DESIGN ALLOWABLES: CONSIDERING THE TENSILE AND COMPRESSIVE BEHAVIOUR OF NOTCHED AND UNNOTCHED CFRP.

Paul R Spendley [1], Stephen L Ogin [1], Paul A Smith [1] and Andrew B Clarke [2]

[1] Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, GU2 7XH, United Kingdom
[2] QinetiQ, Cody Technology Park, Ively Road, Farnborough, Hampshire, GU14 0LX, United Kingdom

ABSTRACT

This paper presents an experimental study which examines the tensile and compressive response of a quasi-isotropic carbon fibre reinforced polymer (CFRP) laminate subjected to ambient conditions and environmental extremes associated with aircraft design. Specimens with and without holes are considered within the context of structural features and associated design allowables. The data obtained, relating to the effect of sample replicates and specimen geometry on the variability in failure strength, support the concept of a reduced qualification test programme for CFRP.

1. INTRODUCTION

Early aircraft adopted natural composites in the form of wood and bamboo to produce efficient lightweight structures. These materials were often limited by their anisotropic nature. With the development and availability of lightweight alloys during the 1930s, the aircraft design engineer was able to consider multi-directional loading. Metallic materials led this weight-dominated industry until the discovery of fibre reinforced plastic or, more specifically, the commercialisation of CFRP in the 1980s. This material offered enormous advantages over aluminium alloys, although these benefits were often associated with the unidirectional strength of the CFRP rather then an appropriate multi-directional lay-up associated with an application – there is a compromise to be met between optimum unidirectional properties and an appropriate balanced lay-up. Over the years, a number of standard coupon test methods and a process of determining a material design allowable have been developed, based on methods for metallic materials. With these test methods representing low maturity for CFRP, the properties recorded are often of variable quality and as such require considerable conservatism or safety margin during the design of a safety-critical component such as an aircraft. Ultimately this conservatism also compromises the efficient use of these materials. This paper examines the generation of typical CFRP materials data for aerospace design and considers the variability in CFRP laminates test results as a consequence of test configuration [1]. Generating design allowables based on test data alone can result in artificially low design strengths although the conservative nature of airworthiness certification means that this is an acceptable approach [2, 3]. Since the certification approach for composite structures was developed however [4-6], the knowledge and understanding of composite laminate behaviour has increased significantly (*e.g.* [7-9]).

With regard to design allowables, the variability and the lack of significant reference data on specific CFRP laminates often suggest it is necessary to test a large number of specimens in order to determine the failure strength with an acceptable degree of confidence. The effect of environmental extremes (based on application) and structural features (*e.g.* fastener holes) on the laminate is addressed by further testing or combining knock-down factors. Practical and economic constraints can mean that only a comparatively low number of non-ambient tests are performed. Consequently, the use of small sample methods and knock-down factors [10] for calculating design strengths has been proposed as a 'quick' method although this may often result in over-conservative design allowables.

This present study examines the tensile and compressive response of notched and unnotched quasi-isotropic CFRP laminate specimens under ambient and non-ambient conditions. The paper starts by considering the material and test methods, which are based essentially on existing ASTM methods. The effect of specimen number and the influence of a circular notch on the variability in failure strength are of particular interest in this study.

2. EXPERIMENTAL METHODS

2.1 Material preparation

The pre-preg used in this study, high tensile strength PAN-based carbon fibres within a toughened epoxy matrix, had an approximate mass of 140 g/m^2 and a cured ply thickness of 0.125 mm. Sample quasi-isotropic composite plates with ply orientations of $(+45/0/-45/90)_{4s}$ and measuring approximately 300 mm x 300 mm x 4 mm were fabricated in a high quality environment. Tensile and compressive specimens with nominal dimensions of 280 mm x 32 mm and 132 mm x 32 mm (recommended by ASTM), respectively, were cut from the various plates. Specimens for drilling and for subjecting to the various environmental conditioning regimes were selected from the tension and compression sample sets in a randomised manner. Where notches were required, holes of 6 mm diameter were drilled carefully in the centre of the specimen using sickle-point drill bits. The hot wet (HW) samples were exposed to an environment of 80ºC, 90% RH until saturation was achieved, typically after about a 1000 hours. The complete test matrix is shown in Table 1.

