TENSILE AND DIAMETRICAL COMPRESSION TESTS OF SIGMA SM1140+ FIBRES

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ABSTRACT

SiC Sigma fibres are commonly used as reinforcement in metal matrix composites. Prediction of composite behaviour requires a precise knowledge of the fibre behaviour. Fracture of Sigma SM1140+ fibres has been studied using tensile and diametrical compression tests. In this paper the effect of the test specimen length in the tensile strength is discussed, and a comparison between compression and corresponding tensile tests is presented. A model and equations incorporating the volume effect is described. This model allows to correctly predict the fibre behaviour in tension from modified Brazilian test results and vice versa.

INTRODUCTION

In multitude of engineering applications a material with high stiffness is desired. The material with the biggest elastic modulus is, undoubtedly, diamond, but its use is limited to available forms and high prices. The next candidate to provide great stiffness is SiC. Their properties are outstanding [1-3]. Its high elastic modulus and hardness are remarkable. Stiffness is the most important requirement in several aeronautical and space components in which weight must be kept to a minimum. In those mechanical parts in which deformation must be restricted, the introduction of this type of material as reinforcement fibres is enormously attractive.

The use of ceramic fibres, intrinsically brittle, entails dispersion in properties, greater than the habitual ones in metallic alloys, and size effect: the longer the fibre introduced, the bigger is the largest defect and, consequently, worse properties are obtained.

Tensile tests are usually employed, in the characterisation of the mechanical behaviour of brittle materials, although these tests have two problems when applied to brittle materials: i) great dispersion in measurements (surface defects in this type of test are critical), and ii) results are very sensitive to alignment of samples. This highlights the importance of settling an alternative method of test, such as the Brazilian Test or Disk Test [4-6]. This test consists on diametrical compression between two flat surfaces of the analysed material. In our case, however, it is difficult to obtain contact surfaces flat enough to avoid bending problems, because of the small diameter of the tested fibres. For this reason pieces about 40 mm long of Sigma fibres have been tested under compression of a knife against a plate (one of the test tools had the form of a wedge). These compressive tests, Brazilian disk tests, avoid the afore-mentioned problems (dispersion and alignment) and may be used instead of tensile tests. The results obtained by former tensile tests are reproduced avoiding mentioned problems.

MATERIAL

Tests were carried out with Sigma SM1140+ fibres produced by DERA (UK). These fibres have a 15 µm Tungsten core on which the main component material of the (β-SiC) fibre is grown by CVD. Finally a graphite coating is applied to improve the interface for later processing of the composite materials and to protect the fibre itself during handling. Nominal diameter of tested fibres is 104 µm, reaching 115 µm with the carbon coating.

EXPERIMENTAL PROCEDURE

Tensile tests

Samples of 14, 104 and 204 mm were prepared sticking both ends of each fibre to sandpaper with a contact glue, to avoid sliding between fibre and grips. The overall lengths between grips were 10, 100 and 200 mm, respectively.

Samples were tested at room temperature in an Instron electromechanical machine, with a 500 N load cell. Crosshead displacement rates were 0.05, 0.5 and 1 mm/min. for samples of length 10, 100 and 200 mm, respectively. Applied loads were sampled at intervals of 6 s.

Compression tests

Fibre samples about 40 mm long were chopped (note that length is not relevant in this kind of tests). Samples were diametrical compressed between a CW wedge and a hard steel plate at room temperature in an Instron electromechanical machine, with a 500 N load cell. Test displacement rate was 0.1 mm/min. The load and displacement were recorded as in the tensile tests.

RESULTS AND DISCUSSION

Tensile tests

All tested samples displayed linear elastic behaviour until fracture. Ultimate loads are shown in Table 1. Mean values, corresponding to each one of the tested lengths, as well as the coefficients of correlation for the normal, log-normal and Weibull distributions, are shown in Table 2.

