How do we measure transverse strengths of composites and the factors affecting it?

Federico París[1], Michael R. Wisnom[2], Yentl Swolfs[3],

[1]*Escuela Superior de Ingeniería, Universidad de Sevilla, Spain, fparis@us.es*
[2]*Bristol Composites Institute, University of Bristol, UK, M.Wisnom@bristol.ac.uk*
[3]*Department of Materials Engineering, KU Leuven, Belgium, yentl.swolfs@kuleuven.be*

In our first workshop we defined strength as the maximum stress that the material can sustain under uniform uniaxial loading and in the absence of other stress components [1]. The second workshop discussed UD tensile strength [2], the third one dealt with UD compressive strength [3] and the fourth addressed UD composite strength under shear [4]. We now move to transverse strength under tension and compression and the factors affecting it. The main difficulty here is not associated with the determination of the property in a test, as the conditions associated with the aforementioned definition of strength can be reasonably accomplished, but the representativity of the values obtained to the actual performance of the material in a laminate.

Both tensile and compressive strength (Y_T and Y_C) will be considered in this workshop. The corresponding tests for both cases are, in general terms, similar to those for the determination of strengths along the direction of the fibres. In the transverse case they are regulated by the corresponding standards, EN2597 (tension) [5] and EN2850 (compression) [6], for instance. The latter standard is used in compression both for tests parallel and normal to the fibres.

In spite of the similarity of these transverse tests to determine Y_T and Y_C compared with those to determine X_T and X_C along the direction of the fibres, they are not performed as commonly. In fact, the list of material acceptance tests of major aeronautic manufacturers only considers tests along the direction of the fibres as a requisite to consider the material "flight worthy".

In any case, these tests present similar problems to those identified in previous workshops. In the case of compression, premature failure may appear due to the gripping system that produces local stress concentrations very near to the gauge zone. It is worth to mention that the response in compression is highly non-linear (with an apparent inclination angle of 53-55 degrees), compared to the usual brittle response in tension. In both tension and compression cases, a certain dependence of the properties on the thickness of the specimens has been observed. Finally, also in both cases, the typical scatter associated with loading in a direction normal to the fibres appears, this scatter being more noticeable under tension that under compression.

As suggested at the beginning, the main problem associated with the strength in the direction transverse to the fibres is the representativity of the values obtained. Parvizi et al [7] for glass fibres and Flaggs and Kural [8] for carbon fibres found how the apparent value of the strength of the weakest laminae (typically those oriented at 90 degrees) increased when the thickness of these laminae was decreased. This behaviour led to generate the concept of "in-situ strength", associated with a "scale effect", a concept not fully understood when first defined.

There were several trials to explain this in-situ strength concept. The first was based on a global balance of energy, Garret and Bailey [9], that explained the increase of resistance of the 90 degree lamina when the thickness tended to zero, but gave no explanation of the opposite case. Dvorak and Laws [10] gave an explanation of the scale effect based on a model involving the presence of internal damage defined as a non-Griffith crack. Li and Wisnom

[11], accepting the pre-existence of defects, developed an approach based on a statistical model. Much more recently, García et al. [12] revisited the problem following an approach based on a double stress and energy criterion, again with a homogeneous view of the material.

In terms of experimental observations Asp et al [13] found evidence of cavitation of the matrix as the initiation of the transverse damage. París et al [14,15,16] connected experimental evidence with predictions based on micromechanical transverse representations of the material, see Figure 1, where the observed angle of breakage of the specimen under compression is associated with the predicted angle at which the debonding crack abandons the fibre-matrix interface and penetrates into the matrix.

