The Use of Carbon Fibre Composites in Divertor Target Plate Tiles and Structures

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ABSTRACT

Carbon-Carbon fibre composite (CFC), in the form of target plate tiles, is a standard material for intercepting conducted power in divertors. Its good thermal conductivity and ability to withstand high temperatures without melting give it an advantage over other materials for plasma facing components. Supporting structures are generally made from stainless steels or Inconels. In a radiating divertor, designed to operate with detached plasmas, heat is deposited by radiation on to both plasma facing components and supporting structures. Consequently CFC has been chosen as a structural material to overcome the limitations of metal structures. The various material properties such as thermal conductivity, strength, rigidity and anisotropic behaviour need to be taken into account for the design. Tests have been carried out on a range of CFC materials from different manufacturers to determine these properties. Thermal behaviour has been studied through power load tests in the JET Neutral Beam Test Bed. Structural properties have been measured through mechanical tests on prototype assemblies. Clamping and joining methods have been developed for the assembly of CFC plates to form structurally and thermally robust tile carriers for a radiating divertor.

INTRODUCTION

The selection of CFC material for use in a divertor depends upon a number of factors such as working environment, component application, mechanical stresses, thermal stresses and material properties. CFC has become a standard material for intercepting conducted power on to target plate tiles owing to its good thermal conductivity and shock resistance, low atomic mass and ability to withstand high temperatures without melting. The next design of the JET divertor is expected to operate with radiating plasmas which will subject the supporting structure to radiated powers up to 2MW/m^2. This level can lead to buckling and distortion in conventional metallic structures so consequently CFC material will be used for the supporting structure as well as for the plasma facing tiles.

INPUT PARAMETERS

The following parameters are assumed for purposes of assessing the performance of CFC material:

A. Conducted power on tiles $\leq$ 20MW/m2.
B. Conducted power on structure <6MW/m2
C. Radiated power $\leq$ 2MW/m2.
D. Max. allowable stress = 0.6 x minimum guaranteed failure value (table 1). Design factor $\approx$5.
E. Maximum allowable temperature $\leq$ 1500°C.

MATERIAL PROPERTIES

Manufacturers of CFCs tend to use in-house techniques for the production of their material and consequently a fairly wide range of properties is found between the different brands. The basic production technique consists of building up the material to the required thickness with woven carbon fibre sheets. This leads to 2-dimensional (2D) material but fibres can be introduced through the thickness of the sheet by dragging some fibres perpendicular to the layers by means of a "needling" process to produce 3D or quasi-3D material. Fullscale weaving through the layers is also possible. The next stage is to fill the voids between the fibres with carbon, either by pitch or resin impregnation or chemical vapour deposition (CVD). This results in a structure with low thermal conductivity but good strength. The thermal conductivity is enhanced by high temperature (>2000°C) graphitization in a furnace but with some loss of mechanical strength. These processes vary in detail between different manufacturers

The non-isotropic nature of CFC affects the material properties in the following way:

- Material strength depends upon the loading direction with the maximum strength along the fibre direction.
- Thermal conductivity depends upon the fibre direction, being highest along the fibres and lower across the fibres.
- Thermal expansion is dependent on the fibre distribution, being lower along the fibres and highest across the fibres.
- Bowing caused by thermal gradients under surface heating is dominated by thermal expansion with some contribution from thermal conductivity such that the bowing is maximum across and minimum along the fibre direction.
- Density variations are an unavoidable consequence of the carbon impregnation process and can affect strongly the thermal conductivity.
- Graphitization of the carbon improves the thermal conductivity but decreases the mechanical strength.

For any particular product there will be variations in properties owing to variations in the process conditions. Manufacturers are able to predict these properties reasonably accurately and consequently will guarantee minimum values Any design should be based on these minimum values.

MATERIAL SELECTION

The following requirements and considerations are relevant in the selection of materials for both tiles and structure:

Table 1: Thermal and Mechanical Properties of Some Carbon Fibre Composites Considered by JET for Fusion Applications

n/a means data not available or not asked for by JET.