TABLE 1

SIGMA SM1140+ FIBRE FRACTURE LOADS IN TENSILE TESTS

Test-piece id.	Fracture load (N)			Test-piece id.	Fracture load (N)			Test-piece id.	Fracture load (N)		
	10 mm	100 mm	200 mm		10 mm	100 mm	200 mm		10 mm	100 mm	200 mm
1	23.40	17.26	20.35	11	28.31	25.10	25.17	21	29.48	27.28	26.47
2	24.12	22.23	21.03	12	28.36	25.32	25.23	22	29.66	27.34	26.83
3	25.97	22.31	23.45	13	28.38	25.34	25.26	23	29.81	27.40	26.85
4	26.31	22.54	23.57	14	28.47	26.36	25.30	24	30.00	27.48	26.90
5	27.76	22.87	23.73	15	28.64	26.50	25.41	25	30.04	27.53	26.99
6	27.79	23.88	23.84	16	28.71	26.64	25.57	26	30.19	27.79	27.02
7	27.97	23.97	24.15	17	29.06	26.66	25.61	27	30.23	28.08	27.26
8	28.13	24.78	24.51	18	29.11	26.66	26.09	28	30.23	28.16	27.38
9	28.25	24.93	24.63	19	29.22	26.90	26.24	29	30.64	28.44	27.50
10	28.28	24.95	25.14	20	29.26	26.95	26.36	30	30.64	28.98	27.57
								31	31.22		

Figure 1 a) shows, in a normal plot, the cumulative distribution function (cdf) of the fracture loads for the three tested lengths (200, 100 and 10 mm). It is clear in these diagrams, that the experimental data fit neither to the normal distribution (straight lines on the diagram) nor to log-normal distributions, even when these distributions usually fit the behaviour of most brittle materials [7]. Figure 1 b) shows the cdf on a Weibull plot. It is clear, from Fig. 1 and Table 2, that Weibull distribution fit better the experimental results than normal or log-normal cdfs.

TABLE 2

SUMMARY OF TENSILE TESTS OF SM1140+ FIBRE FOR DIFFERENT SAMPLE LENGTHS

	10 mm	100 mm	200 mm
Fracture average load (N)	28.6	25.7	25.4
Normal correlation coefficient	0.938	0.934	0.950
Log-normal correlation coefficient	0.923	0.905	0.936
Weibull correlation coefficient	0.982	0.972	0.976
Weibull modulus (standard deviation)	19±3	16±3	17±3

Figure 2 collects the results from the three tested lengths on a cdf plot. Solid lines represent the predictions for the shortest fibres using the results for the longer fibres (200 mm). The prediction is given by:

$$F_\sigma^N = 1-\left(1-F_\sigma\right)^N \tag{1}$$

where N represents an N times longer fibre than the one that have been used to obtain the distribution function, F_σ [7].

Predictions obtained in Fig. 2 are reasonably promising, but they are limited to the tensile stress range observed for the fracture of the longest fibres (it is not possible to make probability predictions for loads that have not been observed in 200 mm long fibres). However, we can consider that when testing smaller lengths, it is the range of highest stresses and highest values for the cdf what is being sampled.

Figure 3 shows, on a Weibull plot, all the experimental results when the cumulative failure probability is normalised considering tested lengths. It is clear that the results fit reasonably well to a straight line, and therefore they correspond to a single Weibull distribution. Consequently, the following fitting to ultimate load in tension of the Sigma SM1140+ fibre is proposed:

$$F = 1-\exp\left[-\frac{L}{100}\left(\frac{P}{26}\right)^{19.6}\right] \tag{2}$$

where L is given in mm and P in N.

Figure 3 shows the experimental results (in open symbols) and the predictions (in solid line) obtained using Eqn. 2.

Samples are clamped to the test machine using emery-paper grips (square pieces of 20 × 20 mm); the fibres facing the paper side. As a result of the gripping system, it is questionable to what extent the fibre length, that is within the grips, is also being tested. Although not all the fibre length is uniformly tested, it seems reasonable that a given portion of the transfer length, within the grips, should be considered to obtain a reliable prediction. This effect will be particularly relevant for the shortest samples and almost negligible for the longest ones, since the length introduced in the grips is constant in all the tests.

