NLR TECHNICAL PUBLICATION

TP 91290 L

GARTEUR COMPRESSION BEHAVIOUR OF ADVANCED CFRP

by

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This paper has been prepared in the format required for AGARD workshop "Utilization of advanced composites in military aircraft", San Diego, October 1991

Division: Structures and Materials

Prepared: WGJ'tH/

Approved: RJHW/

Completed : 910723

Order number: 043.022

Typ. : JvE

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(8 pages in totaal)

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SUMMARY

The susceptibility of currently used CFRP to impact damage has stimulated the development of improved composites. This new generation of composites usually shows increased toughness and damage tolerance as well as improved tensile performance. This is generally not matched, however, by a similar improvement in compressive properties which then becomes a limiting design factor.
For improvement of the compressive strength a better understanding of the compressive failure behaviour is needed. This aspect is part of a cooperation programme within GARTEUR*. The compressive failure behaviour is being examined at the microscale level (single fibre and bundle tests) and at coupon level.
For experimental verification of failure models special attention has to be paid to compressive test procedures in order to archieve optimal strength values with a minimum of scatter. To evaluate the most appropriate compression test method a Round-Robin test programme was performed on unidirectional laminates of the materials T800/6376; HTA7/982; HTA7/6376; T800/5245; T800/924; IM400/5245 and T400/6376.
In the present paper the results of the Round-Robin test programme are discussed.

Keywords: carbon fibre reinforced plastics, compressive strength, test methods.

1 INTRODUCTION

The low resistance to impact damage of carbon fibre reinforced plastics (CFRP) is one of the major restrictions for applications of CFRP in load-bearing primary aircraft structures. In current composite structures the designer is forced to restrict design loads to levels far below the capabilities of the composites in order to compensate for possible impact damage. Effects of low velocity impacts (e.g. dropping tools) have been widely described in the literature (Ref. 1).

Large static strength reductions can be expected without a visible indication of the damage.The effect is most significant for compression loaded structures where internal delaminations contribute to premature local buckling of the composite. The consequences of this susceptibility to impact damage is that design strain levels of only 3000 μ strain and 4000 μ strain are used for compression and tension loaded components in current composite structures.

This susceptibility of CFRP to impact damage has stimulated the development of improved composites. It was recognized that impact resistance could be improved by applying fibres with a higher tensile failure strain in combination with a tough matrix. Evaluation of a number of these improved composites in the framework of GARTEUR cooperation revealed an increased tensile performance which was not generally matched by a similar improvement in compression properties (Ref. 2). The reason for this is that a higher toughness of a resin is frequently coupled with a lower modulus, and lower modulus may lead to a lower compressive strength for the undamaged composite. Further, some higher fracture strain fibres are smaller in diameter, which can promote microbuckling.

To predict changes in compressive strength as a result of changes in constituent properties more accurately, a better understanding of the compressive failure behaviour is needed. This could be achieved by studying and modelling the failure process and by experimental verification. The most critical parameters and failure modes have to be identified to enable the development of composites with better compressive strengths.

A GARTEUR cooperation programme was initiated to enable better understanding of compressive failure mechanisms. The participating members are the national European aerospace institutes DLR, ONERA, RAE and NLR, and the aerospace industries, Fokker, DA and Westland Hel. The objectives of the cooperation are

- To improve the understanding of the mechanisms by which compressive failure is caused in relation to critical parameters.
- To develop and correlate failure models with experimental data.
- To formulate guidelines for CFRP with a higher compressive strength.

Verification of improved compressive performance should, in fact, be done on a structural level but compressive failure models should be verified on the lowest material level, that is, in the unidirectional ply. For this particular purpose a Round Robin Programme on compression testing was performed first. The main goal of the test programme was to examine whether the current test methods can be used for experimental investigation of the effect of changes in constituent properties on the compressive strength.

In the present paper the results of a Round-Robin compression test programme are discussed. Compression tests were carried out on seven types of unidirectional and three multidirectional CFRP's. In this manner the best performance is evaluated not only in assessing strength values but also in ranking of materials. The latter aspect is of importance when differences in strength between basic and improved material systems have to be established.

2 MATERIALS AND EXPERIMENTAL PROGRAMME

The materials selected for this investigation were 7 advanced CFRP's. Each participant moulded

* Group for Aeronautical Research and Technology in Europe, a cooperation agreement between the Governments of France, Germany, The Netherlands and United Kingdom

unidirectional laminates* of one specific material and distributed pieces of the u.d. laminate among the other participants for compression testing. Three partners also tested multidirectional laminates. Table 1 shows the materials involved and the lay-up for the multidirectional laminates.