2.2 Mechanical testing

All tests were performed using an Instron universal testing machine with suitably rated hydraulic grips and a 250 kN load cell. Specimens were tabbed prior to testing, using end tabs cut from a ±45° glass fibre reinforced polymer laminate. ASTM test guidelines were employed where possible (see Table 1). A temperature cabinet was used to test the HW aged samples at a nominal temperature of 80^oC. Cold-dry specimens were pre-cooled to -55^oC prior to testing and a test temperature of -55^oC was maintained by surrounding the samples with solid carbon dioxide pellets. For some specimens, strain measurements were made using longitudinal and transverse strain gauges and for the compression tests, strain gauges were bonded to both faces of the specimens.

Table 1: Test matrix showing the abbreviations used for the unnotched and notched specimens tested at room temperature ambient, hot-wet and cold-dry conditions, together with the number of specimens tested at each condition.

Specimen type	Test condition and number of specimens, *n*		
	RT (room temperature, ambient: 22ºC ±2º, 60% RH)	HW (Hot-wet: aged at 80ºC and 90% RH, tested at 80ºC)[e]	CD (Cold-dry: tested at -55ºC)
PT (Unnotched tension)	21[a]	14	14
PC (Unnotched compression)	33[b]	12	12
OHT (Notched tension	17[c]	15	15
OHC (Notched compression)	33[d]	14	15

Notes:
(a) [a]ASTM D3039/D3039M, [b]ASTM D3410/D3410M 1995, [c]ASTM D5766, [d]ASTM D6484/D6484M, [e] ASTM D5229/D5229M-92
(b) Test specimen identification is constructed from specimen type and environmental condition, *e.g.* Unnotched tensile (PT) tested at Cold Dry (CD) becomes PTCD.

3. RESULTS & DISCUSSION

3.1 Mechanical response

A summary of the mechanical test results is given in figure 1, in which the mean strengths and standard deviations are shown for unnotched and notched tension and compression specimens at each of the three test conditions (Cold Dry, CD; Room Temperature, RT; Hot Wet, HW). The number of specimens tested, *n*, is also indicated for each type of test.

The basic trends of the data are much as would be expected. The (mean) tensile strength of the unnotched coupons does not appear to change significantly with test condition (i.e. PTCD, PTRT, PTHW), as would be expected for a fibre-dominated property. The compression strength of the unnotched coupons is significantly lower than the tensile strength, by about 30 % at the RT condition. Moreover the compression strength decreases progressively from CD, through RT to HW. This is likely to be a reflection of the progressive lowering of matrix properties with increasing temperature and moisture content of the matrix (*e.g.* 11, 12) and an associated reduction in the resistance of the composite to fibre micro-buckling. Residual stresses will also change significantly over the test temperature range [13].

Turning to the notched properties, these are substantially lower than the unnotched properties, as would be expected for these notch-sensitive laminates. The strength reductions under RT conditions of 40 – 50% are more than twice those that would be expected simply on the basis of the reduction in the net-section cross-sectional area (19%). The notched strength trends with test condition differ for the tension and compression samples. The notched tensile strength shows an increase for the HW condition compared to the RT condition, while the notched compression strength shows a decrease. Degradation of the matrix and the fibre-matrix interface is likely to promote matrix cracking/splitting damage mechanisms which act to reduce the stress concentration at the notch edge and so delay fibre fracture in tension until higher levels of applied laminate stress. Under compressive loading, however, the matrix and interface degradation are likely to lead to fibre micro-buckling at lower levels of applied stress than in the RT condition.

