# INFLUENCE OF MICRO-VOIDS ON THE FATIGUE BEHAVIOUR OF GLASS/EPOXY LAMINATES

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**Abstract**
In the present work, $[0/90_2]_S$ and $[0/45_2/0/-45_2]_S$ glass/epoxy laminates were produced by resin infusion moulding. Different infusions were carried out keeping the lay-up constant, and changing some process parameters such as resin degassing and inlet pressure, which can potentially lead to production cost savings and that in turn lead to the presence of voids in the laminates. Specimens extracted from the infused panels were tested under uniaxial tension-tension fatigue. The damage evolution, consisting of initiation, growth and multiplication of cracks in the off-axis plies, was monitored throughout all the tests. The presence of micro-sized voids revealed to be extremely deleterious for the fatigue performances of both $[0/90_2]_S$ and $[0/45_2/0/-45_2]_S$ lay-ups, in terms of number of cycle to first crack initiation, crack density evolution and stiffness degradation.

## 1. Introduction

Thanks to their outstanding mechanical properties combined with low density, composite materials have undergone a wide development in many industrial fields in the last decades. Many structural parts made of composite materials are indeed employed in the aeronautical, naval, automotive and wind energy industries. However, the main obstacle to the diffusion of composite materials to the large scale production is the quite high cost, not only due to the materials themselves, but mainly due to the absence of predictive models and well defined design procedures.

This fact forces companies in expensive and time consuming experimental and prototyping activities. Accordingly, one of the main goals of the scientific community is to provide predictive models and reliable design procedures for industrial applicability to decrease the costs of the design phase. In addition, the optimisation of the manufacturing process has a fundamental role in decreasing the cost of structural composite parts. The choice of process variables has a direct influence both on the manufacturing costs and, in view of the possible introduction of manufacturing defects, on the fatigue performance, the latter being the major driver for the in-service and maintenance costs.

The optimisation of the manufacturing process requires the knowledge of the relationship between process variables and the presence of defects, as well as the link between type and amount of defects and fatigue performance. The most typical defect in composite laminates is represented by voids.

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The presence of voids is detrimental for static [1-5] and fatigue [6-14] properties of composites. Concerning fatigue behaviour, S-N curves were found to be steeper and shifted towards shorter fatigue life in presence of voids [8-11] both under tension-tension and compression-compression loading conditions. This was found also under bending loads for unidirectional [7,11] and woven laminates [6].

A linear trend was reported by Lambert et al. [12] between the fatigue life of $[0/45/-45]_{3S}$ laminates and the size of the largest defect in critical positions. Conversely, no clear trend was evident between fatigue life and global void content or the largest defect in the whole specimen [12]. An interesting, though qualitative, analysis of fatigue damage evolution, allowed Lambert and co-authors [12] to identify which were the critical plies in which the presence of voids played a deleterious role. In their study of the inter-laminar tensile strength (ILTS) under fatigue, Seon et al. [13] correlated the life reduction under cyclic loading to the presence of a single void in critical position. Recently, Sisodia and co-authors [14] analysed damage evolution in multidirectional laminates under fatigue loading, showing that the density of off-axis cracks, and the subsequent stiffness degradation, were higher in the presence of voids.

Most of the experimental investigations in the literature deal with specific laminate configurations and aim at characterising the influence of voids on the total fatigue life, without providing quantitative data on damage evolution, which would be important to be considered.

In fact, the fatigue life of multidirectional laminates is characterised by a progressive damage evolution beginning with the initiation and propagation of off-axis cracks [15,16]. As the number of cycles is increased the crack density and length increase causing the degradation of the global elastic properties. Since the stiffness is often a fundamental parameter in the design of composite parts, understanding the influence of voids on damage evolution, instead of the final failure only, is fundamental. This means characterising the influence of voids on the cycles spent for the initiation of the first cracks, on the through-the-width crack propagation and crack density evolution.
In addition, the analysis of the influence of voids on the damage mechanisms responsible for crack initiation and propagation is fundamental for defining reliable predictive models.
In this frame, the aim of the present work is to understand the effect of some important parameters related to the liquid resin infusion process on the presence of defects, and subsequently to characterise the influence of such defects on fatigue crack initiation, propagation and crack density evolution.
To this aim, laminates with lay-up $[0/90_2]_S$ and $[0/45_2/0/-45_2]_S$ were manufactured with different process parameters and tested under fatigue loading.

