Round-robin validation exercise for the determination of pin bearing strength

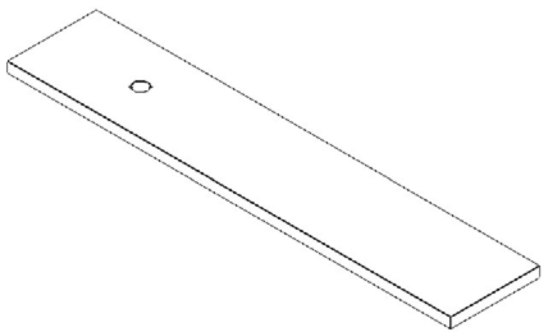
Summary

This Measurement Note details a round-robin exercise undertaken in order to provide precision data to support the proposal of the pin bearing test as a new work item for ISO test methods. This is a continuation of the work conducted under a previous program, Composite Performance and Design (CPD), to validate three structural test methods: open-hole tension, open-hole compression and pin bearing.

The preliminary manufacture of coupon specimens was carried out by NPL, from four different materials. Subsequent hole machining and specimen testing was performed by seven different participants. The test results were analysed statistically according to ISO 5725-2 using 95% confidence limits, to determine the method's repeatability and reproducibility.

The test method reproducibility and repeatability values using the updated procedure are an improvement on the previous round-robin conducted on pin bearing specimen tests.

The work was carried out as part of the "Measurements for Materials Systems" (MMS) programme funded by the Department of Trade and Industry.



R M Shaw and G D Sims

April 2003

Introduction

A previous round-robin conducted on the pin bearing strength test highlighted an important issue, namely the set-up of the specimen within the bearing rig before testing. The correct clearance between sample and test rig was emphasised in the revised test procedure. A round-robin validation exercise was then undertaken to obtain precision data for this revised draft procedure for the determination of pin bearing strength in polymer matrix composites. These data would support the progress of this test method as a proposal for an ISO new work item (NWI).

The exercise was conducted using seven test-laboratories and four materials. Each participant received coupon specimens machined to size and were required to machine a hole in the correct position and then conduct the test according to the draft procedure. A pin bearing fixture was available for loan to the participants if required.
The results were then analysed according to

The materials investigated were:

- Material 1 – Quasi isotropic carbon fibre/epoxy, autoclave moulded (CFRP)
- Material 2 – Woven glass fibre/epoxy, press moulded
- Material 3 – Chopped strand-mat glass fibre/ polyester (CSM) hand lay-up
- Material 4 – Glass fibre/polyester mixed format, pultrusion (PUL)

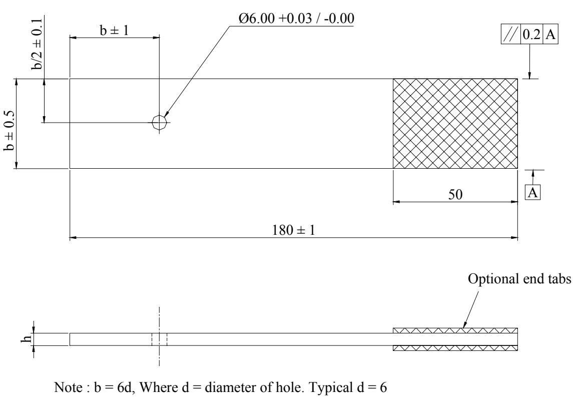


Figure 1 - Pin bearing specimen dimensions.

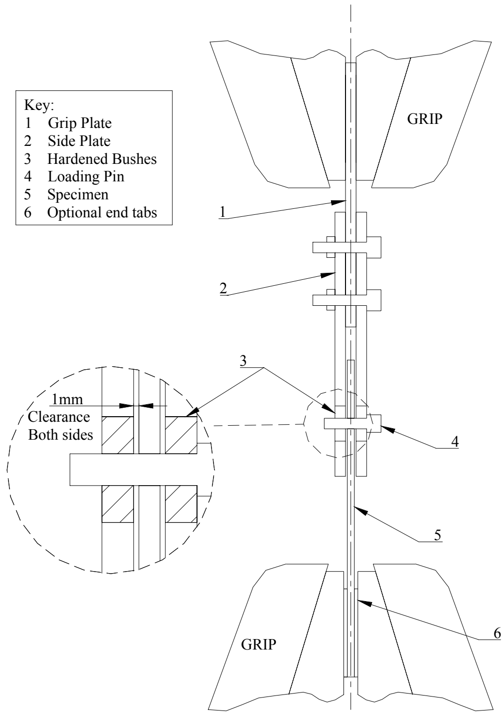


Figure 2 - Schematic of pin bearing fixture.