Figure 4 also shows the prediction for a 20 mm fibre length (dotted line) that is equivalent to consider that the sample effective length is 5 mm per grip (about one fourth of the grip-embedded length) longer than the distance between the grips.

All observed fractures have been originated at the interface between the Tungsten core and the SiC. Fracture in SiC has a radial appearance with origin in the nucleus of W, see Fig. 5.

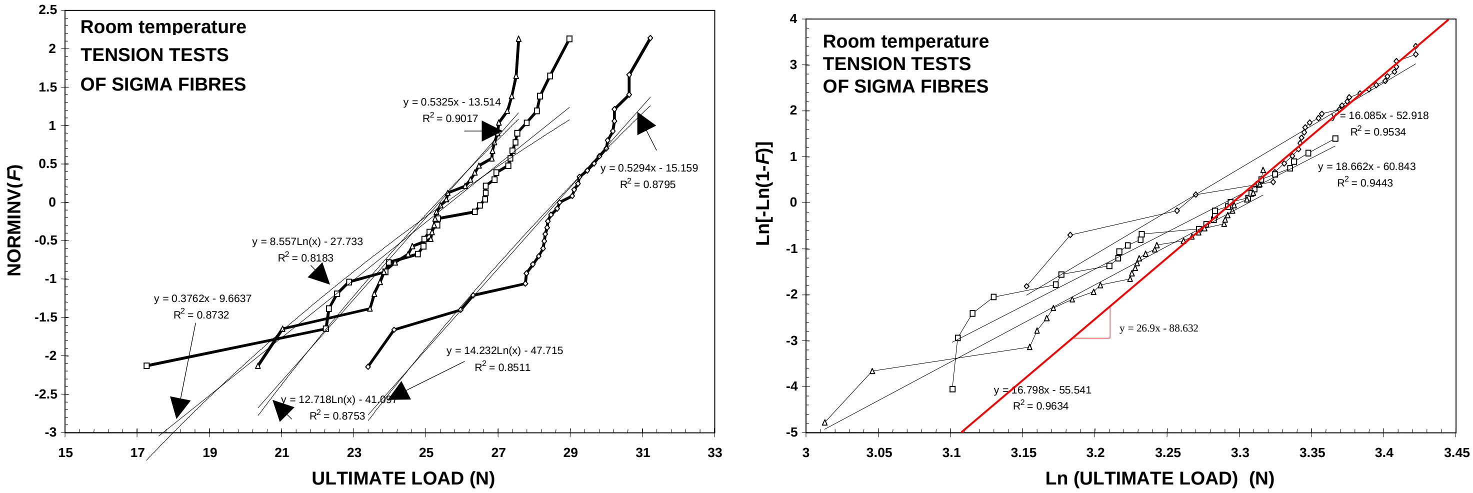

Figure 1: Cumulative distribution function (cdf) of the fracture loads **a)** on a normal paper (log-normal in solid lines) and **b)** on a Weibull plot. Fittings on individual tested lengths and on the whole set are represented

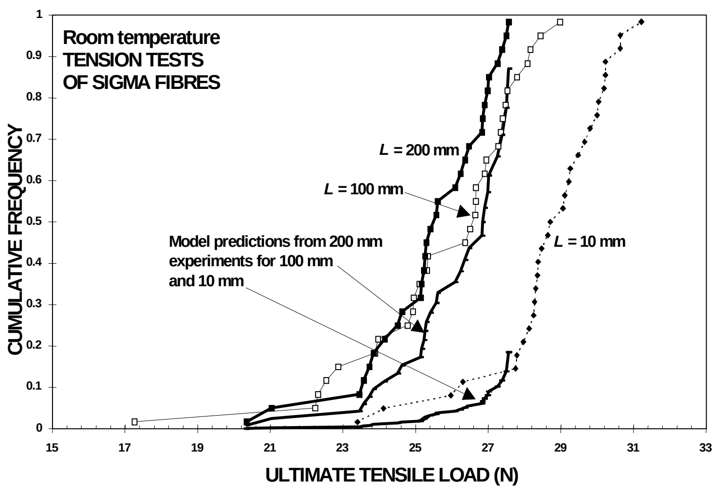

Figure 2: Cumulative distribution function (cdf) of the fracture loads of Sigma SM1140+ fibre for three sampled lengths. Predictions were computed for 100 and 10 mm (in solid lines) based on experimental data for 200 mm long fibres.