* Laminates were processed in accordance with the specifications given by the manufacturer. After moulding the laminates were C-scanned to guarantee that void-free laminates were used in the test programme.

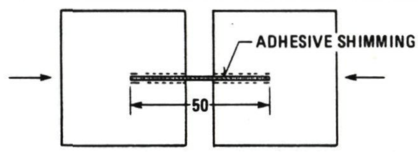
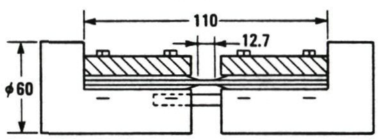
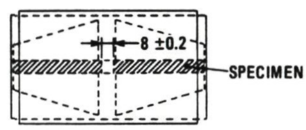
In the Round-Robin test programme about 6 room temperature compression tests were performed on each material. The compressive strength was calculated for nominal and actual specimen thicknesses. Nominal thicknesses of 2 mm and 3 mm were used for unidirectional and multidirectional laminates, respectively. For specimens with strain gauges the secant E-modulus was determined for the strain range $\epsilon = 0.1$ to 0.5 %

$$\left[E = \frac{\sigma(\epsilon=0.005) - \sigma(\epsilon=0.001)}{0.004} \right].$$

TABLE 1
Overview of materials used for Round-Robin compression tests

unidirectional laminates		multi directional laminates	
moulded by	material code/manuf.		
ONERA	T800/5245 BASF	WHL	HTA/982 $(0, 90, \pm 45)_{s2}$
RAE	T800/924 Ciba Geigy Fibredux	RAE	T800/924 $(\pm 45, 0, 90)_{3s}$
Fokker*	T800/6376 " " "	NLR	T400/6376 $(45, 0_2, -45, 0_3, -45, 0_2, 45)$
NLR	T400/6376 " " "		
DA	HTA7/6376 " " "		
WHL	HTA7/982 ICI Fiberite		
DLR	IM400/5245 BASF		

* Aerospatiale moulded the laminates and sent them to Fokker for distribution and testing

PARTNER	SPECIMEN TYPE		TEST METHOD
ONERA*	L x W mm 10 x 10	• NO TABS • END LOAD INTRODUCTION • TEST RATE 1 mm/min	
RAE	10 x 10	• Al-TABS, STRAIGHT, t=0.9 mm • CLAMPING LENGTH 12 mm • SPECIMEN ADJUSTMENT WITH ADHESIVE SHIMMING	MODIFIED CELANESE CONICAL WEDGES
FOKKER	12.7 x 6.35	• GLASS TABS TAPERED • CLAMPING LENGTH 16 mm	CELANESE CONICAL WEDGES
NLR *	12.7 x 6.35	• GLASS TABS TAPERED • END LOAD INTRODUCTION • CLAMPING LENGTH 16 mm • TEST RATE 1 mm/min	
DA	8 x 6.35	• MACHINED SURFACE • CARBON ±45 TABS CO-CURED, 1 mm • CLAMPING LENGTH 12.7 mm • TEST RATE 1 mm/min	MODIFIED CELANESE RECTANGULAR WEDGES 
WHL	10 x 10	AS RAE	STANDARD CELANESE
DLR *	8 x 6.35	• GLASS FABRIC TABS • NOT TAPERED • CLAMPING LENGTH 12.7 mm	MODIFIED CELANESE AS DA

** SPECIMENS PROVIDED WITH 2 STRAIN GAUGES*

L = FREE LENGTH
W = SPECIMEN WIDTH

Fig. 1 Test methods and used specimen type (u.d. material)

3 COMPRESSION TEST METHODS

3.1 U.D. Laminates

Each partner in the compression test programme used his own compression test method and specimen type. These test methods are frequently the result of an evaluation of many years for obtaining the best test method. This has unfortunately not resulted in an unambiguously accepted test method.

In figure 1 detailed information is given on the used test methods and specimen types. It is seen that the Celanese test fixture (standard or modified) is used most frequently: by RAE, DA, DLR, Fokker and WHL. At ONERA the compression specimens are fixed in steel clamping blocks using adhesive shimming. The NLR used a simplified IITRI based test fixture with load introduction through the specimen ends.