ISO 5725-2[1] using 95% confidence limits.

The proposed method uses a plain pin to provide a basic ‘material’ property test. This method is similar to the ASTM D 5961M[2] test which uses a torqued bolt. The torqued bolted test is not preferred as it has several difficulties concerning the level of torque, the choice of failure criterion, the washer and thread size and effect of composite/washer friction.

The pin bearing strength test consists of a specimen machined to the dimensions shown in Figure 1 and a test fixture which is flexible enough to be used for torque tests, and different sample thickness to ensure the required clearance, shown in Figure 2. The fixture is clamped by the grip plate in the upper wedge grip of the test machine. The specimen is then placed in the fixture and the pin located. Once the pin has been placed in position, the bush spacing is checked and adjusted as necessary to ensure the required clearance, shown enlarged in Figure 2. The specimen is then clamped in the lower wedge grip of the test machine. It may be necessary at this point to re-adjust the spacing of the bushes before testing begins. The specimen is then loaded at a displacement rate of 1 mm/min in tension.

The cross-head displacement and load are recorded throughout the test.

Once the first test of a batch has been carried out the test rig can remain clamped in position in the test machine simply requiring a new specimen to be inserted.

The pin bearing strength, σ_p (MPa), is then calculated using the equation:

$$\sigma_p = \frac{F}{hd}$$

where:
F is the maximum load, (N);
h is the specimen thickness, (mm);
d is the diameter of the loading pin, (mm).

Failure of the specimen occurs in bearing as shown in Figure 3(a); other failure modes such as tension and shear-out shown in Figures 3(b)-(c) are not acceptable.

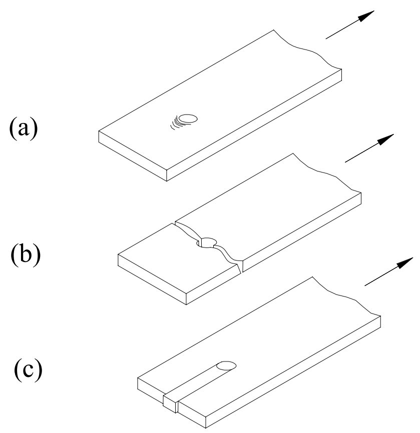


Figure 3 - Specimen failures (a) Bearing (b) Tension and (c) Shear out

Round-robin procedure

Plain coupons of the four materials were sent to participants. These were pre-cut to the required width and length. The participants then machined the pin loading hole and conducted the test according to the draft test procedure, written by NPL.

Participants were asked to test five specimens per material type and fill in a report sheet detailing the machining techniques used, specimen geometry and the test data. A pin bearing fixture was made available to loan from NPL to all the participants.

The decision to conduct the round-robin in this manner was taken for two reasons:

- A previous round-robin[3] for the pin bearing test showed a high scatter in results due to confusion over the separation of the hardened bushes, with some participants not allowing a defined clearance against the specimen face. This in effect behaving as a torque test giving artificially high results. The procedure for this round-robin was amended to take this issue into account and give clear illustration as to the required clearance, as shown in Figure 2.

- Previous work conducted by NPL on machining of composite materials[4] called into question whether the current tight tolerance on the hole position was needed and the participants would be able to achieve it. For this reason the specified hole tolerance was left tight, but participants were asked to measure the geometry of the specimen before testing to assess if it had actually been achieved.

Manufacture and testing

Details of the manufacturing process adopted by different laboratories are given in Table 1. This information was collated from report sheets returned by participants.

Table 1 - Variations in specimen machining.