## 2. Materials and Methods

Laminates with stacking sequence $[0/90_2]_s$ and $[0/45_2/0/-45_2]_S$ were manufactured by means of the liquid resin infusion process. Unidirectional glass fibres UT-E500 by Gurit were adopted as reinforcements, whereas the matrix system was composed by RIMR-235 resin and RIMH-235 hardener by Momentive.

For the $[0/90_2]_s$ panels, resin (400g) and hardener (134g) were mixed for 3 minutes at 300 rpm with a DISPERMAT TU shear blender from VMA-Getzman. For producing the first laminate, the mixing was followed by extensive degassing of the resin (at 0.05 mbar for 20 minutes), to consistently reduce the amount of air entrapped in the resin during the mixing. Then the 300x200 mm laminate was infused with an outlet pressure of 0.05mbar, while the inlet pressure was continuously adjusted by the operator during the infusion process to control the speed of the resin and ensure the best filling of the mould. The laminate was cured at room temperature for three days and then post-cured in an oven for 12 hours at 60°C.

A second laminate was then manufactured with the only difference that the resin was not degassed

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after mixing. This led to saving in the infusion time (20 minutes for a 6-layers 300x200 laminate), but also to the presence of voids, as shown in the edge view of Figure 1a. From the edge of the specimens an average void area fraction (Av) of 0.34% was calculated, whereas no voids were found in the degassed specimens. The average void diameter was equal to 44µm.

A third laminate was manufactured with non degassed resin and keeping a constant inlet pressure of 1 bar during the entire infusion process. This third process leads to lower production costs as it does not require the constant presence of an operator. In this case much more voids were found, as shown in Figure 1b, with an average void area fraction of 6.7% and an average diameter of 45µm.

Two $[0/45_2/0/\text{-}45_2]_S$ panels were produced according to the first and second manufacturing procedure used for the [0/902]S laminates. 600g of resin and 201g of hardener were used for each panel, followed in the first case by 35 minutes of degassing at 0.05 bar, for which no voids were detected. A void area fraction of 0.96% was found in the second laminate, with an average diameter of 45 µm (Figure 1c).

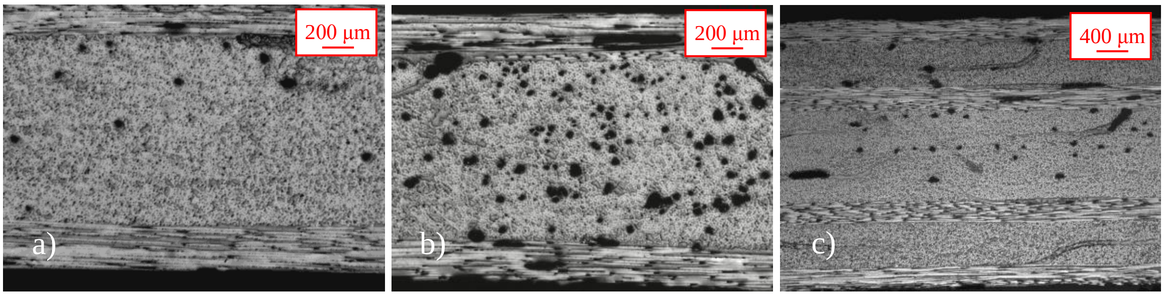


**Figure 1.** Voids in: a) second $[0/90_2]_S$ panel, b) third $[0/90_2]_S$ panel, c) second $[0/45_2/0/\text{-}45_2]_S$ panel.

From the infused panels 23 mm-wide specimens were cut and polished on the edges. Fatigue tests were performed by means of a MTS 858 MiniBionix hydraulic machine. An axial extensometer MTS632.29F-30 with an initial length of 25 mm was mounted to monitor the stiffness during the tests.

