A MULTI-SCALE MODELLING APPROACH TO PREDICT THE EFFECT OF POROSITY ON TRANSVERSE STRENGTH

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Summary: *Voids are a common defect in composites and have a detrimental impact on their mechanical performance. A composite design will have a unique set of void characteristics, so it is of great importance to understand how they affect the material properties. This study presents a method to simulate how the tensile and compressive strength is impacted using information from void characterisation. Experimental results showed that in both tension and compression the strength was significantly affected as porosity increased. A novel multiscale modelling technique was then employed which is a development of the current approaches by enabling three-dimensional void geometry to be accounted for, where in previous studies this has not been included. The experimental data was used to validate the technique by creating representative models of the testing which correlated well.*

1 INTRODUCTION

Energy consumption and its impact on the environment is of great concern which is particularly true within the automotive industry. A great deal of attention has been focused on improving the efficiency of powertrains as well as turning towards electrification. However, to minimise energy usage as much as possible, attention must also be given to lightweight structures[1]. One method to reduce the mass of vehicles is to make use of composites, however, due to their complex nature there is a large variety of defects that occur in the manufacturing stage[2]. Unless significant time is spent characterising defects for a specific manufacturing process and subsequently how those defects affect the mechanical performance, there can be a large amount of uncertainty in designs[3]. This leads to higher safety factors and heavier designs which goes against the design decision to use composites[2].

A common and significant defect are voids, which are defined as regions distributed throughout the composite where the matrix has not fully penetrated the fibres leaving gaps[4]. They are detrimental since the role of the matrix is to support the fibres as well as distributing load between them and so by having regions without matrix will lead to a reduction in mechanical performance. It is near impossible to produce a component with a 0% void content[3], therefore, understanding how the porosity impacts the material properties is important. Although empirical testing can be utilised this can not only be costly (time wise as well as financially), but the microstructure is extremely difficult to control meaning that parameters cannot be kept constant between tests.

For this reasoning, microscale computational modelling can be used to investigate porosity as it allows for individual factors to be investigated. One common approach is to use a 2D analysis where the fibres and matrix are modelled all on a single plane and voids are included by removing matrix regions[5]–[7]. The benefit of this approach is that it can be computationally efficient, meaning that it is possible to run parametric studies in greater detail. Also, algorithms can be utilised to automate random fibre and void distribution. However, a major drawback to this approach is the assumption that voids are infinitely long, which has been shown not to be true[7], and so the models will not capture any 3-dimensional geometric features. Another approach emerging is a 3D analysis where instead of removing regions to act as voids, elements are randomly selected and consequently the material properties for those specific elements are reduced to near-zero[8]–[10]. Although thickness is now included into the model only '*micro-voids*', small voids between the fibres, are modelled since the elements are of this scale. Larger voids that can span multiple fibres or further cannot be captured. Also, another consideration of this approach is that the voids must take the shape of the element that has be designated as a void. If void geometry is to be investigated the mesh will need to be altered, and since elements are typically constructed using flat faces and nodes the representative void will also therefore have these geometrical features.

The work presented here develops the current modelling approaches by accounting for realistic void geometry. The approach is a multiscale modelling technique where a representative void(s) is modelled as a stress concentration and the impact on the matrix is studied. This information is then used in a second model, which includes the fibres, to output ply level material properties. Experimental investigates, in section 2, are first carried out to show the impact porosity has on a specific composite and to validate the modelling approach which is described in further detail in section 3.

2 EXPERIMENTAL TESTING

2.1 Material and specimen preparation

All specimens were manufactured from Skyflex K51 unidirectional prepreg (USN200B), manufactured by SK Chemical. Fibre properties can be found in Table 1. Since this study focuses on tensile and compressive strength, ASTM standards D6641 and D3039 were followed for specimen manufacture and test procedure. Two layups, $[90]_8$ and $[90]_{16}$, were manufactured to test either in tension or compression, respectively. As recommended by the supplier, the layups were cured in an autoclave under a dwell cure cycle. The temperature was ramped at 3°C/min to 80°C and held for 30 minutes, then from that temperature the same ramp was applied to increase the temperature to 125°C and held for 90 minutes. Each layup was manufactured three times, however, with differing cure pressures. The cure pressures used were 0.5, 4 and 6 Bar. The aim of changing the cure pressure was to introduce differing void contents between the laminates. For the tensile testing laminates nine specimens were cut out, however, due to the smaller width of the compressive specimens 12 specimens were able to be created. Specimen edges were polished using 120 and 240 grit abrasive paper, to remove machining marks, which may have affected the results. Specimens can be seen in Figure 1.

Table 1: Fibre material properties.