Machining Process	Drill Type	Speed (rpm)	Feed Rate (mm/min)	Backing Material
Vertical milling machine	HSS			Wood
Pillar drill	Klenk	450	Manual	Glass epoxy
Pillar drill	Dagger	1000	10	Wood
Turret head drilling machine	HSS	650	Manual	None

Critical dimensions of the specimens were measured by the participants prior to testing (with the exception of Laboratories 2 and 6). The exact hole positions in relation to the centre line of the specimens are shown in Figure 4, the grey line indicating the maximum tolerance level specified in the procedure. Table 2 details the typical machined hole diameters.

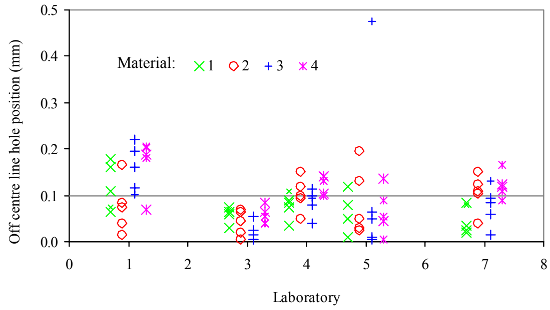


Figure 4 - Hole position relative to specimen centre line: grey line represents tolerance limit.

Table 2 - Typical hole diameters (mm).

Laboratory	1	2	3	4	5	6	7
Material 1	5.99		6.02	6.00	5.99		5.99
Material 2	6.00		6.02	6.00	6.03		6.00
Material 3	6.00		6.02	6.00	5.97		6.00
Material 4	5.99		6.02	6.00	6.02		5.99

A brief investigation into the measured data shows:

- <u>All laboratories</u>: machined the hole diameter to within ± 0.03 mm.
- <u>Most laboratories, with the exception of laboratory 3</u>: experienced difficulties in machining the position of the pin loading hole to the tolerances set in the draft procedure.
- <u>Laboratories 2 & 6</u>: did not provide dimensional data as measurements were not made prior to testing by these participants.

Details provided by participants on the testing of the specimens showed that all participants had conducted the test to the required speed of 1 mm/min. A typical set of stress/displacement traces from a batch of five correctly tested specimens in Figure 5 show the close grouping of results achievable.

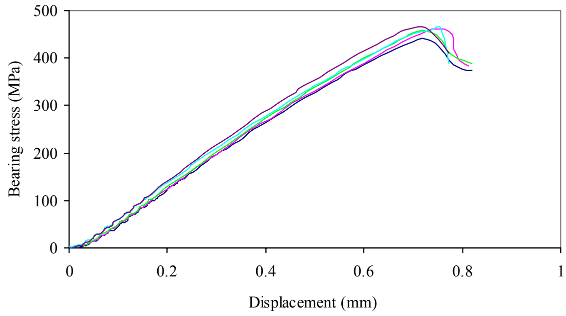


Figure 5 - Typical failures curves.

Figure 6 gives an indication of the bearing strengths achievable under different test conditions. It can be seen that, when performed correctly, the pin bearing test produces curves similar to (a) which shows a peak load followed by a distinct drop in load after the bearing failure. If the test is continued past this point the load will drop for a short period and then start to rise again, achieving a higher load than the initial peak load as in (b). In some situations this can cause the wrong bearing strength value to be stated, especially where the loading train is not very stiff introducing noise into the system and masking the initial failure point.

Curve (c) indicates the failure obtained if the specimen bushes are positioned incorrectly, pressed against the specimen faces and inducing a slight torque loading effect on the specimen.

Curves (d) and (e) show the increase in bearing strength produced when the specimen is torqued prior to testing, (d) simulates a finger-tight bolt (3 Nm) and (e) a fully torqued bolt (12 Nm).

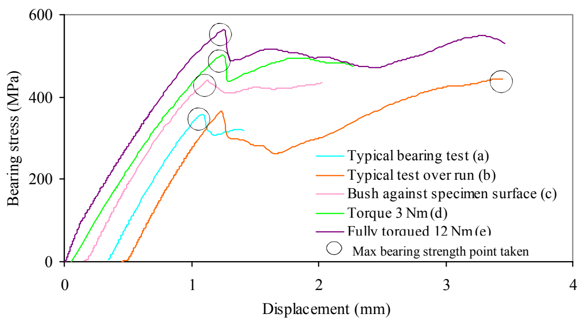


Figure 6 - Failure curves for different test conditions.