For laminates, cycles were applied in load control with a frequency of 10 Hz and a load ratio (minimum to maximum cyclic load) of 0.05. Four load levels were considered, corresponding to a global applied stress of 50, 60, 70 and 80 MPa, apart from the third panel for which tests at 80 MPa were not carried out. For laminates, a frequency of 4 Hz was used to avoid an excessive heating of the specimen during the tests and specimens were tested under global applied stresses of 100, 110, 120and 130 MPa.

Exploiting the glass/epoxy specimens translucency, and with the aid of a LED system mounted behind the specimen, damage was monitored by taking periodical pictures of the samples in an observation region of 60 mm length. The analysis of the pictures allowed us to count and measure the transverse cracks and thus to characterise the life to crack initiation, the crack density evolution and the crack growth rate.

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## 3. Fatigue tests results

For both the stacking sequances, the first observable event of damage was the initiation of cracks in the off-axis plies. Cracks were seen to initiate both at the edges and on the central part of the specimens and stably propagated along the fibres direction.

The S-N curves for the initiation of the first crack in every specimen are shown in Figures 2, where a dramatic detrimental effect of the presence of voids can be observed.

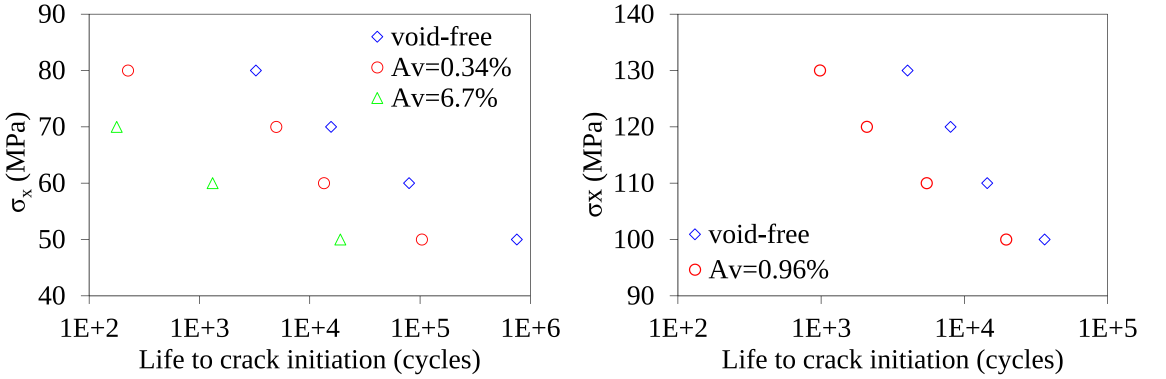


**Figure 2.** S-N curves for the initiation of the first crack in a) $[0/90_2]_S$ panels, b) $[0/45_2/0/\text{-}45_2]_S$ panels.

As highlighted in Refs. [15,16], if cracks are far enough from each other they propagate without interacting and in a steady state manner. This means that the Energy Release Rate (ERR) is not a function of the crack length and therefore the crack propagation rate is constant.

This phenomenon was observed also for the specimens under analysis, as proven by the crack propagation curves in Figure 3 exhibiting a linear trend, the slope of the straight line representing the crack growth rate. It was calculated that for $[0/90_2]_S$ laminates, the crack growth rate for the specimens with Av = 0.34% is about 75% higher than that for the void-free specimens at the same stress level, whereas an increment of 60% was found for $[0/45_2/0/\text{-}45_2]_S$ laminates with Av = 0.96%, highlighting the detrimental effect of voids also on crack propagation. Because of the high void content, the specimens of the third panel were not very translucent and therefore only results concerning the first crack initiation (not propagation) are reported.