Tow Count	Fibre areal weight	Fibre diameter	Tensile strength	Young's Modulus	Elongation at break	Fibre content, by volume
15K	200gm^{-2}	7µm	4.12GPa	235GPa	1.8%	67%

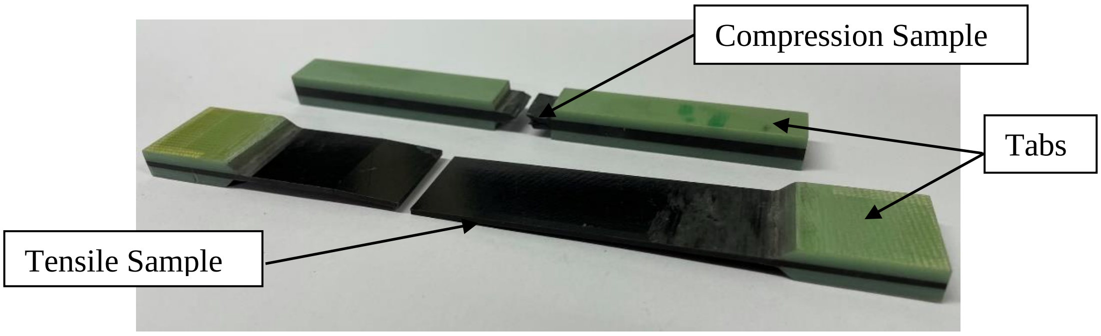

Figure 1: Tabs bonded onto specimens for tensile and compressive testing.

2.2 Experimental Procedure

Tensile testing was performed on an Instron 8801 servo hydraulic testing machine. Load was applied at a constant displacement rate of 2mm/min and samples were loaded to failure. Compressive testing was carried out on a ZwickRoell Z050 testing machine using a combined loading compression fixture. Specimens were aligned into the fixture ensuring both ends are flush with the fixture and clamped by tightening the bolts to a torque of 3.5Nm. The Compression setup can be seen in Figure 2. Load was applied at a constant rate of 1.3mm/min and specimens were loaded to failure. For both tests, force and displacement were recorded, and strain was measured using a video gauge system from iMetrum

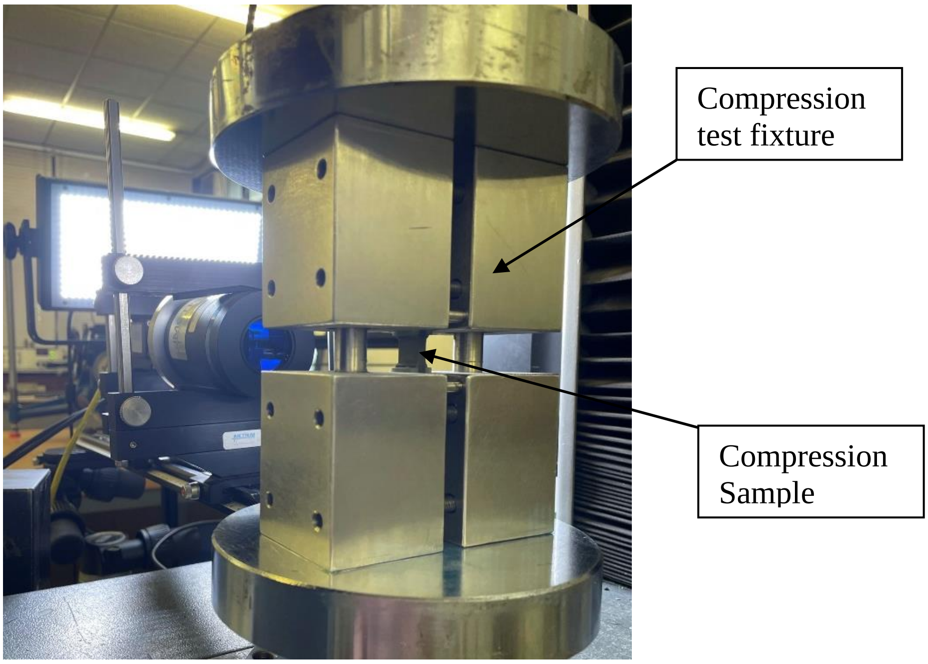

Figure 2: Compression Test setup.

2.3 Void Characterisation

The void content was measured to understand how porosity affects the material behaviour. For this study microscopy was chosen as this is not only an efficient process but also allows geometrical information to be identified and used in the modelling stage. A Leica DM LM microscope was used to inspect the microstructure of the composites. An iDS UI-1460LE-C-

HQ camera captured the images which was then processed using Buehler OmniMet Modular Imaging System. Three tested samples were selected at random and both sides running perpendicular to the fibre direction were polished to 4000 grit.

To get geometrical information, particularly the aspect ratio of the voids, a 20x/0.40BD lens was used to capture the characteristics of the voids. Dimensions can be measured using the Buehler OmniMet software directly as images are taken. To characterise the porosity for each laminate, the samples were inspected using a 10x/0.25BD lens as this gives a sufficiently large image area. A Python script was used to process the images to isolate the voids from the rest of the material and calculate the void content. The script works by converting the image to greyscale and applying a Gaussian filter to improve contrast. A threshold is set such that the greyscale pixels are either set high or low and the ratio between them gives the void content. An example of how an image is processed is shown in Figure 3.