		SEP N11	SEP N11-2	SEP A11	DMS 728	DMS 712	SGL 1502 ZV22	SGL 1002 ZV22	Le Carb Lorr A035
Tensile strength x (MPa) Room Temp	Typ	40	40	75	70	70	n/a	n/a	n/a
	G min	34	35	n/a	n/a	n/a	n/a	n/a	n/a
Flexural Strength (MPa) Room Temp	Typ	80	80	150	105	105	200	80	n/a
	G min	48	70	n/a	85	85	150	70	60
Interlaminar shear strength (MPa) Room Temp	Typ	18	20	30	13	10	8	8	n/a
	G min	14	15	n/a	10	7	7	7	n/a
Ther. Exp. Coeff x, y/z (10^{-6}) RT to 300°C	Typ	2/2	2/2	<2	0/10	0/12	-0.5/12	-0.5/7	1.0/1.5
	G max	3/3	3/3	n/a	0.5/12	1/15	-0.7/15	-0.7/10	2.0/3
Thermal conductivity x, y/z ($Wm^{-1}.k^{-1}$) 300°C	Typ	120/90	55/40	18/12	150/160	210/60	190/22	125/30	170/n/a
	G min	105/80	50/35	n/a	110/145	140/40	170/20	115/25	150/145
Youngs modulus x, y/z (GPa) Room Temp	Typ	20/15	16/12	25/12	30/30	30	120/n/a	28/n/a	n/a
	G min	n/a	n/a	n/a	n/a	n/a	90/n/a	25/n/a	n/a
Elec. Res. x, y/z μΩm Room Temp	Typ	6/10	17/25	n/a	n/a	4/13	4/n/a	25/n/a	n/a
	G min	n/a	n/a	n/a	n/a	n/a	n/a	7	n/a
Type		Needled	Needled	Quasi 3D	2D	2 D	2 D	2D	Quasi -3D

- Specific gravity >1.6 to minimise both deuterium absorption and outgassing as well as to maximise the strength and thermal conductivity.
- Full graphitization of the impregnated carbon at temperatures >2000°C to minimise the deuterium absorption and outgassing while increasing the thermal conductivity. The decrease in strength as graphitization proceeds is unavoidable.
- Differences in thermal conductivity and strength along the three axes will influence the way both mechanical and thermal loads can be applied to the material. Table 1 gives manufacturers' minimum guaranteed values and the average values for some of the materials tested at JET. A point worth noting is the link between high thermal conductivity in the fibre directions for the 2D materials and the lower thermal conductivity and lower strength perpendicular to the fibre direction. In the case of the 3D or quasi-3D materials, the increase in strength and thermal conductivity along the third axis leads, in general, to a consequent reduction in these properties along the other axes. The consequence of this is that the 2D materials would be the natural choice where high thermal conductivity is essential and that 3D materials are more suitable for structural applications where mechanical loads appear on all axes. One of the main challenges when working with 2D materials is ensuring that mechanical stresses in the cross-fibre direction do not exceed the relatively low allowable values.
- Resistance to thermal shock, especially in tile material, is essential. Experimental studies at JET on a range of CFC materials [1] have shown that these materials can withstand much higher flux levels than expected, based upon finite element analysis using mechanical data. Information in this area is limited and tends to be classified in military areas.
- Bowing of CFC material under non-uniform heating is mainly a function of the expansion coefficients. Two-dimensional material has significant differences between the bowing in the directions along and across the fibres. This can affect strongly the choice of fibre direction for tile applications. If, for example, conducted power is intercepted at a very shallow angle, say <2°, than a large bowing effect will increase the interception angle over the front half and decrease it over the rear half of the tile. In this case the preferred fibre direction would be in the direction of the incoming power to minimise the bowing effect. For large interception angles, the bowing effect becomes negligible.
- Impurity levels in the CFC need to be kept as low as possible to avoid contamination of the plasma.
- Electrical conductivity is a factor in the generation of electro-magnetic forces on tiles and structures but generally is of secondary importance in material selection compared to other properties such as thermal conductivity and strength. The highest forces on divertor tiles and structures come from halo currents [2] reacting with the poloidal and toroidal magnetic fields.

These considerations of material properties and expected thermal and mechanical loads on the next JET Divertor design have led to the choice of Dunlop DMS 712 (2D) material for the tiles and Sepcarb N11 and N11-2 (3D) material for the carriers. The fibre direction in the tiles will be into the thickness for good thermal conductivity and either poloidal or toroidal, depending upon the requirement for low thermal expansion and bowing. The uniformly distributed strength of Sepcarb N11-2 makes it suitable for carrier construction but the greater thermal conductivity, despite the lower strength, of N11 dictated its use in areas of high radiated or conducted power. A typical application is a protection rib shown in figure 1 where it can intercept conducted power up to $6MW/m^2$ for 10 seconds. The corresponding temperature contours at the end of such a pulse have been computed with ABAQUS and are shown in figure 2. The maximum surface temperature is ≈1100°C.