The compression test specimens involved were quite different concerning free gauge length, length between clamping, and specimen width. Furthermore different tab materials, chamfered or not, were applied. The free gauge length of the DA specimens is achieved by machining of the bonded tabs into the base material, see figure 2. This resulted in a specimen thickness that was about 20 % below the moulded laminate thickness, see specimen thickness in table 2.

3.2 Multidirectional Laminates

For multidirectional laminates the RAE and WHL used the CRAG test method (Ref. 3). An anti-buckling guide as shown in figure 3 was used to support the 250 mm long, 20 mm wide strip specimens. The NLR used the same specimen type and testing device as used for the u.d. laminates.

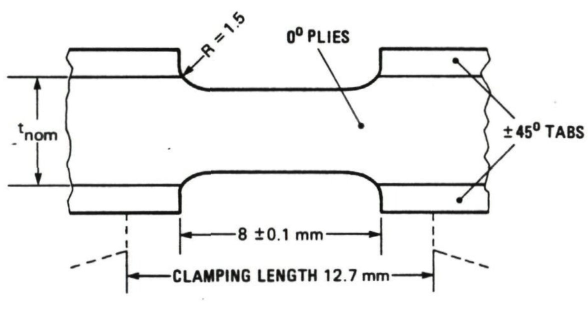


Fig. 2 Detail of DA compression specimen

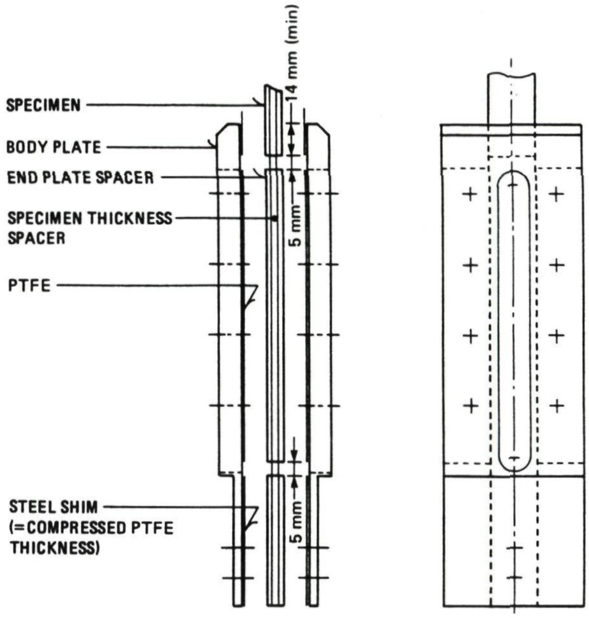


Fig. 3 Anti-buckling guide for multidirectional laminates (CRAG ref. 3)

4 TEST RESULTS

4.1 Unidirectional laminates

An overview of compressive strength and standard deviation is given in table 3. The strength values are based on actual and nominal thickness. The large scatter in mean compressive strength between the participants is striking. To visualize the effect of different test methods and test procedures including human factors on composite strength a comparison was made for the mean strength of the tested materials, see figure 4. Material T800/6376 was excluded since this material was not tested by all participants. Figure 4 shows that the highest strength values are obtained by DA with their test method and specimen type. Relatively low values were obtained by ONERA, RAE and Fokker.

Despite the large differences in strength, depending on test method, the material ranking for the tested materials was generally similar. This is illustrated in figure 5a,b for T800 composites and resin system Narmco 5245 with two fibre types.

TABLE 2
Specimen thickness: mean values and standard deviation

material u.d. / member	T800/5245	T800/924	T800/6376	T400/6376	HTA7/6376	HTA7/982	IM400/5245	number of specimens
ONERA	1.91 (0.04)	2.17 (0.11)		1.89 (0.01)	2.19 (0.03)	1.98 (0.02)	2.24 (0.02)	5
RAE	1.98 (0.03)	2.22 (0.02)	2.16 (0.02)	1.88 (0.04)	2.35 (0.11)	2.02 (0.05)	2.37 (0.05)	10
Fokker(AS)	1.95 (0.01)	2.13 (0.11)	2.02 (0.11)	1.81 (0.01)	2.03 (0.02)	2.04 (0.02)		10
NLR	1.92 (0.02)	2.22 (0.03)	2.09 (0.01)	1.87 (0.04)	2.09 (0.03)	1.97 (0.04)	2.24 (0.05)	6
DA**	1.62 (0.05)	1.50 (0.08)		1.59 (0.04)	1.91 (0.03)	1.81 (0.04)	1.43 (0.07)	6
WHL	1.86 (0.08)	2.12 (0.07)		1.85 (0.04)	2.28 (0.02)	1.91 (0.04)	2.23 (0.03)	6
DLR	1.90 (0.02)	2.14 (0.01)	2.00 (0.01)	1.84 (0.02)	2.06 (0.02)	2.02 (0.02)	2.19 (0.01)	6
mean val.*	1.92 (0.04)	2.17 (0.04)	2.07 (0.07)	1.86 (0.03)	2.17 (0.13)	1.99 (0.05)	2.25 (0.07)	