Results

The pin bearing strength results are detailed in Table 3, with the corresponding averages and standard deviations given in Tables 4 and 5.

Investigation of the failed specimens and results provided by the participants showed a clear irregularity:

- Laboratory 2 all materials: failures were invalid, failing in shear out or tension, in addition higher mean results and standard deviations were obtained on the materials.

Specimen failures from all other laboratories were seen to be in bearing, in accordance with the draft procedure.

In order to ascertain the sensitivity of the measured bearing strength to the hole

Table 3 - Original data: Bearing strength (MPa).

Laboratory \ Material	1	2	3	4
1	620.9 616.0 634.5 649.1 621.4	383.3 379.4 385.8 389.9 401.7	234.2 248.3 224.0 266.0 266.8	304.7 305.9 306.1 253.9 283.7
2	1293.8 947.5 965.3 914.6 880.1	608.7 549.1 593.6 563.7 556.5	367.1 353.5 275.6 279.4 301.1	454.8 327.2 400.7 434.6 392.2
3	533.9 633.0 533.9 612.6 570.0	380.4 400.7 384.3 404.2 398.5	236.7 251.8 252.6 258.2 248.5	297.2 268.9 244.6 261.8 312.4
4	576.4 522.3 566.2 493.6 500.2	368.9 399.4 395.2 346.6 382.8	196.8 239.1 253.2 223.8 245.0	302.4 310.7 297.8 305.8 -
5	698.3 674.0 929.1 655.0 711.1	447.2 467.9 446.4 471.9 503.6	311.4 318.0 310.1 305.8 296.5	294.2 276.4 332.5 295.1 325.1
6	658.3 590.9 621.4 570.9 593.1	444.2 468.8 458.3 456.7 460.3	180.5 190.6 206.3 287.5 188.4	273.0 259.6 272.9 262.1 269.7
7	621.4 627.2 618.4 607.3 643.4	426.0 430.8 426.2 424.2 406.0	305.4 303.7 323.7 283.8 291.6	336.4 344.2 363.1 302.9 370.6

Table 4 - Cell means : Bearing strength.

Laboratory \ Material	1	2	3	4
1	6284	388.0	2479	290.9
2	1000.3	574.3	315.3	401.9
3	576.7	393.6	249.6	277.0
4	531.7	378.6	231.6	304.2
5	733.5	467.4	308.4	304.7
6	606.9	457.7	210.7	267.5
7	623.5	422.6	301.6	343.4
Global mean	1479.5	440.3	585.8	312.8

Table 5 - Standard deviations: Bearing strength.

Laboratory \ Material	1	2	3	4
1	13.5	8.6	19.0	22.7
2	167.3	25.6	42.5	48.8
3	45.2	10.6	8.0	27.4
4	37.8	21.5	22.2	5.5
5	111.5	23.4	7.9	23.4
6	33.9	8.9	44.0	6.2
7	13.3	9.6	15.2	26.5