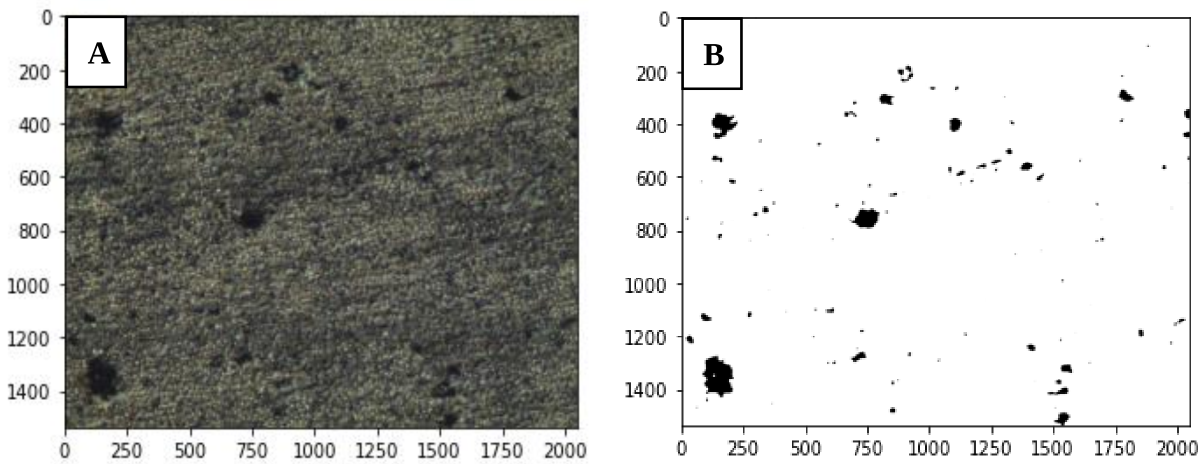

Figure 3: Original (A) and processed (B) microscopy image to calculate the void content.

2.4 Experimental Results

The impact of changing cure pressure on laminate porosity is presented in Table 2. The results from the experimental testing for both tension and compression against the void content can be seen in Figure 4. The error bars for both strength and void content represents 1 standard deviation of results. The large error bars from the void content analysis are due to the non-uniformity of the microstructure; some regions have very few voids whereas in other regions large voids form. This effect is pronounced further on lower cure pressure laminates. The variation across the microstructure is picked up by the microscopy/void content analysis.

It was found that by increasing the void content there is a significant negative impact on strength for both tension and compression. Lower porosity values were found to be more sensitive, particularly in tension. However, past a certain point, approximately 1%, the impact of increasing void content is reduced. This endorses the aerospace standard of not producing parts above a void content of 1%[4]. It should also be noted that the tensile specimens with a void content of 2.21% did not fail in the gauge section, but at the grips. In fact, experience has shown that it is very difficult for specimens to fail correctly for any transverse tensile test and a great amount of effort has gone into improving the test procedure to minimise incorrect failures. It is probable that the stress concentrations at the grips coupled with the elevated void content means that it would not be possible in any circumstance to have a correctly failed specimen with a high void content. Even if the specimens were to fail correctly, it is not expected that the strength would improve significantly.

Overall, the results have shown that as porosity changes the strength of the composite is significantly affected in both compression and tension. In both cases it was found that strength was more sensitive to a change in porosity at lower void contents, however, this was more pronounced in the tensile testing.

Table 2: Calculated void content for each laminate.

Test Configuration	**Cure Pressure / Bar**	**Average void content / %**	**Average Void Dimensions / µm**	**Void Module Dimension / µm**
Tensile	6	0.92 ± 0.93	18.8 x 11.2	72.4 x 21.5 x 21.5
	4	1.06 ± 0.84	20.7 x 30.7	76.1 x 56.3 x 56.3
	0.5	2.21 ± 2.7	11.7 x 16.5 & 230 x 91.2	568 x 142 x 142
Compression	6	1.39 ± 2.2	15.6 x 11.1	52.4 x 13.6 x 13.6
	4	0.48 ± 0.27	9.91 x 7.35	47.4 x 17.6 x 17.6
	0.5	3.3 ± 2.5	56.6 x 49.3 & 223 x 63.5	714 x 119 x 119