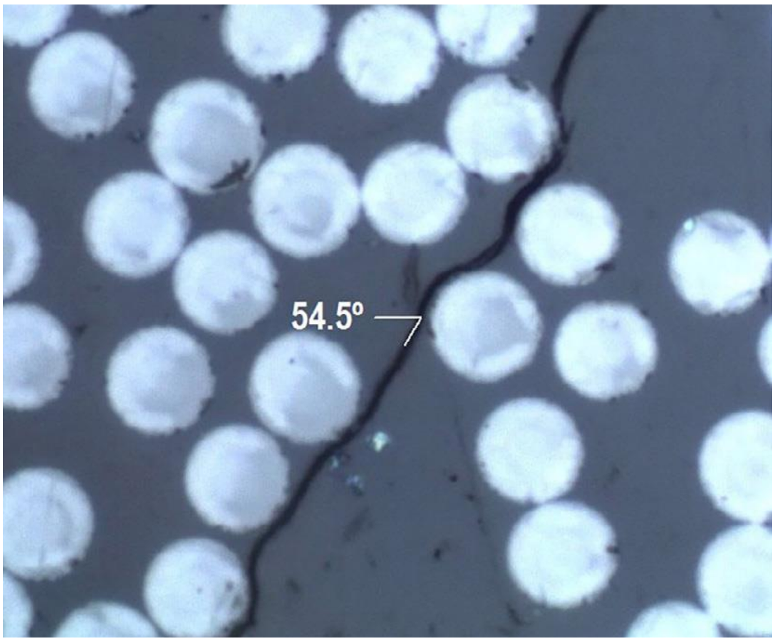

Figure 1. Transverse failure under compression connecting the micromechanisms of failure with the mesomechanical aspect of the breakage of a specimen in a compression test, which presents an inclination of the crack at 53-55 degrees [16].

Studies have shown that the transverse tensile strength of CFRP depends on the volume of stressed material and can be fitted with a Weibull model, e.g. Arndt et al [17]. A new test approach to determine the transverse tensile strength with regard to the size effect has been proposed by Liebig et al [18], using the remaining part of an already tested specimen. The approach tries to elucidate whether the first failure is dominated either by the most critical flaw of the material or by the tensile strength of the matrix.

The appearance of ultrathin plies has focused again the attention of the composites community on this matter. From an experimental point of view, Saito et al [19] performed tests with ultrathin plies in a cross-ply laminate observing the evolution of the damage with the thickness of the 90° lamina. París et al. [20] have given a fully physically based explanation of the scale effect under consideration focusing the attention on the damage observed experimentally in the 90° laminae and connecting it with the different mechanisms of damage involved in the failure. Figure 2 shows the damage observed in the 90° lamina of a $[0,90]_S$ laminate, the 90° lamina being an ultrathin ply of 50 μm.

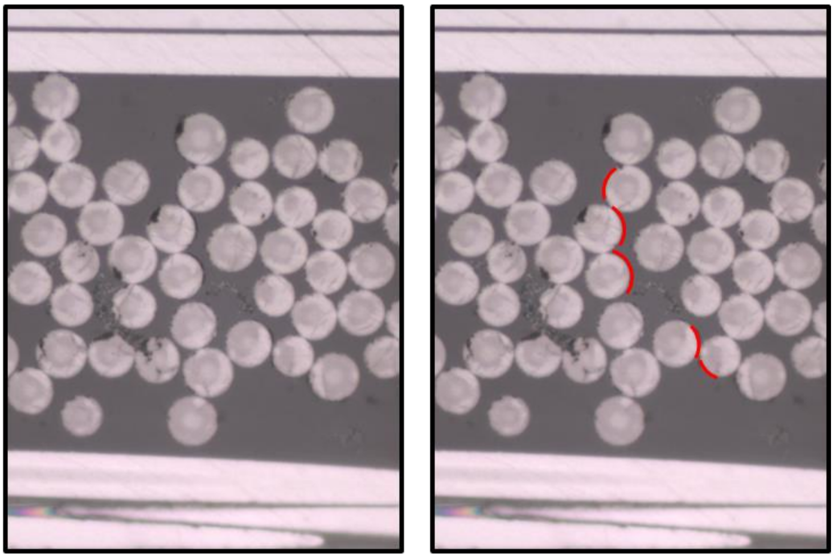

Figure 2. Micrography of the damage in the 90 degree lamina consisting of isolated debondings.

The term in-situ strength now takes a full meaning, the updated question being then what is the definition of strength: a concept associated with the appearance of some incipient damage (typically isolated debonds) or with the presence of a full transverse crack with some delamination-like damage associated?