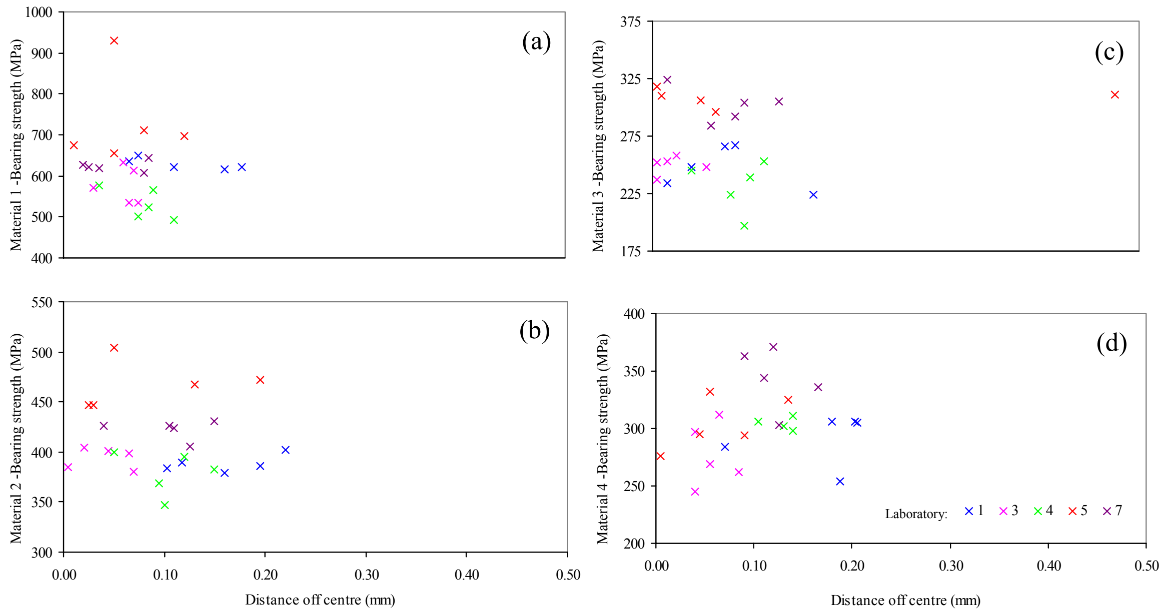


Figure 7 - Bearing strength vs. off-centre hole position data:
(a)-(d) corresponding to materials 1-4 respectively.

position the off-centre position of the holes were plotted against the pin bearing strength data for each specimen, and are shown in Figure 7(a)-(d). These highlight:

- Material 3: significant off-centre hole positioning by Laboratory 5 for one specimen resulted in the correct failure mode and had no apparent effect on the bearing strength.
- Materials 1-4: plots show that although the specimen hole positions were not all within the tolerances set in the draft procedure, no discernible trend or significant effect on the results can be observed.

Statistical evaluation of results

Laboratory 2 produced anomalous results and failure modes as highlighted earlier. Subsequent communications with Laboratory 2 in regard to the erroneous results and modes of failure found that the participant had misunderstood the definition of the point of failure and had continued loading the specimen past the bearing failure point, as indicated in Figure 6(b). This caused the specimens faces to push up against the bushes creating artificially high load values. Unfortunately, data had not been recorded throughout the test for all the specimens, with only two load/displacement traces being made available to prove a peak bearing load had been witnessed.

Since a full set of bearing strength data were unavailable, Laboratory 2 was excluded from any further analysis.

Data from the remaining participants was then analysed in accordance with ISO 5725-2[1] using NPL in-house written software.

The data from the remaining 6 participants is shown graphically in Figure 8(a)-(d). These show:

- Laboratory 5: potentially has an individual outlier for Material 1.
- Laboratory 6: potentially has an individual outlier for Material 3.
- Laboratory 3: consistently produces lower mean values from the global average.
- Laboratories 5 & 7: show higher than average values for Material 3.
- Laboratory 5: generally exhibits larger intra-laboratory standard deviations than the other participants.