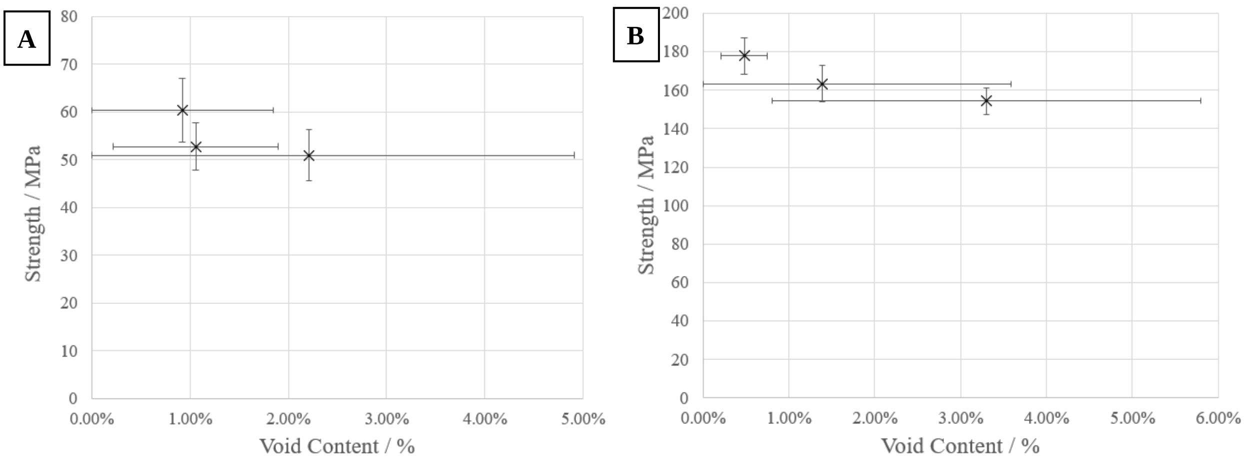

Figure 4: Strength results for (A) Tension and (B) Compression

3 NUMERICAL MODELLING

3.1 Model Description

There are two commonly used approaches to modelling the impact of porosity on mechanical performance in continuous fibre reinforced composites; either voids are assumed to be infinitely long through a 2D analysis or take the shape of elements in a 3D analysis. The modelling approach presented here can account specifically for how the voids are generated by not only considering void content but also the shape, size and distribution of the voids.

ABAQUS/CAE 2019 has been used to develop and run all simulations. The modelling process uses the assumption that voids will only affect the matrix properties and fibre properties are left unaffected. This allows the use of a multiscale modelling approach since first the voids within the matrix can be modelled at the microscale to see how the voids, acting as stress concentrations, degrade properties. This model is known as the 'void module'. This is done without including the fibres at this stage and gives homogenised '*effective*' matrix properties. Then secondly, the effective matrix can be used in a mesoscale model, where fibres are included, which outputs ply level material properties. This model is known as the Repeating Unit Cell (RUC). A schematic of how the multiscale modelling approach works can be seen in Figure 5. The model can be used efficiently to see how different porosity factors affect ply properties.

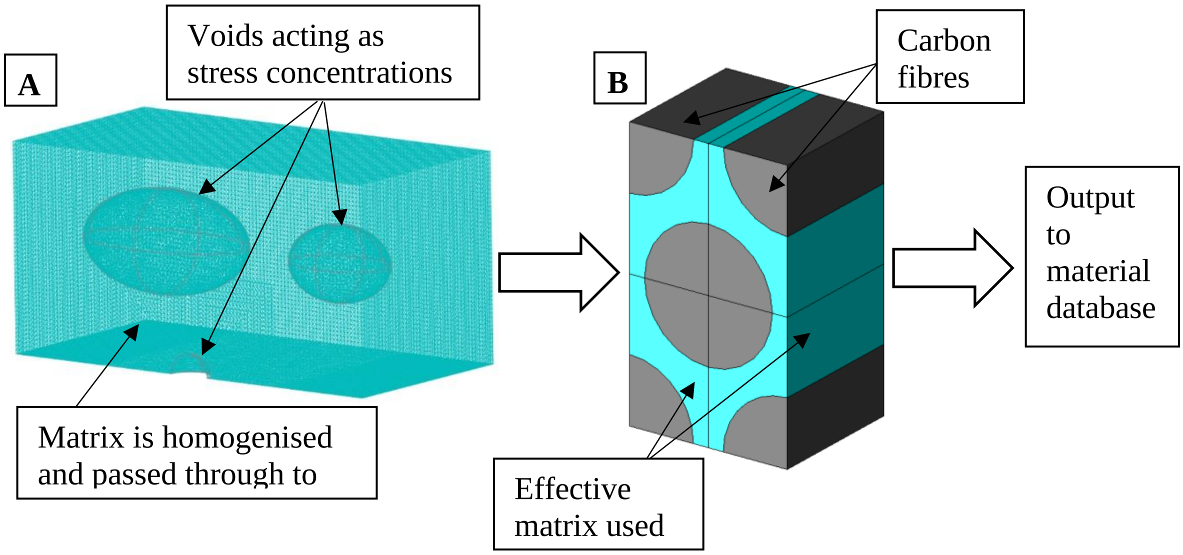

Figure 5: Diagram representing the multiscale modelling process

3.2 Model Geometry

The void module geometry is based on the information from the microscopy on how the voids form in the laminate. The first parameter to be decided is how many different types of voids are formed (based on shape and size) and how often they repeat. For example, if voids are approximately evenly spread out and have similar size then only one void can be modelled, however, if clusters of voids form or there are voids which vary significantly in size then this will need to be accounted for. Once void formation and void sizes are established, the size of the unit cell can be calculated based on the void content. The second stage in the modelling process is where the RUC accounts for the fibres. A uniform fibre distribution is used for the RUC, therefore, along with fibre diameter the average distribution must be measured.