* without DA
** specimens were machined to a specific thickness

Elastic moduli determined for the strain range ϵ = 0.1 to 0.5 % are given in table 4. For the different testing techniques used by ONERA, NLR and DLR equal moduli were obtained with a low standard deviation. The relatively low strain to failure for materials tested by ONERA can be associated with the low compressive strength values given in table 3.

4.2 Multidirectional laminates

The compressive strength for two quasi-isotropic (QI) and one highly anisotropic laminate is given in table 5. There is a large difference between the RAE and WHL results. This is striking since the same CRAG test method was used. For the anisotropic

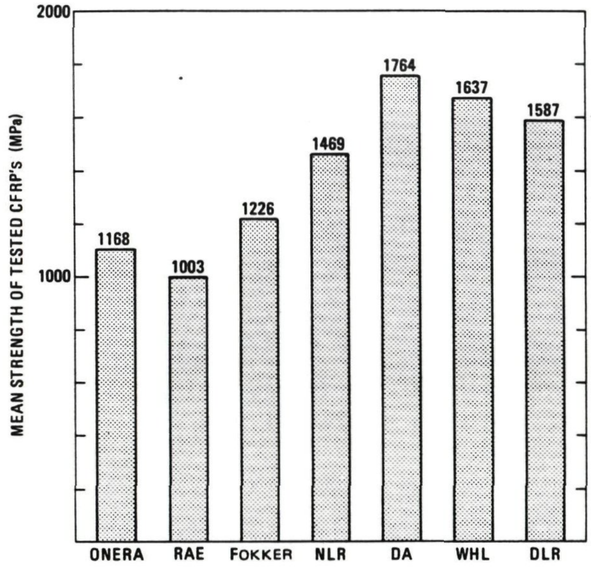
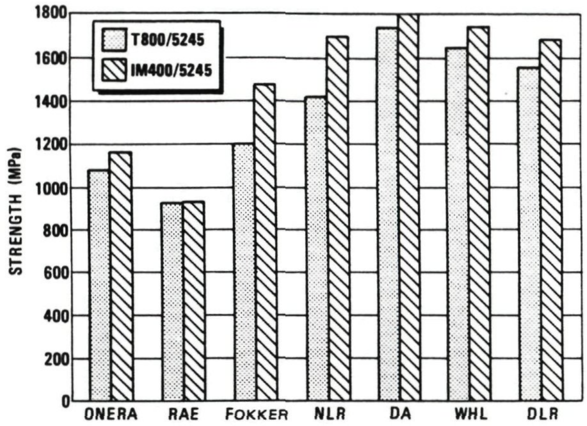
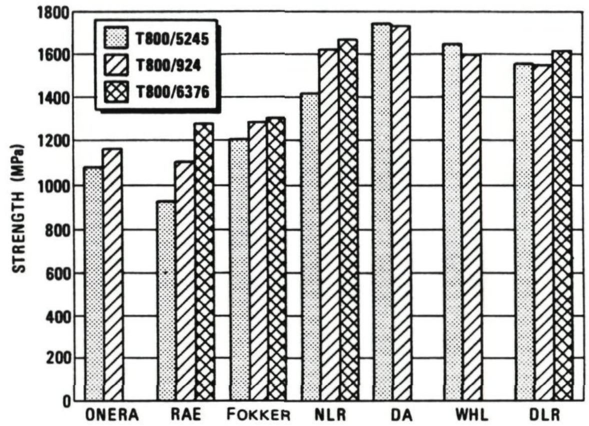


Fig. 4 Compression test performance of participating institutes and industries based on testing the same package of u.d. materials



a) Fibres T800 and IM400 in Narmco 5245



b) Fibre T800 in various resin systems

Fig. 5 Compressive strength of various fibre/matrix systems showing the same material ranking