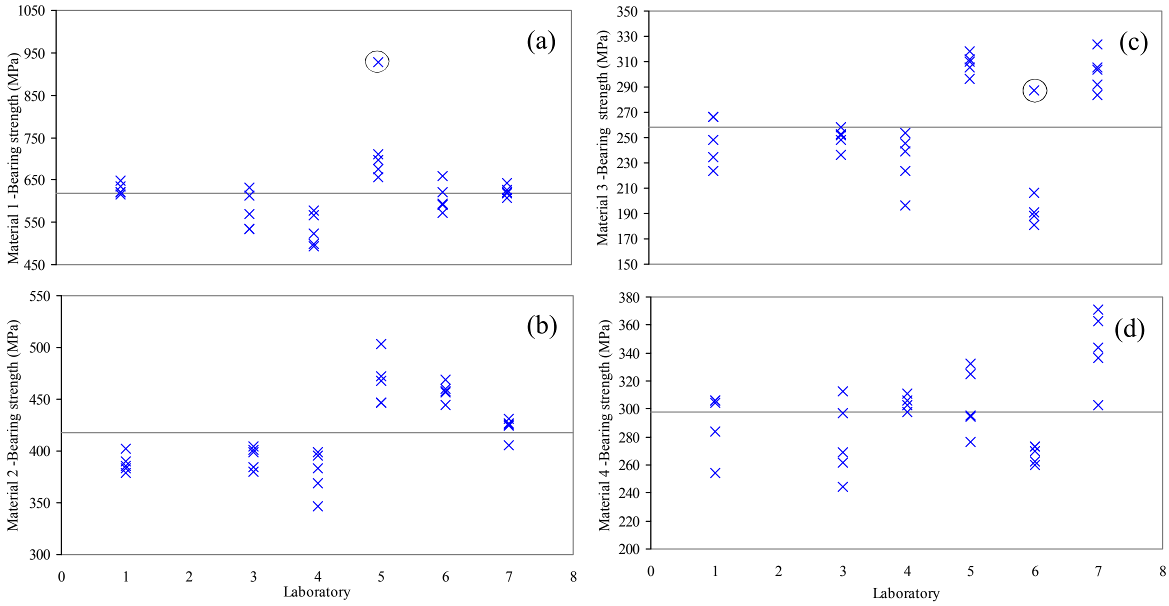


Figure 8 - Data from pin bearing test: (a)-(d) corresponding to materials 1-4 respectively, grey line represents global mean.

Using Mandel's statistics on the data, a graphical representation of the laboratory consistency can be shown. Mandel's *h* statistic, shown in Figure 9(a), is a measure of how the mean value for each laboratory and material differs from the mean value amongst all participating laboratories. The *k* statistic, shown in Figure 9(b), is the measure of standard deviation for each laboratory and material in relation to the sum of the variances for all the laboratories. The 1% and 5% significance levels are shown on the plots. If a value lies beyond these limits it needs to be inspected as it could be classified as a straggler or outlier. Using this method, we can verify that Laboratory 5 shows statistically greater scatter when compared to the other laboratories for Materials 1 and 2 and Laboratory 6 has greater scatter for material 3.

Two differing statistical tests were then conducted to find any numerical outliers within the data:

Cochran's test measures within-laboratory variability against the sum of variances for that material in all participating laboratories. However this criterion tests only for high values and so is a one-sided test for outliers. Application of this test to the data indicated the following outliers, circled in Figure 8(a) and (c):

- Laboratory 5 - Material 1,
- Laboratory 6 - Material 3.

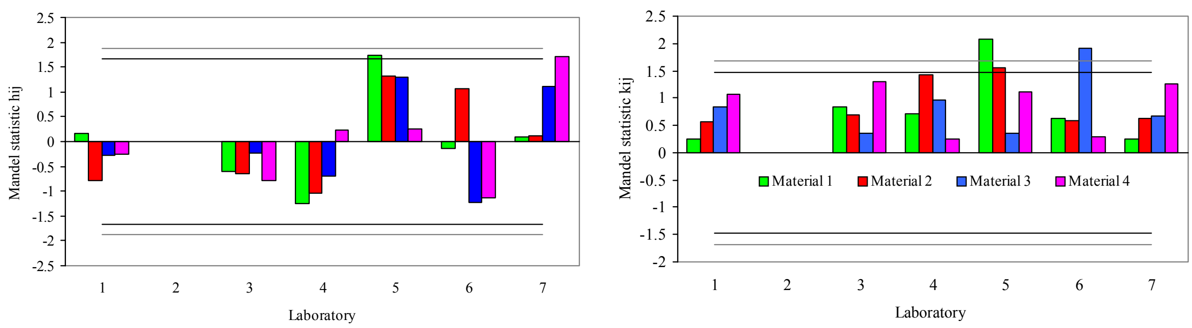


Figure 9(a)-(b)- Mandel's *h* and *k* statistics for all included laboratories, grey and black lines represent the 1% and 5% significance levels respectively.

Table 6 - Repeatability and reproducibility limits and standard deviations.

