Strength knock-down assessment of porosity in composites: modelling, characterising and specimen manufacture

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Strength knock-down assessment of porosity in composites: modelling, characterising and specimen manufacture

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Abstract. Porosity and inclusion of foreign material is known to reduce the strength of materials, and this paper addresses the particular problem of strength knock-down assessment due to porosity in composite materials. Porosity is often measured in terms of percentage of voids per unit volume of a component, because this can be related directly to ultra-sound absorption. Nevertheless, this is a poor indicator of actual strength knock-down, as it provides little information about void size, shape, orientation and whether they are evenly distributed or are clustered. Characterisation of void clustering enables a link between a cluster characteristic and the strength knock-down. Laboratory based testing achieves controlled porosity in specimens by introducing pin-holes into the RTM in-flow pipework, which entrains voids into the body of the preform within mould tooling. Specimens are manufactured to create resin regions bounded by a fibre reinforced picture frame, to allow for easy load application. Strength knock-downs from test are related to the theoretical expectations.

1. Introduction

Porosity and inclusion of foreign material is known to reduce the strength of materials, and this paper addresses the particular problem of strength knock-down assessment due to porosity in composite materials. Porosity is often measured in terms of percentage of voids per unit volume of a component, because this can be related directly to ultra-sound absorption, which is a straight-forward Non-Destructive Evaluation (NDE) procedure. Nevertheless, this is a poor indicator of actual strength knock-down, as it provides little information about void size, shape, orientation and whether they are evenly distributed or are clustered [1]. It is well known that manufacture process parameters influence porosity, and the effect of particular process parameters on particular porosity characteristics is a topic of on-going research [2].

Computational models of material with randomly distributed voids can be undertaken, but the results have shown that the stress-raiser effect on the surface of clustered voids depends critically on cluster characteristics. Schemes for characterising void clustering are proposed, and put into practise using synthetic model geometry, thus enabling a link between a cluster characteristic and the strength knock-down.

Laboratory based testing first requires a method of introducing controlled porosity into a specimen. This is achieved by introducing pin-holes into the RTM in-flow pipework (see figure 2), which

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entrains voids into the body of the preform within mould tooling. In order to allow for convenient load application in the test machine, the specimen preform is modified to create resin regions bounded by a fibre reinforced picture frame. Strength test results are related to the theoretical expectations.

2. Porosity modelling challenges

The main challenge in modelling porosity is to create geometry that is representative of reality. On the one hand, it is desirable to keep things simple, for example to make each pore or hole in the material the same size and shape. On the other, it is necessary to allow sufficient variation to capture the more important emergent details. For example, it is well known to punch a row of slots into paper cheques and tickets to assist in tearing off counterfoils. A more scattered pattern of slots, or slots with different orientations would not be suitable for a tear-off counterfoil, so in this case, the emergent detail is the alignment of the slots.

Another intuitively obvious emergent detail would be clustering of holes. In this case, a number of holes might be said to be "near" to each other, and that this relative proximity might have some impact on the material properties. While such a geometrical configuration might be easy described in human language, to give it a precise mathematical description requires significantly more thought.

It is not simply a matter of choice of words; creating an appropriate mathematical description is the first step to being able to create a geometrical model with the appropriate features.

2.1 Placement of holes

The most obvious approach to placement of holes is to select numbers at random to represent the coordinates of the centroid of the hole within the material domain. While a very simple model would have circular holes, a somewhat more complex model might use ellipses, with the orientation of the ellipse defined by another random number [3]. Choosing numbers at random does not result in a well distributed pattern of holes, and so a system is required to define exclusion zones around currently placed holes and features, and to reject subsequent random number combinations which would otherwise have placed a hole into an exclusion zone [4].

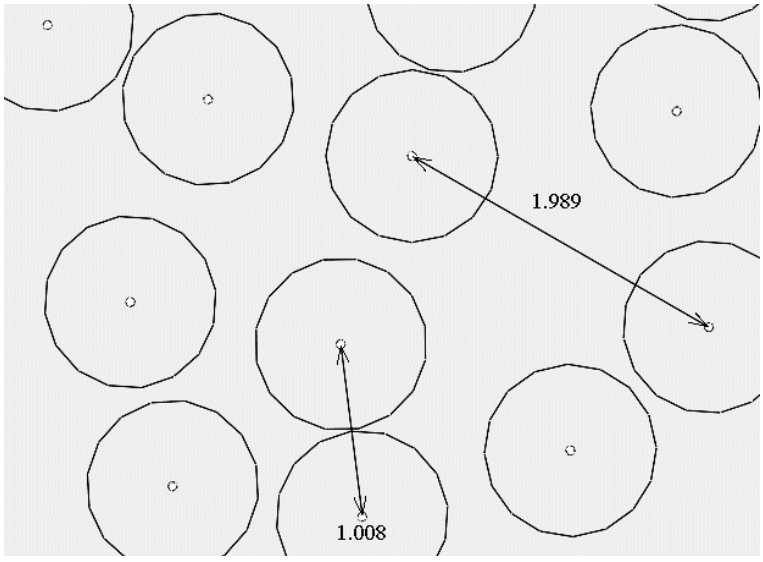

Figure 1. Placement of circular holes; larger circles describe the semi-exclusion zone.