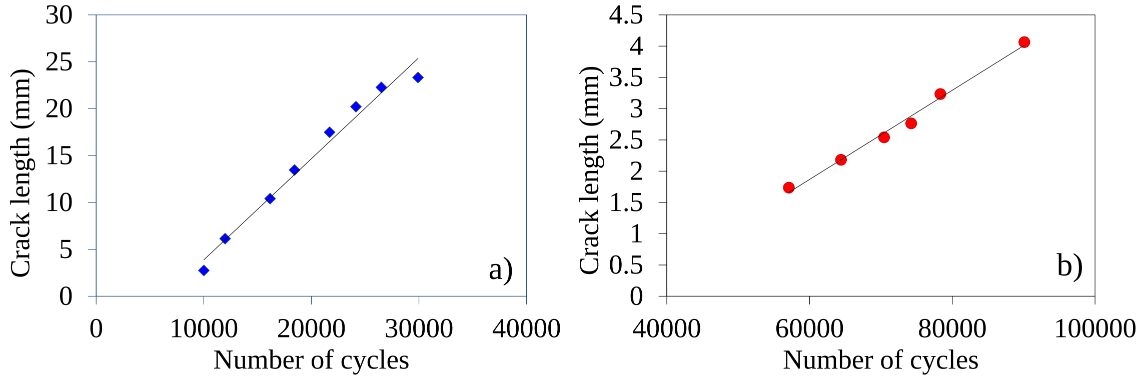


**Figure 3.** Crack propagation curves for a) a void-free $[0/90_2]_S$ specimen tested at 70 MPa and b) a void free $[0/45_2/0/\text{-}45_2]_S$ specimen tested at 100 MPa.

As previously mentioned, the crack density (number of cracks per unit length, $cd_w$) increased with the number of cycles. Examples of crack density evolution are shown in Figure 4, respectively for  for $[0/90_2]_S$ (80 MPa) and $[0/45_2/0/\text{-}45_2]_S$ ( MPa). In $[0/90_2]_S$ laminates, as expected the crack density increases much more steeply and reaches saturation much earlier in the specimen containing voids. A smaller effect of voids can be seen $[0/45_2/0/\text{-}45_2]_S$ laminates, which can be attributed to the fact that in such specimens voids were seen to be aggregated in some locations, so thet their influence is larger on the initiation of the first cracks.

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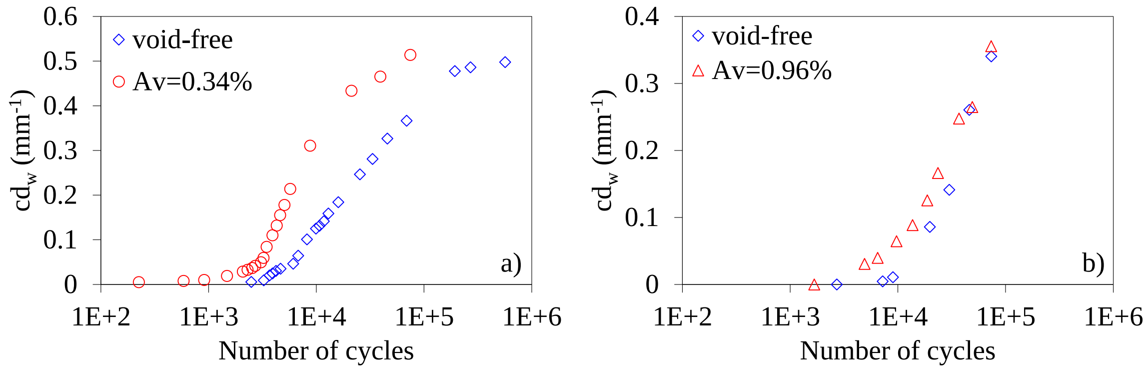


**Figure 4.** Crack density evolution for a) a $[0/90_2]_S$ specimens tested at 80 MPa, and b) $[0/45_2/0/-45_2]_S$ specimens tested at 120 MPa.

## 4. Conclusions

Laminates with stacking sequence $[0/90_2]_S$ and $[0/45_2/0/-45_2]_S$ were manufactured by means of the liquid resin infusion process using different process parameters, which may reduce the production costs inducing, on the other hand, voids in the final laminates. In particular, a void area fraction of 0.34% and 0.96% was obtained, respectively, for $[0/90_2]_S$ and $[0/45_2/0/-45_2]_S$ laminates, when the resin was not degassed prior to infusion.