3.3 Model Setup

The constituent material properties for the Skyflex K51 unidirectional prepreg are required for the model. Only linear elastic properties are included in the model since the matrix is assumed to have brittle behaviour[11]–[13] and so any non-linearity close to failure will be minimal. The Young's Modulus for the fibres can be found from the datasheet, however, the Poisson's Ratio is unknown. Likewise, the datasheet for the resin has not been released meaning these properties, along with tensile and compressive strength, are missing. Since the model is only used in the transverse direction fibre strength is not required, however, is included in Table 3 for completeness. Typical Poisson's Ratios along with the Young's Modulus for the resin have been selected based on literature[12]–[14]. Rather than assuming strength properties for the matrix, it is possible to use a datapoint from the testing to derive the tensile and compressive strength. Detailed explanation of this process is given in section 3.4. Finalised material properties can be found in Table 3.

Table 3: Constituent material properties used in model.

Constituent	Young's Modulus / GPa	Poisson's Ratio	Tensile Strength / MPa	Compressive Strength / MPa
Fibre	235	0.20	$4.12x10^3$	N/A
Matrix	3.0	0.35	93.3	285.8

To improve computational efficiency of the void module, a quarter model was used with symmetry boundary conditions. The void module was loaded by a displacement boundary condition and constrained using a symmetric boundary condition on the opposing face. The symmetric boundary conditions were chosen as it prevents the surface to displace in the loading direction yet allows the face to reduce from the Poisson affect. The RUC model was constrained and loaded in the same way. Symmetric boundary conditions were used on the top and side surfaces to align the RUC correctly as it is loaded. This is necessary since the Poisson's ratio differs between the matrix and fibre region, without these boundary conditions unrealistic deformation would occur. A schematic of where these boundary conditions are applied is shown in Figure 6.

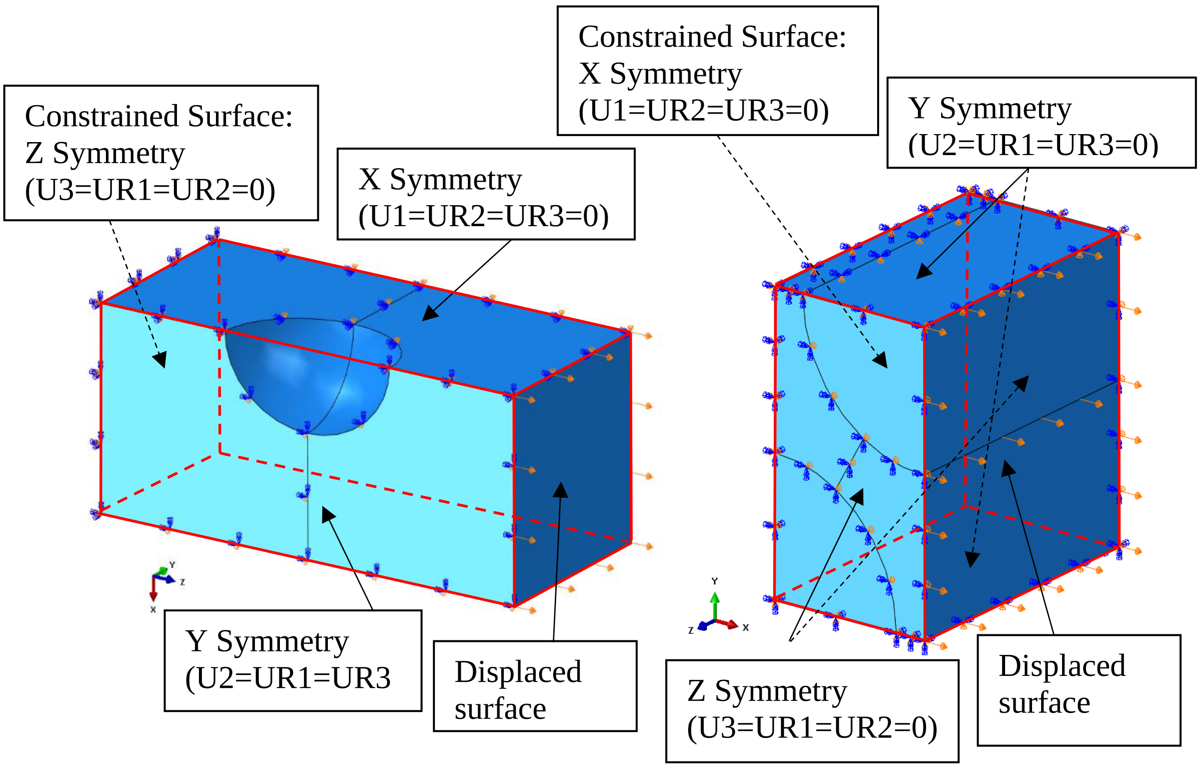

Figure 6: Boundary Conditions. Solid arrows point to front faces and dashed arrows point to rear faces

To generate the mesh on the unit cells, implicit C3D8R elements were used on both the void module and RUC. Since the stress concentration around the voids in the void module is used to dictate when failure has occurred a fine mesh is required. The mesh sizing was selected such that approximately 20 elements were placed on the circumference of the void (on the quarter model). This can result in excess of 100,000 elements hence why it is necessary to use symmetry boundary conditions to reduce computation times. A typical mesh used on the void module can be seen in Figure 7.