The problem now becomes more important as aircraft manufacturers are trying to reduce manufacturing costs by using thick laminae. This, in the light of [20] leads to a more complicated development of damage in thick laminae in a double sense: damage appears suddenly, and its development is more detrimental since it may reduce the performance of the laminate under other type of loadings (for instance, shear, bending, torsion…). This will be for sure a focus in the near future.

References

1. Wisnom MR, Paris F, "How do we define and measure strength of a composite?", 2020. Definition-of-strength-Workshop (bristol.ac.uk)
2. Wisnom MR, Swolfs, Y, Paris F, "How do we measure fibre direction tensile strength and the factors affecting it?", 2021. tensile-strength-paper.pdf (bristol.ac.uk)
3. Wisnom MR, Swolfs, Y, Paris F, "How do we measure fibre direction compressive strength and the factors affecting it", 2021. compressive-strength-paper.pdf (bristol.ac.uk)
4.- Paris F, Wisnom MR, Swolfs, Y, 2022: "Measuring shear strength and the factors affecting it", 2022. Measuring-shear-strength-and-the-factors-affecting-it.pdf (bristol.ac.uk)
5. EN2597 Carbon Fibre reinforced Plastics. Unidirectional Laminates. Tensile test perpendicular to the fibre direction.
6. EN2850 Carbon fibre thermosetting resin unidirectional laminates. Compression test parallel to fibre direction.
7. A. Parvizi, K. V. Garret, J. E. Bailey, Constrained cracking in glass fibre-reinforced epoxy cross-ply laminates, J. Mat. Sci. 13 (1978) 195–201.
8. D.L. Flaggs, M.H. Kural, Experimental Determination of the In Situ Transverse Lamina Strength in Graphite/Epoxy Laminates, J. Com. Mat. 16 (1982)103-116.
9. K. W. Garret, J.E. Bailey, Multiple transverse fracture in 90º cross-ply laminates of glass fibre reinforced polyester, J. Mater. Sci. 12(1) (1977) 157-168.

10. G.J. Dvorak, N. Laws, Analysis of Progressive Matrix Cracking In Composite Laminates II. First Ply Failure, J. Comp. Mat. 21 (1987) 309–329.
11. D.S. Li, M.R. Wisnom, Evaluating Weibull Parameters for Transverse Cracking in Cross-Ply Laminates, J. Comp. Mat. 31 (1997) 935–951.
12. I.G. García, V. Mantič, A. Blázquez, F. París, Transverse crack onset and growth in cross-ply [0/90n]s laminates under tension. Application of a coupled stress and energy criterion, Int. J. Sol. Struct. 51 (2014) 3844-3856.
13. L.E. Asp, L.A. Berglund, R. Talreja, A criterion for crack initiation in glassy polymers subjected to a composite-like stress state, Comp. Sci. Tech. (1996) 56(11): 1291-1301.
14. F. París, E. Correa, J. Cañas, Micromechanical view of failure of the matrix in fibrous composite materials, Comp. Sci. Tech. 63 (2003) 1041–1052.
15. F. París, E. Correa, V. Mantič, Kinking of Transversal Interface Cracks Between Fiber and Matrix, J. Appl. Mech. 74 (2007) 703–716.
16. P.L. Zumaquero, E. Correa, J. Justo, F. París, Microscopical observations of interface cracks from inter-fibre failure under compression in composite laminates, Comp. Part A. 110 (2018), 76-83.
17. C. Arndt, N.V. de Carvalho, M.W. Czabaj, Experimental reexamination of transverse tensile strength for IM7/8552 tape-laminate composites, J. of Comp. Mat. 54, (2020) 3297-3312.
18. W.V. Liebig, C. Leopold, T. Hobbiebrunken, B. Fiedler, New test approach to determine the transverse tensile strength of CFRP with regard to the size effect, Comp. Communications, 1, (2016) 54-59.
19. H. Saito, H. Takeuchi, I. Kimpara, Experimental Evaluation of the Damage Growth Restraining in 90° Layer of Thin-ply CFRP Cross-ply Laminates, Adv. Comp. Mat. 21 (2012) 57–66.
20. F. París, M.L. Velasco, E. Correa, The Scale Effect in Composites: A Physically Based Explanation on the different mechanisms of damage involved in the failure, Comp. Structures, Vol. 257, (2021) 113089.