Uniaxial fatigue tests revealed a detrimental effect of voids on crack initiation, crack propagation and crack density evolution during fatigue life for both the stacking sequences.

## References

[1] P. Olivier, J. P. Cottu, B. Ferret. Effects of cure cycle pressure and voids on some mechanical properties of carbon/epoxy laminates. *Composites*, 26:509-515, 1995.

[2] Y. Huang, J. Varna, R. Talreja. Statistical methodology for assessing manufacturing quality related to transverse cracking in cross-ply laminates. *Composites Science and Technology*, 95:100-106, 2014.

[3] P. A. Carraro, L. Maragoni, M. Quaresimin. Influence of manufacturing induced defects on damage initiation and propagation in carbon/epoxy NCF laminates. *Advanced Manufacturing: Polymer and Composites Science*, 1:44-53, 2015.

[4] J. Hapke, F. Gehrig, N. Huber, K. Schulte, E. T. Lilleodden. Compressive failure of UD-CFRP containing void defects: In situ SEM microanalysis. *Composites Science and Technology*, 71:1242-1249, 2011.

[5] N. Kosmann, J. M. Karsten, M. Schuett, K. Schulte, B. Fiedler. Determining the effect of voids in GFRP on the damage behaviour under compression loading using acoustic emission. *Composites: Part B*, 70:184-188, 2015.

[6] M. N. Bureau, J. Denault. Fatigue resistance of continuous glass fiber-polypropylene composites consolidation dependence. *Composites Science and Technology*, 64:1785-1794, 2004.

[7] A. R. Chambers, J. S. Earl, C. A. Squires, M. A. Suhot. The effect of voids on the flexural fatigue performance of unidirectional carbon fibre composites developed for wind turbine applications. *International Journal of Fatigue*, 28:1389-1398, 2006.

[8] C. W. Dill, S. M. Tipton, E. H. Glaessge, K. D. Branscum. Fatigue strength reduction imposed by porosity in a fiberglass composite. *Damage Detection in Composite Materials*, ASTM STP 1128, 1992.

[9] F. Schmidt, M. Rheinfurth, P. Horst, G. Busse. Multiaxial fatigue behaviour of GFRP with evenly distributed or accumulated voids monitored by various NDT methodologies. *International Journal of Fatigue*, 43:207-216, 2012.

[10] F. Gehrig, E. Mannov, K. Schulte. Degradation of NCF-epoxy composites containing voids. *Proceedings of the 17th International Conference on Composite Materials ICCM17, Edimburgh, UK, July 27-31, 2009*.

[11] M. A. Suhot, A. R. Chambers, The effect of voids on the flexural fatigue performance of unidirectional carbon fibre composites, *Proceedings of the 16th International Conference on Composite Materials ICCM16, Kyoto, Japan, July 8-13, 2007*.

[12] J. Lambert, A. R. Chambers, I. Sinclair, S. M. Spearing, 3D damage characterization and the role of voids in the fatigue of wind turbine blade materials, *Composites Science and Technology*, **72**, 2012, pp. 337-343.

[13] G. Seon, A. Makeev, Y. Nikishkov, E. Lee, Effects of defects on interlaminar tensile fatigue behavior of carbon/epoxy composite', *Composites Science and Technology*, **89**, 2013, pp. 194-201.

[14] S. Sisodia, E. K. Gamstedt, F. Edgren, J. Varna, Effects of voids on quasi-static and tension fatigue behaviour of carbon-fibre composite laminates, *Journal of Composite Materials* (doi: 10.1177/0021998314541993).

[15] M. Quaresimin, P. A. Carraro, L. P. Mikkelsen, N. Lucato, L. Vivian, P. Brøndsted, B. F. Sørensen, J. Varna, R. Talreja, Damage evolution under internal and external multiaxial cyclic stress state: a comparative analysis between glass/epoxy laminates and tubes, *Composites Part B-Eng*ineering, **61**, 2014, pp. 282–290.

[16] M. Quaresimin, P. A. Carraro, Damage initiation and evolution in glass/epoxy tubes subjected to combined tension-torsion fatigue loading, *International Journal of Fatigue*, **63**, 2014, pp. 25-35.

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