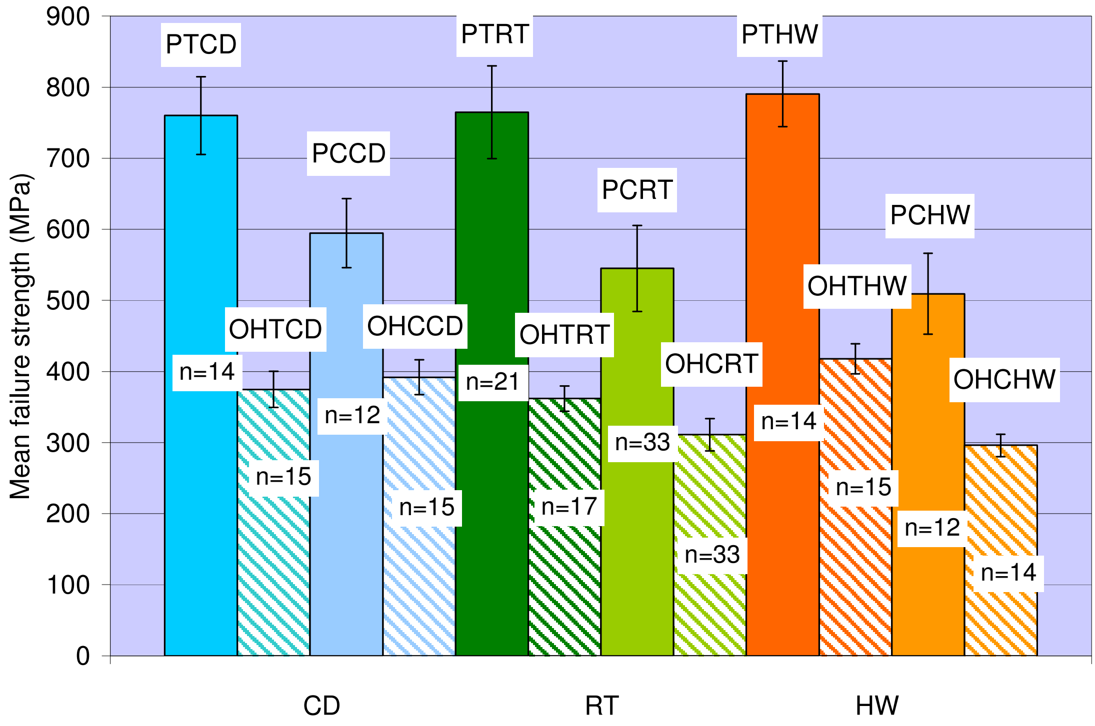

Figure 1: Histograms showing mean failure strengths (MPa) for each specimen type against test condition (error bars represent one standard deviation).

3.2 Observations on strength variation

An alternative method of presenting the variability of the test data is to plot the probability density function against failure strength for each sample type and test condition (figure 2). This method of presenting data allows an appraisal of the scatter associated with each data set. Figure 2 shows clearly that there is significantly reduced scatter in the results for the notched data sets for all testing conditions. All of the unnotched data sets have relatively large standard deviations and there is considerable overlap between the data sets. The results show that the notched specimens not only provide a stress concentration at the centre of the specimen but that the stress concentration reduces the scatter of the results.