Material	Repeatability Conditions		Reproducibility Conditions		Mean σ_p (MPa)
	S_r	r	S_R	R	
1	30.8	86.2	57.1	160.0	606.0
2	15.1	42.2	40.0	111.9	418.0
3	15.0	42.1	44.9	125.6	257.3
4	21.2	59.3	33.1	92.7	297.7

Grubb's test measures the difference between the mean value from a laboratory against the average mean value of all the participating laboratories for a given material. Application of this test to the data indicated no stragglers or outliers.

Investigation of the specimens observed as failing the Cochran's test for variance showed physical evidence of the hardened bushes imprinted on them. This indicates that the specimens had not been positioned with the required clearance before testing, thus similar restraint to a torque bearing test was placed on the specimen producing higher strengths. These have been excluded from any further analysis.

Precision data

The repeatability and reproducibility of the pin bearing strength test method was then investigated, using the accepted data.

Repeatability, *r*, refers to tests that are conducted within the same test house using conditions that are as constant as possible:

- single operator,
- same equipment,
- tested in short time interval.

Reproducibility, *R*, refers to test that are preformed in a wide variety of conditions:

- different laboratories,
- different operators,
- different equipment.

Thus repeatability and reproducibility are two extremes, with repeatability measuring the minimum and reproducibility measuring the maximum variability in the precision of the results and therefore the test method. Table 6 details the repeatability and reproducibility, *r* and *R*, of the specimen manufacture and testing; the repeatability and reproducibility standard deviations, s_r and s_R and the general mean. Table 7 represents this same data as a percentage of the mean pin bearing strength, σ_p.

Table 7 - Repeatability and reproducibility data expressed as percentage of the mean.

Material	Repeatability Conditions		Reproducibility Conditions	
	S_r (%)	r (%)	S_R (%)	R (%)
1	5.1	14.2	9.4	26.4
2	3.6	10.1	9.6	26.8
3	5.8	16.4	17.5	48.8
4	7.1	19.9	11.1	31.1

Additional tests

Two further issues highlighted by participant feedback and information obtained from this round-robin were:

- Criticality of the hole position.
- Effect of drill type/hole quality on bearing strength.

Additional tests were undertaken at NPL to investigate these. Tests were conducted on a single material similar to material 1, due to the limited time available. This was selected as it was the most difficult to machine due to its brittle nature. Although these issues were raised during the round-robin exercise, it was felt that using a single operator to machine and test the specimens would remove any variability seen in the results so far.

An investigation into the effect of hole quality on bearing strength was performed using three different drill types: ball nose, klenk and dagger, shown in Figure 10 (a)-(c).

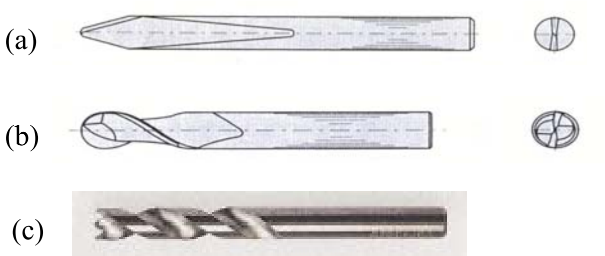


Figure 10 - Drill types (a) Ball nose, (b) Klenk, (c) Dagger.

Holes were drilled according to spindle speed and feed rates shown in Table 8.

Table 8 - Drill machining speeds and feeds.

Machining process	Drill Type	Speed (rpm)	Feed Rate (mm/min)	Backing material
CNC Vertical milling machine	Ball nose	3500	150	Glass epoxy
Pillar drill	Klenk	475	Manual ≈ 12	Glass epoxy
CNC Vertical milling machine	Dagger	3000	100	-

It can be seen from the results shown in Figure 11 that there is little difference in pin bearing strength for the three drill types.