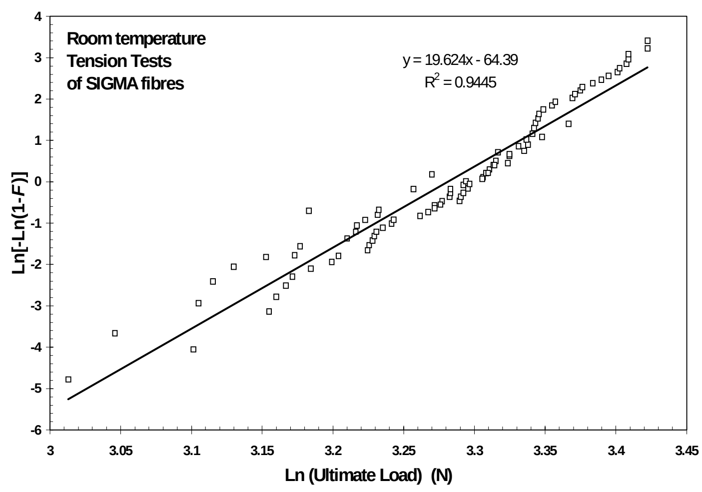

Figure 3: Fracture load cdf on a Weibull plot when frequency, F, is computed according to Sigma SM1140+ fibre tested length, Eqn. 2

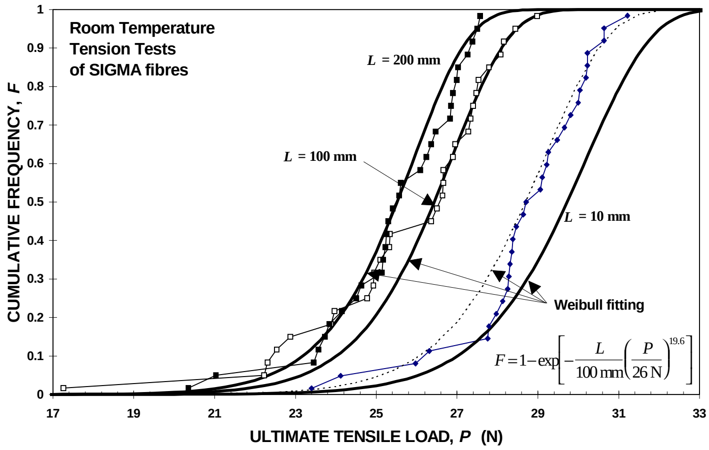

Figure 4: Cumulative distribution function (cdf) of the fracture loads for three different lengths of Sigma SM1140+ fibre. Tensile tests at room temperature, and predictions from Weibull fitting

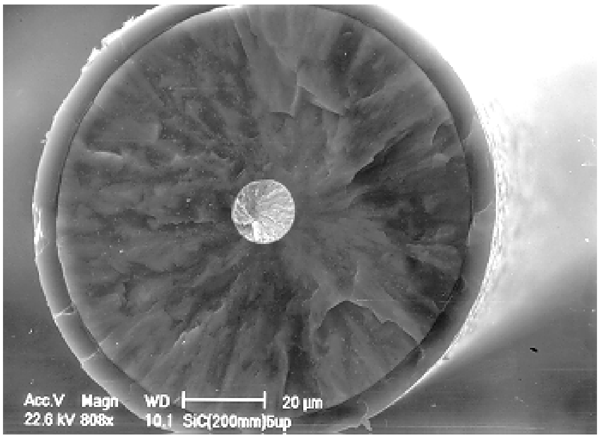

Figure 5: SM1140+ fibre fracture is initiated at the interface with the tungsten core and progresses radial in the SiC. SEM micrography

Compression tests

The stress state obtained in a diametrical compression test has been previously analysed by many authors [5,6]. A diametrical compression produces an almost uniform tensile stress in perpendicular direction to the one of the applied load; its value is given by:

$$\sigma_x = \frac{2P}{\pi d t} = \sigma_3 \tag{3}$$

and a compressive stress in all points that is three times the tensile one at the centre of the disk:

$$\sigma_y = -\frac{6P}{\pi d t} = \sigma_1 = -3\sigma_x \tag{4}$$

where P is the applied load, d is the disk diameter and t is its thickness.