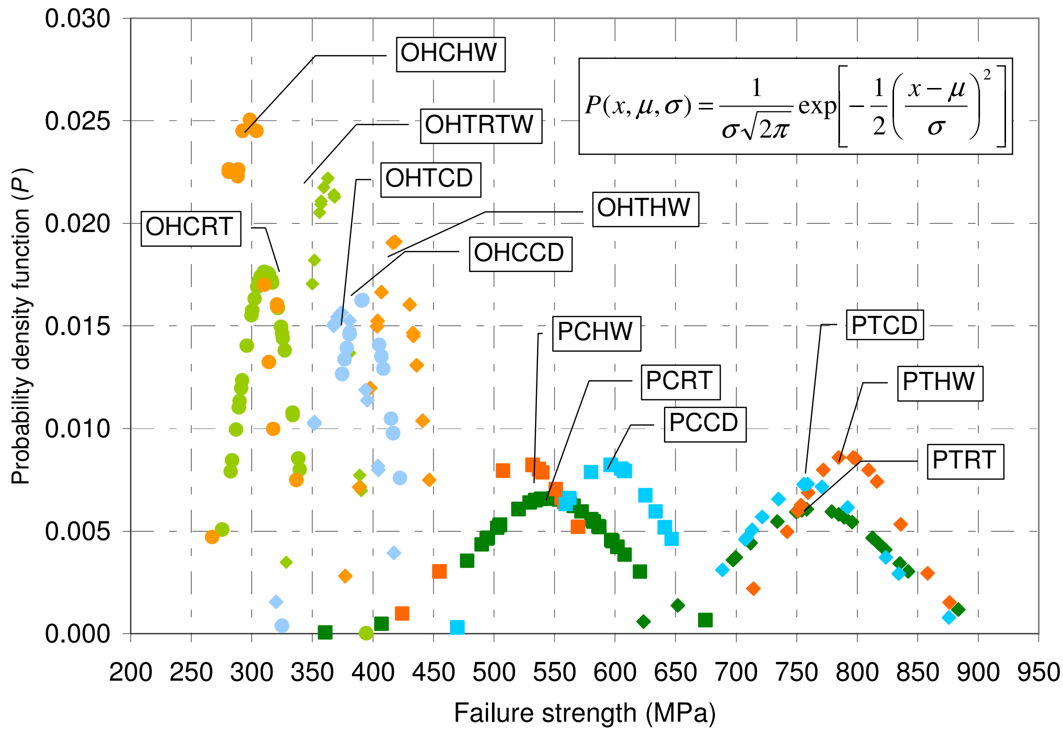

Figure 2: Test data plotted as probability density functions (x = strength value, μ = mean and σ = standard deviation).

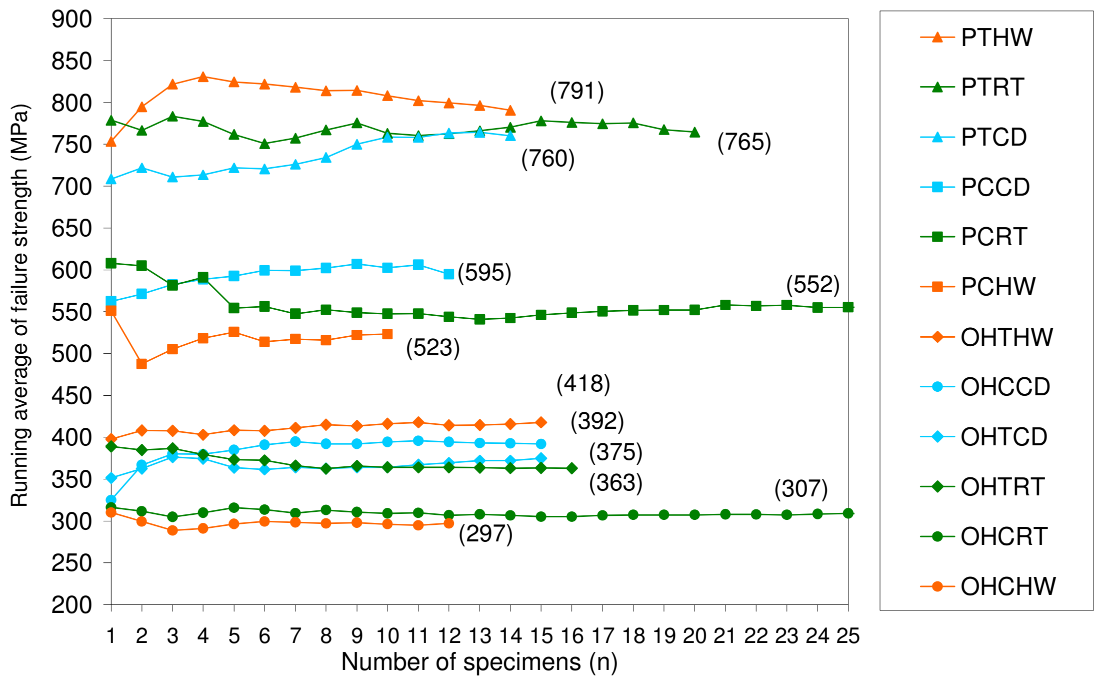

Figure 3: Test data sampled by plotting running average against the number of specimens (n). (Mean failure strength values presented in parentheses)