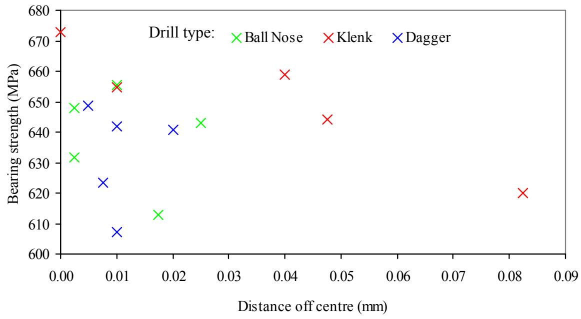


Figure 11 - Effect on bearing strength with different drill types.

Hole positioning was investigated by machining specimens using a ball nose drill with hole centre-line offsets of 0.5 and 1 mm compared with a control set of specimens drilled precisely on the specimen centre line. Results from this are shown in Figure 12.

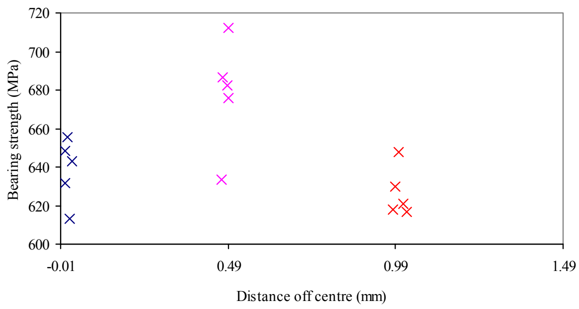


Figure 12 - Effect on bearing strength with different hole off-centre position.

From this it can be seen that holes drilled within 1 mm of the specimen centre line show no marked differences in pin bearing strength.

Concluding remarks

The data presented in this report suggests the following:

- The test method reproducibility and repeatability is generally good, with the highest variability associated with Material 3 (CSM).
- The current procedure highlighted a problem with regard to the positioning of the bearing hole to the accuracy required. A recommendation can be made from the data obtained that this tolerance be relaxed to a more readily achievable ± 0.25 mm.
- The round-robin confirmed findings from previous exercises that the placement of the hardened bushes in the specimen test fixture is critical and can have a marked effect on the failures loads and modes, and thus the repeatability and reproducibility of the results.
- The mean bearing strength values obtained from this round-robin are comparable to other data obtained for this test method from similar materials [3].
- It was proven that employing different drill types to machine the specimen loading the hole made no difference to the results provided a good quality hole was machined, with no visible damage to the specimen. Work however was not conducted to ascertain what effect a poor quality hole had on the bearing strength.
- A recommendation can be made that a separate rig with bushes fixed in position be used for pin bearing testing instead of using the more versatile test rig used in this exercise designed for both torqued and pin bearing test methods.
- The test method reproducibility and repeatability values are an improvement on the previous round-robin conducted on pin bearing[3].

References

1. *ISO 5725-2:1994, Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*
2. *D5961/D5961M-01e1, Standard Test Method for Bearing Response of Polymer Composite Laminates*
3. *J. Niklewicz and G.D. Sims, Round-robin Validation Exercise for Three Structural Test Methods, NPL Measurement Note CMMT (MN) 043*
4. *A. Davies, A. Foreman, R.M. Shaw and G.D. Sims, Fibre Reinforced Plastic Composites - Machining of Composites and Specimen Preparation, NPL Measurement Good Practice Guide No. 38, 2001*

Acknowledgements

The work reported in this Measurement Note was carried out by NPL as part of the "Measurements for Materials Systems" (MMS) programme funded by the United Kingdom Department of Trade and Industry. The authors acknowledge the contribution of their colleagues Dr W R Broughton and Miss M J Lodeiro.

The authors would also like to express their gratitude to the participants for their time and effort without which the round-robin would not have been possible, and to Fibreforce Composites, McLaren and Permali Gloucester for supplying the materials.

The participants in this inter-laboratory exercise were:

- Airbus UK
- Aviation Enterprises Ltd
- CTL (Composite Testing Laboratories) Ltd
- Fibreforce Composites
- INSYS Ltd
- National Physical Laboratory
- Slingsby Aviation Ltd

For further information contact:

Dr Graham D Sims
NPL Materials Centre
National Physical Laboratory
Queens Road
Teddington
Middlesex
TW11 0LW
Direct line: 020 8943 6564
Facsimile: 020 8943 6820