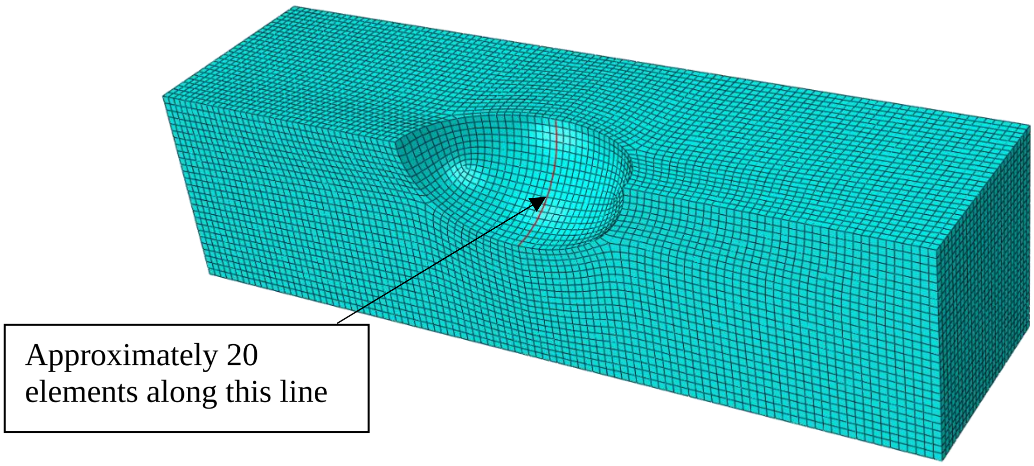

Figure 7: Example mesh used on the microscale model.

3.4 Strength Calculation

The effective strength of the void module is calculated by loading it until a single element has failed using the von mises failure criteria as done by Rouf et al.[11] Since brittle behaviour is assumed the void module is not taken any further. At the point of failure, the reaction force on the constrained surface is measured and is used to calculate the effective strength. This is then used in the RUC, such that the model is loaded until the stress in the model matches the effective strength calculated from the void module. The same procedure using the reaction force to calculate the strength is followed to give ply scale strength.

If the strength of the resin in unknown, and it is therefore not possible to know at what point failure would occur, it is possible to use a single datapoint, from experimental testing to establish a strength value. The data point is used independently from the rest of the dataset and then by running the model procedure 'in reverse' the tensile or compressive strength of the matrix can be derived. The other datapoints do not influence the result and are completely independent of deriving the strength properties. The process works by knowing the ply level strength, from testing, and the porosity characteristics. The RUC is run until the calculated strength matches the experimental testing, at this point the maximum matrix stress informs what the effective matrix strength is. Likewise, a void module is generated, and the model is run until the calculated strength matches the effective matrix strength predicted by the RUC. At this point the maximum stress found at the stress concentration informs what the actual strength of the matrix is without any flaws and can now be used in subsequent simulations. A schematic of this process can be seen in Figure 8.

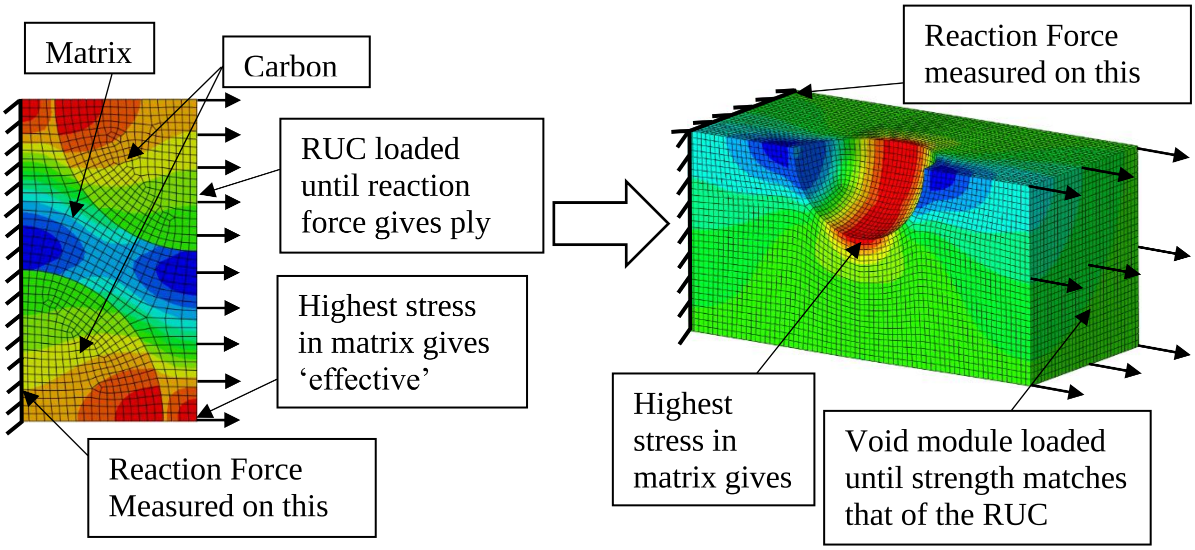

Figure 8: Diagram showing how the modelling process is used in reverse to find the matrix strength

