEI, USA). The voxel size (Table 1) is just large enough to detect larger voids and individual fibres. This may allow small voids to go undetected, but these voids seemed inconsequential to damage propagation; all instances of observed damage during QSI loading propagated from voids that were detected at this resolution. Damage, e.g. delaminations and intralaminar cracks, was distinguished from voids by comparison of the reference (un-indented) and indented states; any growth of the volume of air after the reference state was considered damage [44].

**Table 1.** Scan settings for the Nikon Metrology XT H225 LTM µCT scanner.

|  |  |
| --- | --- |
| Sample size (mm3) | 100 × 150 × 4 |
| Acceleration voltage (kV) | 115 |
| Beam current (µA) | 94 |
| Voxel size (µm) | 14.2 |
| Detector dimensions (pixels) | 2048 × 2048 |
| Number of radiographs | 3142 |
| Exposure time (ms) | 117 |
| Scan time (minutes) | 75 |



**Figure 2.** µCT 3D rendering of a coupon at 3 mm indentation depth with the laminate material cropped to reveal the voids and damage with labels for carbon fibres, binding yarn, voids, cracks and the indent centre.

# Two-point statistical analysis

Two-point statistical analysis has been used is this study to associate the probability of voids and cracks forming around glass-yarns. Two-point statistics constitute a mathematical description of the relative geometrical distribution of features of interest within a structure [47]. For example, if the two-point statistics were taken between human populations and bodies of water across the planet, hotspots towards the centre of the map would indicate that humans and water have a high probability of being close together. In the current study, we are interested in this type of statistical geometrical relationship between microstructural components and damage formation. On the other hand, two point statistics can also produce a map of the statistical geometrical relationship between points in a single type of entity. If the two-point statistics were taken between bodies of water and themselves (the so-called auto-correlations), then the probability of finding a point in a body of water at a certain location relative to another point in a body of water would be captured. If all lakes were circular then the hotspot in the centre of the map would reflect this ‘average shape’ via a circular peak (note that if lakes were elliptical, but with random orientation of the major axis, the ‘average’ geometrical relationship between points in the lakes would also be isotropic – resulting in another circular peak, but with a different steepness).

The two-point correlations between two selected phases (e.g. carbon or glass fibre, or void) encapsulate the average geometrical relationship between sample points that lie within the phases. For instance, the two-point correlations between glass fibre and void in the pristine substrate indicate the probability of the void phase being found at a particular location relative to a point in the glass fibre. Hence, regions of high probability within the two-point correlation map identify locations of high void concentration relative to the glass fibre phase.

When two point correlations are taken of a single phase (the autocorrelations explained above), they capture the probability of a pair of points that are separated by a given vector both lying within that phase. Thus, for vectors close to the origin, contours of high probability within the two point map of voids indicate the average shape of voids within the sample, e.g. the average extent of the boundaries in any direction from the centre point of the void. As for the lake example above, if the voids were elongated but randomly oriented, the peak in the two point map would simply be circular. This is not the case, however, as the voids are prone to extend in particular directions, hence the contour reflects both the extent and directionality of the voids.

To calculate the two-point correlations, a function is defined in MATLABTM 2018b (The Mathworks Inc., USA) that indicates the phase at each point of the samples: *m*(*x*,*h*), where *m* takes the value 1 if phase *h* is present at point *x*, or 0 otherwise. For example, in the current sample, five mutually exclusive arrays would be defined (*h* = 1 to 5), each defining the locations of carbon fibre, resin, glass fibre, void and crack. Then the two-point statistics for phases *h* and *h’* are defined formally by:

 (1)

for any vector *r* [48,49].

# Results and Discussion

# Void characterisation

# Void size, through-thickness distribution and void morphology

Fig. 3 shows the through-thickness position of each void and its respective volumetric size encompassing the entire 4 mm thickness of the laminate. The plot showcases some interesting void characteristics. A relatively high concentration of large voids is present at the uppermost millimetre of thickness (3 ≤ *z* ≤ 4 mm), especially in the +45° and 90° layers. The high concentration in the non-0° layers was also seen in a previous study which investigated only the middle six layers of this same laminate [34]. The non-uniform through-thickness distribution of voids is only observable when examining all 16 layers as is done here. The origin of this skewed distribution is unknown; but it is possible that such may be caused by several factors such as a leak in the mould sealing at that locality, a concentration of binder adhesive at that thickness, or some other local perturbation in the fabric structure. As mentioned earlier, such non-uniform distributions in voids are common in infused composite laminates and allow for a focus on damage development in the upper region where a high concentration of voids exists. The volumetric size range of detectable individual voids spans several orders of magnitude, from 0.085 to 1.2106 µm3 as shown in Fig. 3. There is an apparent transition in void size at a volumetric threshold of 1105 µm3. Voids less than this size are typically equiaxed, “blunt” voids, those greater than this have a higher aspect ratio, appearing as long “sharp” voids. It is clear that the quantity of small blunt voids vastly exceeds long sharp voids.