Along the central vertical line, the compressive stress is given by:

$$\sigma_y = -K\sigma_x \tag{5}$$

where K changes from 3 at the disk centre to infinite (theoretically) at the ends. According to the maximum tensile strain fracture criterion for brittle materials, fracture occurs when the principal tensile strain (ε_3) exceeds the critical value:

$$\varepsilon_3 = [\sigma_3 - \nu\,(\sigma_1 + \sigma_2)]/E \tag{6}$$

In our case, $\sigma_2 = 0$, $\sigma_1 = -K\sigma_x$ and $\sigma_3 = \sigma_x$.

K is 3 at the centre and grows as we go depart from the centre. Thus:

$$\varepsilon_3\, E = \sigma_e = (1+\nu K)\,\sigma_x \tag{7}$$

Is the effective fracture stress, where ν is Poisson's ratio (0.16) and $K = \sigma_y/\sigma_x$.

In diametrical compression tests of Si_3N_4 disks, Ovri & Davies [6] found several fracture modes. In fact, two of them have been observed in Sigma fibres:

- normal fracture mode
- triple-crack fracture mode: the sample is broken in two or three pieces

Typical load-deformation behaviour of Sigma SM1140+ fibres has two stages (see Fig. 6):

- a normal mode load with corresponding tensile stress

$$\sigma = P/\pi dt \tag{8}$$

- a triple-crack mode load with corresponding tensile stress

$$\sigma = (P+2P_f)/2\pi dt \tag{9}$$

where P is the final load for the first stage, P_f is the ultimate fracture load, t is the mean width (20 μm) of the central region observed at the fracture surface, and d is the mean diameter (108 μm) of the fibres.

In Table 3, the first stage final loads, ultimate fracture loads and tensile stresses are presented. Effective stresses of 4.188 GPa (for $\nu = 0.16$) and 5.377 GPa (for $\nu = 0.3$) are obtained from the mean value of the former tensile stresses (2.83 GPa) and Eqn. 7.

If we want to compare this effective fracture stress with the ultimate tensile stress in tension tests it will be necessary to consider a size effect:

$$\sigma_{eq} = \left(\frac{V_D}{V_t}\right)^{1/m} \sigma_e \tag{10}$$

where

$$V_D = t(0.3d)(0.2d) \tag{11}$$

is the volume of the critical region, that is the one that would be affected by the origin of the fracture (the zone in which the effective stress ranges from the maximum to a 10% below this maximum value [5].)

V_t is the sampled volume in the tensile test (three lengths 10, 100 and 200 mm were tested) and m is the Weibull exponent (~ 15 from compressive tests, and ~ 18 from tensile tests.)

TABLE 3

FRACTURE LOADS IN DIAMETRICAL COMPRESSION TESTS OF SM1140+ FIBRE AND CORRESPONDING TENSILE STRESSES

P **(N)**	P_f **(N)**	$\sigma_c = (P+2P_f)/(2\pi dt)$ **(GPa)**
7	15	2.73
10	18	3.38
7.7	16.5	3.00
10.5		
9	16	3.02
6.5	11.25	2.14
9	12	2.43
8	17	3.09

Introducing the size effect, Eqn. 10, the results shown in Table 4 are obtained. It is found that diametrical compression tests results, once corrected by the size effect, agree with those obtained in tensile tests considering the Weibull modulus corresponding to compression tests and fracture in elastic mode (in good agreement with the fractography and the load-displacement traces).