Figure 1 shows a number of holes (the small circles) placed at random, each with an exclusion zone of 1 unit. The large circles have a radius equal to half the exclusion zone distance, thus to obey the exclusion rule, the large circles must not overlap. Holes are placed until it becomes impossible to place any further without compromising the exclusion rule. This technique is known as a fully dense

Poisson Disc fill [5]. A partially dense fill will contain fewer holes than a fully dense fill, and will (almost always) be different to a fully dense fill with a larger exclusion zone between holes. As such, some groups of holes might be said to be clustered.

This describes a convenient method for creating material models, but it is not the only way. Variations on this method might allow for the exclusion zone to shrink as more holes are placed. Such a method might show rather different characteristics to the simpler approach.

Another approach might be to deflect the location of existing holes in order to make space for the new hole to be added. While this might be complicated to implement, it would seem physically reasonable, particularly for modelling of foamed material.

In each case discussed so far, it has been assumed that each hole is of a constant size and shape. A more complex example might start with holes of unit volume, and where two holes are placed sufficiently closely, they merge to form a hole of twice the volume. Rules for surface tension and attraction/repulsion might control the formation of larger holes or deflection of holes that come close but not close enough.

3. Characterising porosity

The description given above relates to the creation of model geometry by means of rules. The method chosen to create the model does not necessarily characterise the model. Further methods for characterising as-created model geometries will be required [4].

Such methods should also be applied to as-measured real material geometries, to confirm that model geometries are truly representative of real materials, or to provide an indication as to how to improve the geometry creation methodology.

4. Manufacture of specimens

Composite plaques were manufactured using the VaRTM method with 8 layers of 8-harness satin weave HS grade carbon fibre (200gsm) cut to 350mm x 350mm using a scalpel blade on a glass cutting table. An initial preforming stage was undertaken to stabilise the preform under vacuum bag and then a caul plate was used in conjunction with a flexible membrane to consolidate the fabric reinforcements under full vacuum, prior to the injection of resin by peripheral gating at a tool temperature of 75°C (see figure 2). Araldite LY564 and Hardener HY2954 (based on bisphenol A epoxy and a cycloaliphatic amine hardener) were mixed and degassed at 2.86:1 by weight before transfer of the resin. After the addition of the resin and hardener, vigorous mixing for approximately five minutes at a temperature of 30°C was undertaken. After injection, a ramp was applied to 100°C. The temperature was held isothermally for 60 minutes; the composite plaque was then de-moulded and post cured for a further 180 minutes at 140°C.

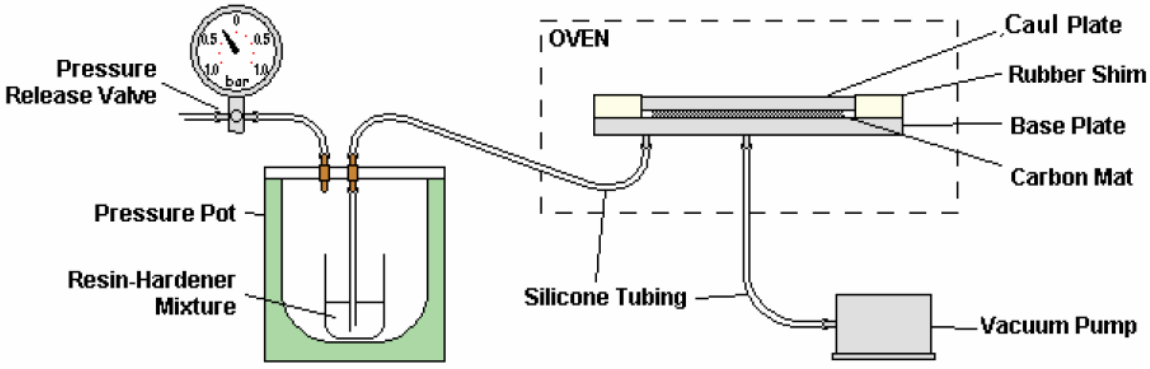

Figure 2. VaRTM apparatus.