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Fig. 3. Void distribution and morphology. Coupon thickness, *z*, versus volume fraction of voids, *VV*; indicated µCT slices of small blunt voids and long sharp voids.

# Void distribution surrounding glass yarns

To measure the void distribution in proximity to the glass yarns, a two-point statistical measurement was made in the upper four layers of the QSI samples by looking at each point along the glass fibre yarns (topological view), and measuring the average probability in respective layer of finding a void in any in-plane vector from that position along the yarn’s length, see Fig 4. This was achieved using the two-point statistical approach described in section 2.4. The technique measures the correlation of void location surrounding a yarn by plotting its probability as a function of distance from any particular yarn; in this case blue and yellow represents areas of low and high void probability respectively [34]. The central blue region indicates the glass yarn itself where no voids can be located. As represented by the yellow colour contours, voids are typically positioned in direct contact with the yarn and extend up to ~0.5-1.0 mm away from the yarn. The octagonal configuration of the plot highlights an orientation sensitivity of voids with a propensity for the voids to be located along the ±22.5°, and ±67.5° directions as well as the fibre directions [34].

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**Figure. 4.** µCT probability of void around the glass yarns based on two-point statistics for the top four laminate layers. Blue and yellow regions represent areas of low and high void probability respectively. The grid lines are spaced 0.5 mm apart.

# Damage characterisation

# Observations of damage from quasi-static indentation

Fig. 5 shows µCT cross-sections of damage development for interrupted out-of-plane indentations. Indicated in the figure is the applied displacement level (1 to 5 mm) and corresponding force. The rendering to the right of each cross-section is a topological projection of all damage and voids in the top four fabric layers for a 4  3 mm region of interest.

In the presence of voids, it is revealed that delamination (i) occurs predominantly above the sample mid-plane, and simultaneously matrix cracks (ii) initiate in the absence of voids below the sample mid-plane. With the increasing displacement, delaminations are observed (i) to grow from previously formed delamination in conjunction with voids; in this case by propagating through the ligaments between voids in the adjacent layers (Fig.5 Topology). An analogous process takes place below the mid-plane in the absence of voids where delamination (iii) progresses away from previously formed matrix cracks [11]. At the highest displacement levels, fibre fractures occur (iv) which initiate below the sample mid-plane beneath the indent site due to tensile stresses, before growing in severity (v). The voids are concentrated along the yarns, and especially at the interlock locations. At indentation depths above 1 mm, the in-plane area projection becomes increasingly saturated with damage until at 5 mm indentation the projected area of the complete region is 100% delaminated. From 2 to 4 mm indentation, delamination originates and grows from the voids, but remains localised around individual void locations, with a lower degree of damage initiation and growth along the yarns where no voids are present.

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**Figure 5.** µCT slices taken at incremental indentation displacements: (i) delamination growth around voids into the undamaged cone after application of prescribed out-of-plane displacement; (ii) increase in crack-opening in absence of voids; (iii) delamination growth following (ii) into the undamaged cone after application of prescribed indent displacement; (iv) initial fibre fracture and (v) substantial fibre fracture. Circle indicates location, displacement and force for indentation, and rectangle indicates topology of void and delamination in the binding weave interface in the top four laminate layers.

# Schematic of interaction between voids and cracks

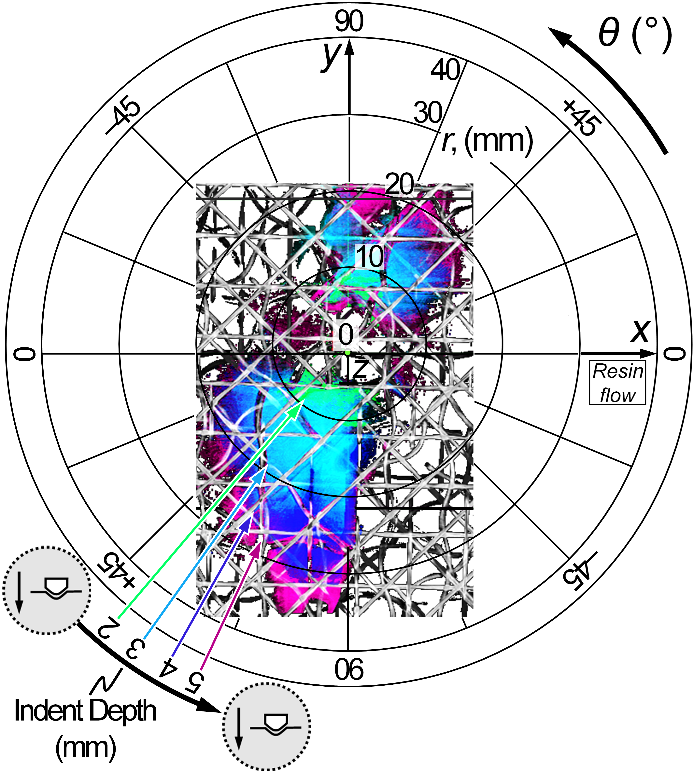
Observations of delamination and void interactions from the µCT cross-sections (Fig. 5) are summarised in Fig. 6. There are three distinct mechanisms controlling the delamination growth in the presence of voids. (I) highlights the initiation of a sharp main-body crack towards a sharp void, (II) illustrates deflection of the main-body crack towards neighbouring voids and (III) highlights crack growth and coalescence ahead of the main-body crack between two neighbouring voids, the latter being the most dominant mechanism observed. As the applied out-of-plane displacements were increased, delaminations were observed propagating between voids ahead of the crack front and coalescing towards the main-body crack. This demonstrates the role of voids in changing the behaviour of an advancing crack front. Such behaviour would require new modelling approaches to capture the significance of these mechanisms.