TABLE 4

PREDICTIONS FROM DIAMETRICAL COMPRESSION TESTS AND COMPARISON WITH TENSILE TESTS RESULTS

Sample lengths (mm)	**10**	**100**	**200**
Actual ultimate tensile strength (GPa)	**3.10**	**2.80**	**2.77**
Fracture stress (m = 15, ν = 0.16)	2.33	2.00	1.91
Fracture stress (m = 15, ν = 0.3)	**3.00**	**2.57**	**2.45**
Fracture stress (m = 18, ν = 0.16)	2.57	2.26	2.18
Fracture stress (m = 18, ν = 0.3)	3.30	2.90	2.79

Fractographic analysis corroborates the considerations about fracture modes that were initially made from the load-displacement curves. Figure 6 shows the typical fracture surface that is obtained in this kind of tests. A central plateau is observed, as a result of triple fracture mode. In contrast, the fractography of a sample broken in simple mode is shown in Fig. 7, together with its load-displacement curve; a single stage is observed.

CONCLUSIONS

- Sigma SM1140+ fibre mechanical strength best fits to a Weibull distribution.
- A method to include different tested fibre lengths in distribution function is proposed.
- Model predictions fit reasonably well experimental results, varying tested fibre length by a factor of 20.
- Fractography indicates that tensile fractured fibres display a flat surface, perpendicular to tensile axis. SiC fracture is radial and it is initiated at the interface with tungsten core.
- Wedge-plate diametrical compression tests for Sigma fibres are simple and useful: ultimate tensile strengths are correctly predicted from diametrical compression tests. This is advantageous with respect to tensile tests for this type of materials, because of material saving and avoiding alignment problems.
- Two different failure modes are observed in the diametrical compression tests: triple-crack, which produces fracture surfaces with a central plateau, and simple fracture.

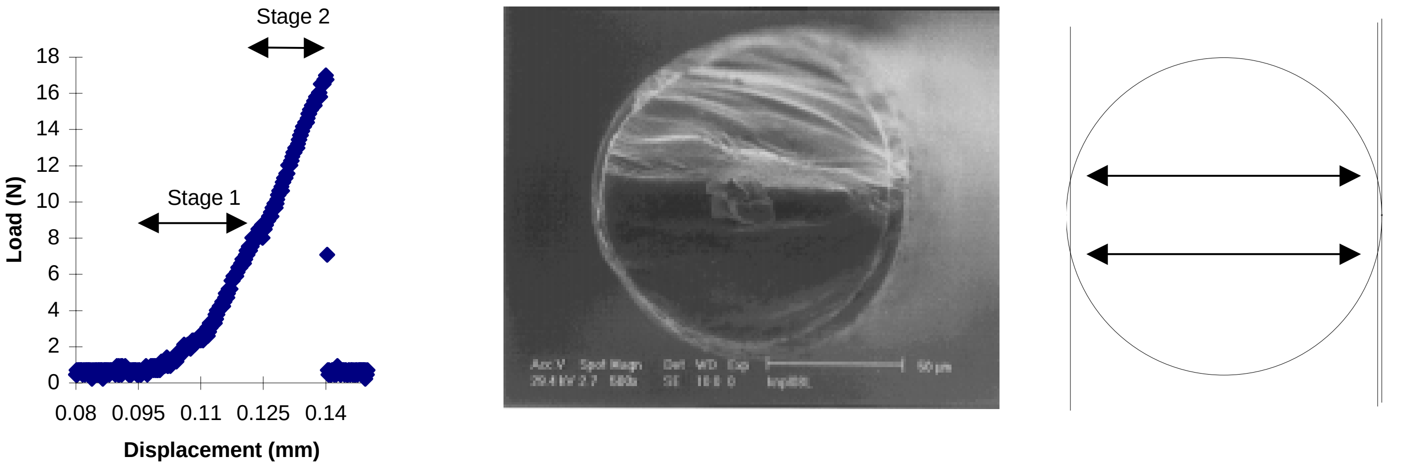

Figure 6: Load-displacement curve and SEM micrograph of a typical triple crack fracture mode from edge-plate compression tests.

Figure 7: Load-displacement curve and SEM micrography of a sample fractured at first stage. No triple-crack fracture mode is observed.

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