3.5 Numerical Modelling Results

To create the void modules the average void dimensions are required. To get an accurate representation of the size of the voids across each laminate, 15 voids were measured per laminate. Since microscopy only captures a 2D image it is not possible to measure the depth of the void. However, research carried out by Mehdikhani et al.[7] found more than half of voids have a 'roundness' ratio, i.e. the ratio between the depth and height, of over 0.6. Based on this it is assumed that the voids are round in cross section. The microscopy showed that when the laminates were cured at above 4 bar the voids were evenly spread out and of similar size meaning that only one void needs to be modelled to form the void module. However, in the two laminates that were cured at 0.5 Bar, there were voids that generated significantly larger in addition to the voids of similar size and distribution to those seen in the higher cure pressure laminates. A representative comparison between the higher and lower cure pressure laminates can be seen in Figure 10. Table 2 shows the average void dimensions and dimensions for the quarter void module. To predict the strength of the matrix in both tension and compression the procedure in Section 3.4 was followed. The data points chosen to predict the matrix strengths were for the lowest void content in each dataset, this resulted in the laminate cured at 6 Bar for the tensile laminate and 4 Bar for the compression laminate being used. The model predicts that the matrix has a tensile strength of 93.3MPa and a compressive strength of 285.8MPa, which are comparable to the results presented by chevalier et al.[13]

The matrix properties were then subsequently used in the models to predict the strength of the two remaining data points. The results from the simulations and the correlation to the experimental results is presented in Figure 11 and Figure 9. For the tensile results, the model follows a similar trend where there is a significant drop in strength between the two laminates with a lower void content and then increasing the porosity has a small effect on strength. The model does predict a slightly higher strength at the higher porosity, which is not what the experimental results show. This is likely due to the added complexity of the model having to account for both larger voids and multiple small voids, rather than a single void. This means that it is an unfair comparison to compare the two directly since the void modules are significantly different and they are not like for like. However, overall, both predictions are well within the margin of error from the experimental testing and correlate well to the experimental results with the largest correlation difference of 5.99% on the laminate with a void content of 2.21%.

The compression model also correlates very well with the experimental results such that as the porosity increases the strength decreases. The largest difference in correlation is 7.2% observed on the laminate with a void content of 3.3%.

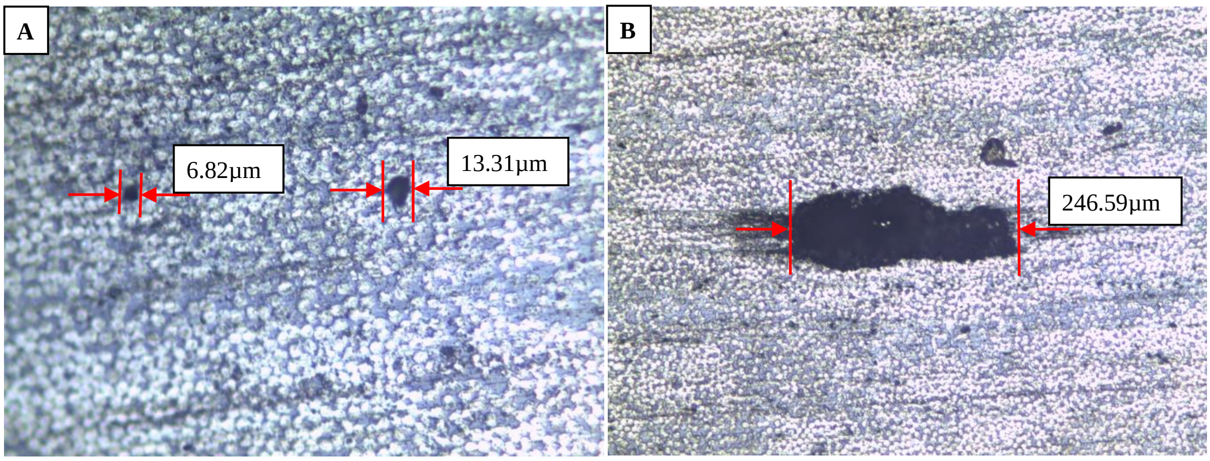

Figure 10: Example of the difference in void lengths found in (A) high cure pressure laminates and (B) low cure pressure laminates.