TABLE 3
Overview of compressive strength (MPa) and standard deviation for u.d. laminates

material / member	T800/5245	T800/924	T800/6376	T400/6376	HTA7/6376	HTA7/982	IM400/5245	number of specimens
ONERA	1081 (115)	1166 (122)		1156 (43)	1270 (55)	1172 (89)	1163 (44)	5
	1132 (120)	1074 (113)		1222 (39)	1255 (61)	1181 (81)	1038 (39)	
RAE	927 (118)	1105 (103)	1278 (96)	970 (57)	1206 (118)	882 (106)	931 (100)	10
	937 (130)	994 (91)	1184 (92)	1031 (61)	1026 (85)	873 (98)	785 (77)	
Fokker(AS)	1204 (70)	1288 (129)	1303 (45)	1030 (19)	1169 (82)	1189 (53)	1478 (62)	5
	1228 (71)	1241 (61)	1293 (43)	1135 (17)	1165 (84)	1161 (84)	1298 (56)	
NLR	1422 (60)	1627 (45)	1669 (78)	1248 (64)	1457 (59)	1358 (54)	1703 (73)	6
	1479 (52)	1465 (46)	1594 (73)	1334 (74)	1392 (64)	1381 (53)	1518 (78)	
DA*	1745	1736		1470	2008	1827	1799	6
	1818 (163)	1600 (129)		1581 (107)	1851 (93)	1836 (134)	1599 (111)	
WHL	1651 (84)	1603 (135)		1613 (90)	1941 (42)	1477 (123)	1751 (250)	6
	1780 (107)	1510 (75)		1750 (87)	1700 (42)	1550 (124)	1570 (220)	
DLR	1558 (102)	1554 (116)	1619 (70)	1504 (122)	1674 (82)	1544 (107)	1689 (56)	6
	1640 (107)	1469 (96)	1619 (70)	1634 (77)	1627 (77)	1528 (112)	1555 (39)	
mean val.*	1370	1440	1467	1284	1532	1350	1502	44

(shaded) strength based on nominal thickness
(open) strength based on actual thickness

* for DA specimens the mean actual strength was transferred to nominal strength using the mean laminate thickness from table 1

TABLE 4
Compressive moduli (GPa, average values and standard deviation) and failure strains (%) for unidirectional laminates

material member	T800/5245	T800/924	T800/6376	T400/6376	HTA7/6376	HTA7/982	IM400/5245
ONERA	139 (2.0)	149 (3.8)		120 (1.1)	119 (6.3)	122 (2.7)	160 (1.8)
	145 (2.0)	138 (3.8)		127 (1.1)	117 (7.3)	123 (2.6)	143 (1.5)
	0.84	0.83		1.06	1.07	1.09	0.91
NLR	142 (1.5)	152 (3.9)	150 (4.3)	121 (1.4)	125 (3.9)	122 (1.6)	160 (2.6)
	148 (2.8)	137 (3.4)	143 (4.3)	129 (2.4)	119 (4.7)	124 (1.8)	142 (3)
	1.12	1.16	1.25	1.2	1.30	1.21	1.22
DLR	145 (4.0)	149 (5.5)	155 (1.0)	121 (1.3)	125 (2.7)	121 (1.6)	161 (1.8)
	152 (4.4)	139 (2.5)	155 (1.2)	132 (1.9)	121 (2.4)	120 (1.3)	147 (1.5)
ϵ	1.15	1.14	1.13	1.40	1.49	1.41	1.15

ϵ: mean of 2 strain gauges extrapollated to maximum load

modulus based on nominal thickness (shaded)
modulus based on actual thickness

TABLE 5
Compressive strength for multidirectional laminates (standard deviation between brackets)

material lay-up member	HTA7/982 $(0, 90, \pm 45)_{S2}$	T800/924 $(\pm 45, 0, 90)_{3S}$	T400/6376 $(45, 0_2, -45, 0_3, -45, 0_2, 45)$	number of tests
RAE	542 (28)	645 (46)	957 (72)	12
	534 (35)	621 (43)	982 (71)	
WHL	380 (66)	564 (83)	481 (157)	6
	342 (58)	538 (75)	531 (170)	
NLR	631 (17)	786 (27)	963 (36)	6
	578 (18)	755 (37)	1011 (38)	
$\bar{\epsilon}$(%)	1.46	1.77	1.32	
E GPa	43.5	50.5	89.3	
NLR $\bar{\epsilon}_{u.d.}$(%)	1.21	1.16	1.20	

strength based on nominal thickness (shaded)
strength based on actual thickness

laminate the NLR and RAE results were similar but for the QI laminates the NLR tests showed somewhat higher compressive strengths.