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**Figure 6.** A schematic of three basic mechanisms that control delamination growth in the presence of voids: (I) both crack and void remain sharp – connected by interlaminar cracks; (II and III) occur subsequent to crack blunting; (II) involves voids both in the interface and within the layer, which are connected by intralaminar cracks causing crack deflection ahead of the main-body crack tip; (III) involves interlaminar crack growth within the main-body crack and the binding weave interface comprised of cracks and voids that form and coalesce about the main-body crack.

# Indent damage visualisation observed from µCT

Fig. 7 shows the topological view of the damage progression for each out-of-plane displacement. From 2 mm to 4 mm, visualisation of damage progression is obscured by the glass yarns. Damage expands gradually for each increment of indenter displacement, at first by growing within the region defined by the glass yarns, resulting in the formation of isolated islands of cracks. At 5 mm indentation, crack extension occurs between these pre-existing crack-filled yarn regions. This leads to increased crack connectivity and when viewed in-plane, complete delamination coverage between 90° and +45° occurs, albeit on different crack planes (Fig. 5).

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**Figure 7.** µCT topology view of the damage segmentation for the top four laminate layers. Point of loading is indicated by the green dot, delamination due to increasing out-of-plane displacement is indicated by arrows, and the grid lines are spaced 10 mm apart.

# Crack growth surrounding voids

Two-point statistics were used to show the average void / void cluster shape and size in Fig. 8 [34]. A similar depiction is noted, in addition to correlating damage growth from the void(s), all for the upper four layers in the coupon, and using the approach described in section 2.4. The average shape and relative size of all manufacturing-induced voids / void clusters in that region is depicted by the blue perimeter at the centre of the plot (note that this line is actually a contour capturing a region of high two-point statistics; hence it does not strictly quantify the average void size, but it gives an indication of typical void / void cluster shape, and can be thought of as depicting an ‘average’ size in a more general sense). Subsequent plots depicted in red illustrate the growth of cracks surrounding voids after application of incremental out-of-plane deflection.

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**Figure 8.** Average void and crack perimeter under QSI obtained by µCT imaging and use of two-point statistics for the top four laminate layers. The average as-manufactured void extent is indicated by the blue contour and the red contours indicate the subsequent extent of cracking away from the initial voids. The contours are plotted in polar coordinates; the origin of the coordinate system corresponds to the initial centre of volume of each void projected onto the x-y plane, and the grid lines are spaced 2 mm apart.

The plot illustrates that no damage growth occurs at 1 mm indentation and that damage growth increases approximately linearly from 2 to 5 mm displacement. The plot also shows that cracks propagate at a rate and direction that is determined by the original void dimension for that direction. Figure 9 clarifies this by plotting the radius of the cracks (from Figure 8) at subsequent applied displacements in each of the ply orientations; the growth is very close to a linear multiple of the original void size in any given direction.

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**Figure 9.** Increase in average void and crack radius with increasing QSI displacement, for each of the four ply orientations, and for the same data illustrated in Figure 8.

As seen in Figures 8 and 9, the average void or void-cluster dimensions are larger in the off-axis directions, +45° and 90°, and damage grows at a faster rate in those directions, than in the 0° and -45° directions. The increased rate of damage growth in the off-axis directions is thought to be resultant from this greater size of voids or void-clusters in those directions. The asymmetry of the void or void-cluster dimensions in the +45° and -45° directions cannot be explained, but may have to do with the fact that the orientation of the adjacent layers is not the same for a +45° layer as it is in a -45° layer in the [0/-45/90/+45]2s layup and that neighbouring layers inevitably influence the void formation due to flow gradients [34]. The smaller void dimensions in the 0° direction are most likely explained by the lower propensity for void accumulation in fibres parallel to the resin flow direction due to the ease of bubble escape as the bubbles are not impeded by the fibres themselves, as they are in the off-axis layers [34,50].