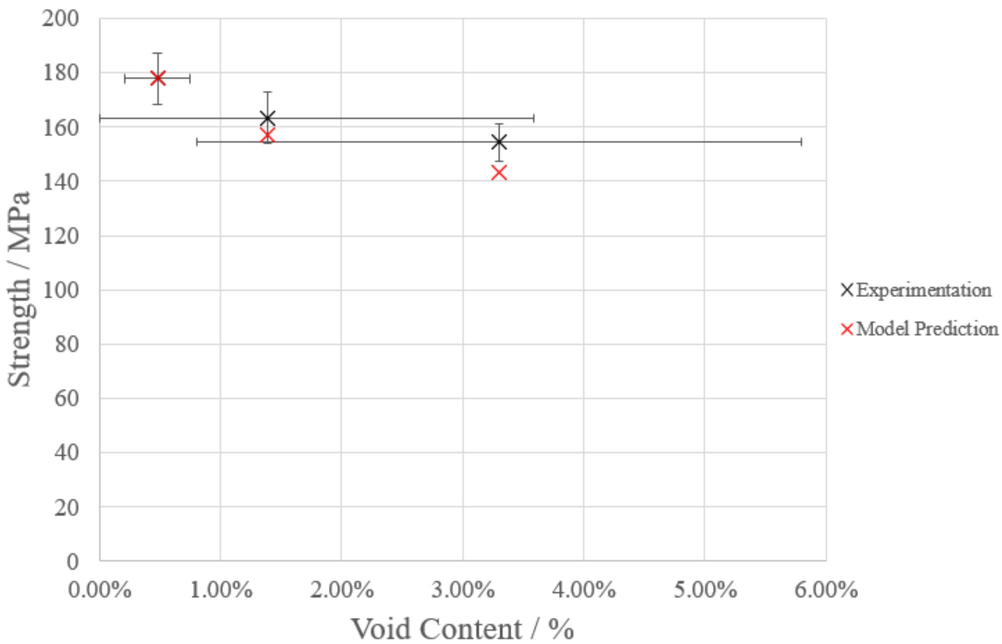

Figure 9: Correlation between experimental strength results in compression and model prediction

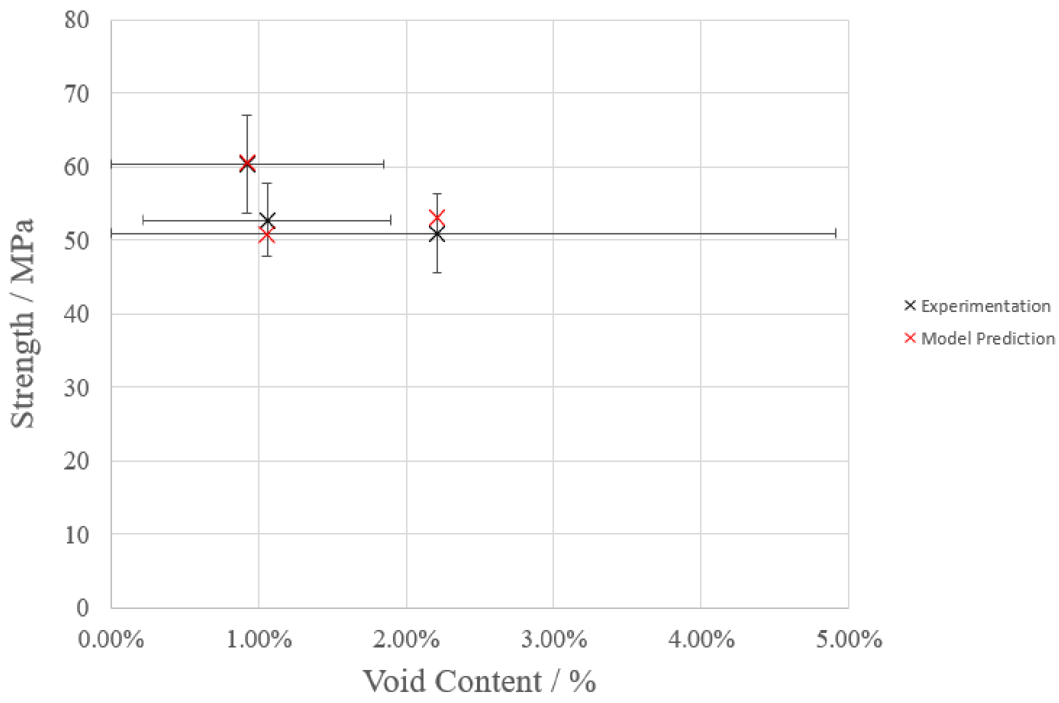

Figure 11: Correlation between experimental strength results in tension and model prediction

4 CONCLUSIONS

Predicting how defects such as voids reduce the strength of a composite is extremely important otherwise the result will end in highly conservative designs, which are both costly and hold excess weight. The work presented here shows the importance of understanding how increasing porosity can lead to a reduction in strength with a novel multiscale modelling approach presented which correlates well with the experimental data. Both tensile and compression testing showed a significant drop off in strength as porosity increased up to approximately 1%. Increasing the porosity further, whilst still reducing strength, did not have as big of an influence on the strength properties. The modelling approach was able to capture the same trend when using information from void characterisation of the porosity found in the material from testing.

When designing a composite component, a region such as a sharp internal radius would traditionally be a cause for concern, therefore the solution would be to use the same material properties but apply a higher safety factor. Alternatively, by using the presented multiscale modelling approach it is possible to accurately predict the reduction in strength due to specific void characteristics found in those regions of concern. This can provide confidence to the designer to work towards an adequate safety factor without overengineering. A major factor in the use of composite materials is for lightweight structures in areas such as the automotive industry, therefore, using tools to prevent overengineering must become more common practise.

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