Comparison of strain to failure under compressive loading for multidirectional and u.d. laminates showed higher values for the multidirectional laminates (NLR results). This effect was most pronounced for the T800/924 material.

5 DISCUSSION

The main goal of the present investigation was to examine whether the compression test methods in use are suitable for experimental verifications in modelling compression failure. In this respect the results of comparative testing of different material systems with different compressive performance are valuable by-products.

The differences in strength values obtained for the same material system on specimens made from the same laminate must be attributable to differences in specimen type and size, the clamping and loading technique and to human factors involved in preparing and performing the tests. The latter aspect cannot be traced but the former two effects will be discussed in some detail.

As shown in figure 1, the free gauge length of the DA and DLR specimens was only 8 mm. This resulted in high strength values. The specimen length

TABLE 6
Mean strength values (MPa) for different fibre/matrix combinations

Resin / Fibre	5245	924	6376	982
T800	1370	1440	1467	
T400			1284	
HTA7			1532	1350
IM400	1502			

between the grips was 12.7 mm for both specimen types but since the DA specimens were machined to a thickness about 20 % below the moulded laminate thickness, the tabs were somewhat more effective in supporting the free gauge length than the tabs for the DLR specimen. This could explain the somewhat higher strength values for DA specimens. Fokker and the NLR used chamfered glass tabs and the length between the grips was 16 mm. As compared to the previous specimens, a lower compressive strength is not unexpected. The low values obtained by ONERA and the RAE cannot be explained properly. However, both institutes apply adhesive shimming for specimen adjustment and this might effect the stiffness of the gripping resulting in premature specimen failure. A more thorough evaluation of the effect of test conditions on failure strength is not possible due to lack of information on the failure modes experienced in the tests.

The compression test results for multidirectional laminates were rather confusing. No proper explanation could be given for the low strength values of WHL as compared to the RAE and NLR results. Strain measurements performed by the NLR showed higher failure strains for multidirectional laminates than for the u.d. laminates, table 5. Especially for the T800/924 material the difference was significant. This indicates that a uniform distribution of load bearing 0° layers between layers with a different orientation has a positive effect on the compressive strength (strain to failure). Further, it should be noted that the standard deviation for the tests on multidirectional laminates is significantly smaller than that for the tests on unidirectional specimens.

6 PRACTICAL SIGNIFICANCE OF THE RESULTS FOR FURTHER INVESTIGATION

The results of the Round-Robin test programme have shown the compressive strength to be strongly dependent on the specimen type and test method. However, the ranking in material strength as obtained by each participant was in general similar. This means that the effects of constituent properties on compressive strength essentially could be investigated by each member using his own test method. On the other hand, for investigation of the most significant parameters in modelling compression failure a low scatter in test results is desirable. It was shown that for multidirectional laminates higher compressive failure strains were obtained than for u.d. laminates with a smaller standard deviation for the strength. Therefore, use of multidirectional laminates should be considered for experimental verification in modelling compression failure.

By testing different fibre/matrix combinations in the present programme, information was obtained on the compressive strength performance of the tested materials. In table 6 the mean strength of the tested materials (from Tab. 2) is given in a format that enables direct evaluation of the best fibre/matrix combinations. The effect of matrix on the compressive strength of composites containing the same fibre is shown for T800 and HTA7 composites. Although the differences are not significant, the 6376 system seems to result in maximum strength values for the mentioned fibres. If different fibre types are combined with 6376, the best compression strength performance is obtained for the HTA7/6376 system.

7 CONCLUSIONS

In the framework of GARTEUR cooperation on compression behaviour of CFRP a Round-Robin testsprogramme was performed involving different test methods and seven modern unidirectional laminates. In addition, limited tests on multidirectional laminates were carried out. The main conclusions that can be drawn from this investigation are:

1. The compressive strengths of u.d. laminates varied significantly dependent on specimen types and test methods.
2. The material ranking obtained by the participants was more or less similar.
3. Testing of quasi-isotropic laminates resulted in an higher strain to failure than that obtained for u.d. laminates, with an smaller standard deviation for the compressive
4. The compression strength of HTA7/6376 was the most promising among the tested fibre/resin combinations.
5. It appears that despite conclusion 1, most of the compression test methods described in this paper can be used for experimental verification of compression failure models that incorporate changes in constituent properties. On the other hand, a low scatter of results is desirable for investigation of the most significant parameters in the modelling of compression failure.

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