# Implication of findings

It is well known that failure modes in composites are highly influenced by heterogeneity in the dispersion of reinforcing fibres and the stochastic nature of voids in epoxy resin layers [1,2,40]. For example, crack initiation has been shown to correlate with maximum (rather than average) fibre spacing [51-53]. Two-point correlations reveal the types of heterogeneity that affect fracture – such as void size and shape, clustering of voids, etc. (section 2.4). However, while there is a well-defined relationship between two-point correlations and physical properties such as elasticity, thermal conductivity, moisture swelling and permeability [49], the averaging approaches used to obtain these properties do not work well for fracture analysis due to their implicit homogenisation, whereas fracture is a localised phenomenon. Hence, while theory development progresses in this area, qualitative analysis of stochastic data can inform failure predictions; for example, indicating the necessary variables or forms of equations in constitutive relations while more physically-based theories are developed. In particular, the two-point statistics provide indications of local heterogeneity that can lead to stress concentrations and local failure.

There is a transition point from small blunt voids to long sharp voids shown in Fig 3. This is quantified by the statistical analysis in Fig. 4. The majority of long sharp voids were located on the upper surface of the ply. This is important as it has been reported that sharp elongated voids can have a significant influence on damage initiation [34]. That the majority of voids form at the upper surface is interesting and is likely to be associated with the manufacturing process (voids being trapped during resin flow). Together, visualisations in Fig. 3 and 4 provide insight as to how the voids originally form – with a strong correlation between glass yarn position and void positions. The two-point correlations in Fig. 4 also illustrate the directionality of the voids / void clusters. The bias layers seem to attract most of the cracks – especially between 90° / +45° orientation (Fig. 7 and 8).

The subsequent scans of damage propagation in Fig. 2, 5 and 7 enable the visualisation of crack generation from void initiators. The more detailed analysis of damage mechanisms, as illustrated in Fig. 6, illustrates the role played by voids in damage progression, including the promotion of crack coalescence ahead of the main, contiguous crack between two neighbouring voids (Fig. 6 III). This behaviour is governed by both debonding and sliding [52,53] and is of significance for micromechanistic modelling [33,55]. Beyond these examples of individual voids, Fig. 8 reveals the ‘average’ shape of voids or void clusters and statistical analysis of associated crack growth. Crack propagation is seen to proceed approximately linearly relative to the original void dimensions, i.e. cracks propagate twice as far, for a given displaced increment, in a direction for which the void extent is twice as long.

Future studies may use these insights to direct manufacturing improvements to reduce initial void formation and increase the shear and delamination resistance of composite structures. It is very clear that the largest voids are present at the biaxial weft / warp glass weave interlock – these voids particularly influence crack growth behaviour such that delamination is promoted and transverse cracks are supressed. This is attributed to the undulating 0° warp yarns that are woven through the weft yarns, creating obstacles for void escape in the interbundle gaps [34,42,50,56-58]. The removal of the glass yarns, potentially by using solely dissolvable fibres to support the weave structure, could help mitigate this potentially harmful dispersion of voids. A previous study on void morphology [34] suggested possibly positioning the mold flow inlets and outlets to put less voids in the plies of a given orientation where the effects of those voids are most detrimental. This study further supports that possibility by confirming that 1) voids accumulate most prevalently along fibres oriented off of the flow direction, and 2) damage during out-of-plane loading progresses most readily in those same off-axis directions.

# Conclusions

Microfocus X-ray computed tomography was used to characterise pores / voids and study damage behaviour in resin infused woven carbon fibre reinforced polymers under quasi-static indentation. Several observations were made about the void homology (size, shape and distribution), in particular, larger voids were located towards the upper surface of the material. There was a clear interaction between delaminations and voids. Three basic delamination-void mechanisms were observed: (i) interaction between sharp cracks and sharp voids, (ii) deflection between cracks and blunt voids, and (iii) crack coalescence ahead of the main-body crack between pairs of neighbouring voids. Mechanism (iii) was the most prevalent, especially around the supporting glass yarn weft / warp interlock. For all three cases, failure propagation is represented largely by delamination with almost no intralaminar transverse cracks observed. Voids correlate strongly with yarn locations, resulting in an octagonal shaped correlation profile. Voids are also more prevalent in the bias layers. This is reportedly attributed to irregularities in the glass yarn tow waviness and the yarn interlock. Statistical analysis of the void-damage evolution using two-point statistics indicates an approximately linear relationship between crack growth and original void size – leading to higher rates of propagation in directions that had longer void dimensions or void clusters. These insights can be used for providing a mechanistic explanation for the role of the voids in order to inform micromechanical modelling.

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