Figure 3 shows the running average for each type of test and indicates the number of specimens required for a reliable strength measurement. Examining the unnotched tension results first, which of course all lie at the higher strength values, all the conditions require about 12 or 13 specimens before the mean value stabilises. The notched data sets, on the other hand, appear to reach a stable value after approximately 5 to 7 data points have been obtained. This suggests that the use of small sample methods employing notched specimens may provide an economical method of measuring strengths, providing the unnotched strengths can be derived from the notched-strength values.

4. CONCLUDING REMARKS

Strength measurements have been conducted on notched and unnotched specimens from a CFRP quasi-isotropic laminate under ambient and non-ambient conditions. The results show that notched specimens containing a centrally placed 6 mm diameter hole exhibit significantly less variation in tensile and compressive failure strength than unnotched specimens. Sampling the data with respect to specimen quantity suggests a mean strength may be obtained with fewer tests if notched specimens are used, provided an appropriate method is available to extract unnotched data from the results.

ACKNOWLEDGEMENTS

The authors would like to thank Mr Peter Haynes and Dr David Jesson of the University of Surrey for their invaluable experimental support and advice. Further thanks go to Ms Linda Clowes and Mr Kevin Denham of QinetiQ for assistance in producing high quality samples. Finally, gratitude is extended for financial support provided by EPSRC and QinetiQ (Farnborough).

REFERENCES

1- Hart-Smith LJ, “Generation of higher composite material allowables using improved test coupons”, *36th International SAMPE Symposium*, 1991.

2- Federal Aviation Administration, Composite Aircraft Structure, Advisory Circular AC 20-107A, 25 April 1984 and companion document by the JAA, ACJ 25.603, Composite Aircraft Structure Acceptable Means of Compliance, 1986.

3- European Aviation Safety Agency., “On certification specifications, including airworthiness codes and acceptable means of compliance, for large aeroplanes”,(CS-25) Decision No. 2003/2/RM, 2003.

4- Rouchon JR, “Certification of large airplane composite structures, recent progress and new trends in compliance philosophy”, *CEAT*, 1439-1447.

5- Whitehead RS., Kan HP., Cordero R. and Saether ES. “Certification testing methodology for composite structures”, *Vols 1 and 2*, *NADC Final Report, Contract No. N62269-84-C-024,*. 1986.

6- Bristow J., “Structural composite airworthiness in civil aircraft”. *Proceedings of 6th SAMPE Conference*, 1985; 39: 1-11.

7- Soutis C., Fleck NA. and Smith PA.,. "Failure prediction technique for compression loaded carbon fibre-epoxy laminate with open holes", *Journal of Composite Materials*, 1991; 25:1476-1498.
8- Sutcliffe MPF., Xin XJ., Fleck NA.and Curtis PT., ."Composite Compressive Strength Modeller", Version 1.4a, 1999, Engineering Department, Cambridge University, Trumpington St, Cambridge, CB2 1PZ.
9- Suemasu H., Takahashi H. and Ishikawa T., "On failure mechanisms of composite laminates with an open hole subjected to compressive load". *Composites Science and Technology*, 2006; 66, 634-641.
10- Hallet SJ, "Derivation of Design allowables at Airbus Filton site", *2nd International Conference on Composites Testing and Model Identification*, 2004.
11- Potter RT and Purslow D., "The effect of environment on the compression strength of notched CFRP - a fractographic investigation", *Composites,* 1983;14: 206-224.
12- Kellas S, Morton J and Curtis PT, "The effect of hygrothermal environments upon the tensile and compressive strengths of notched CFRP laminates Part 1 : Static loading". *Composites*, 1990; 21.
13- Sanchez-Saez S, Gomez-del Rıo T., Barbero E., Zaera R. and Navarro C., "Static behavior of CFRPs at low temperatures", *Composites: Part B,* 2002; 33: 383–390.