For validation of analytical results, a baseline plaque with minimum achievable percentage of defects was manufactured under full vacuum after a vacuum drop test was conducted on the system and a loss of less than 10mBar in 5 minutes was detected. The degassing process described above removes air in the resin/hardener mix that is introduced during mixing. It is essential to remove these bubbles as they can increase the occurrence of gas within processed composite plaques. Degassing was carried out within a water-cooled/oil heated steel chamber with a ToolTemp TT-156E maintaining a degassing temperature of 30°C. The lid of the pressure pot is connected to a vacuum pump to reduce the pressure in the vacuum chamber to 0 mbar absolute. The reduction in pressure caused the trapped air bubbles to rise from within the resin toward the upper rim of the resin container. Once the resin reached the rim of the container the vacuum pipe was sealed, thereby stopping the movement of the resin over the container sides. This process was repeated until no bubbling was observed under the vacuum pressure. This process takes one hour at 30°C.

Two further plaques were manufactured with a range of degassing methods to introduce extra porosity into the composite. These were:

- No degassing
- Degassing for 20 minutes only

Furthermore a final plaque was manufactured with the introduction of deliberate through thickness flaws of various diameters ranging from 1mm to 5mm; during the VaRTM process these holes would be filled with resin and could replicate neat resin regions with picture frames of reinforcement to enable the loading like in the theoretical studies. This was done at the fabric preform stage where the 8 layers of 8-harness were arranged on a cutting table, vacuum consolidated, and holes were carefully drilled in the preform at predetermined locations using a high-speed drill of the required diameter. The locations were recorded to ensure the flaw could be placed at the centre of the subsequent test coupon. A clamping fixture was used to minimise yarn damage in the vicinity to the drilled holes and to ensure that the layers would remain in the preformed position.

5. NDE and testing of specimens

After VaRTM and post cure test coupons were extracted using an OMAX 2626 WaterJet Machining Centre. Fibre volume fraction was measured using the density buoyancy method in which the sample's mass in air is recorded before weighing the sample again in distilled water according to ASTM D792-91 [6]. Therefore, having obtained the specific gravity and knowing the densities of the constituent parts i.e. the fibre and resin, the percentage content of the fibres was calculated. Prior to mechanical testing the specimens were NDT tested using a USN 58 Krautkramer portable A-Scan.

Optical microscopy was carried out on the composite samples in order to ascertain the geometric characteristics of the fabric and the real extent of porosity. A Struers DAP-7 automatic polishing machine was utilised to prepare the samples for microscopy by removing any surface defects left from the cutting process and to also reveal the desired cross section for analysis. Prior to polishing, samples were mounted in Struers Epofix® polymer resin in either 25mm diameter or 50mm diameter circular moulds and rectangular moulds of dimension 75mm x 25mm, depending on the dimensions of the sample. Mounting in Epofix ® ensured that the sample can be firmly gripped in the DAP-7 sample holder and thereby ensuring that the sample is held flat against the polishing discs and so polishing occurs in the same axis as the direction of the intended subsequent micrograph. Samples were polished progressively with silicone carbide paper from 500 grit to 2400 grit. The final finishing polish was carried out using an MD-DAC fabric disc lubricated in DiaPro® diamond suspension polishing solution.

Tensile specimens were tested in the warp and weft direction on a Zwick Z100 universal tester. The testing was performed to CRAG standard 300 [7]. An MTS 632.85F biaxial extensometer was used to determine tensile modulus and Poisson's ratio and a series of 1mm gauge length, 120 Ohms strain gauges were bonded to the specimen to determine changes in strain near the deliberate through thickness flaws.

6. Discussion

Whether the material is real or modelled, random numbers are involved, and the results obtained will all be somewhat different. The key issue is to link particular aspects of the characterisation to particular aspects of the model or physical test results.

In the case of a computational model of a material containing porosity, a block of material is defined, a finite element mesh created, and then boundary conditions and some loading applied. Results of the finite element analysis are then viewed: in previous analysis [3, 4] the maximum and minimum principal stresses were examined, and the peak values in the material domain were recorded. This is approximate, because the values obtained depend on the mesh refinement, nevertheless maintaining a consistent approach means that results can be compared from one model to another. A more adventurous approach is to include the effects of plasticity and/or crack growth as the load is increased so that local stresses exceed the material limits [8].

In the case of real material, an NDT inspection can be performed, to capture actual porosity geometry before and after testing. Differences in geometry will point to localised failure or plastic yield, and the extent to which that has occurred. Comparing these results with computational models will provide insight into the relative importance of porosity hole size, shape, orientation or clustering in the sequence of failure.

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