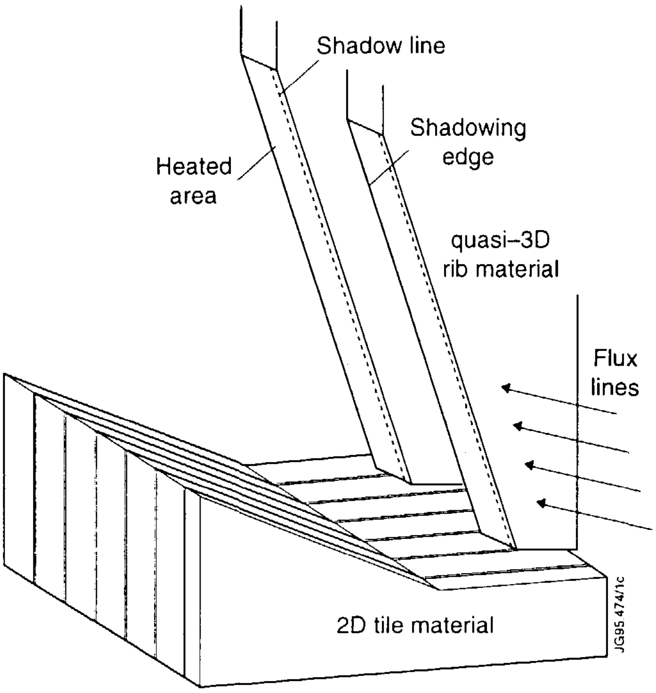

Fig.1: Carrier protection ribs.

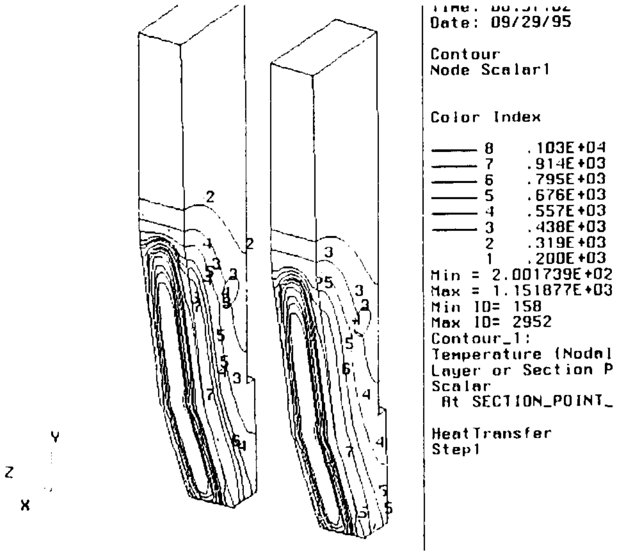

Fig.2: Temperature contours on protection ribs

FIXING AND JOINING TECHNIQUES

The most common technique for attaching tiles inside the JET torus has been through a single central screw fitting. A threaded metal insert is screwed into the rear of the tile and pinned against rotation. This system is suitable only for 3D material or 2D materials with the thread axis perpendicular to the fibre plane if a large bending moment is applied during clamping. The tile attachment, shown in fig. 3, was tested in 2D material with the thread axis parallel to one fibre direction. The tile was supported at each corner and pulled down at the centre. The combination of bending moment and hoop stress across the thread led to inter-laminar splitting of the tile at a load on the insert of 6.4KN. A tile fixing method was developed that would not apply a bending moment across the fibres. Figure 4 shows the chosen dumbbell system which moves the load points to the outside of the tile, in line with the corner contact pads. The bending moment is applied in the strong fibre plane and removed from the cross-fibre direction. Additional tie-rods in tension across the fibres maintain the geometric integrity in the case of thermally induced cracks.

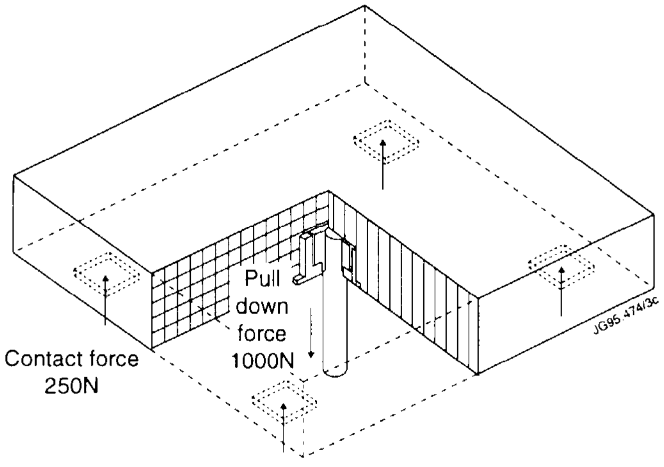

Fig.3: Central tile fixing.

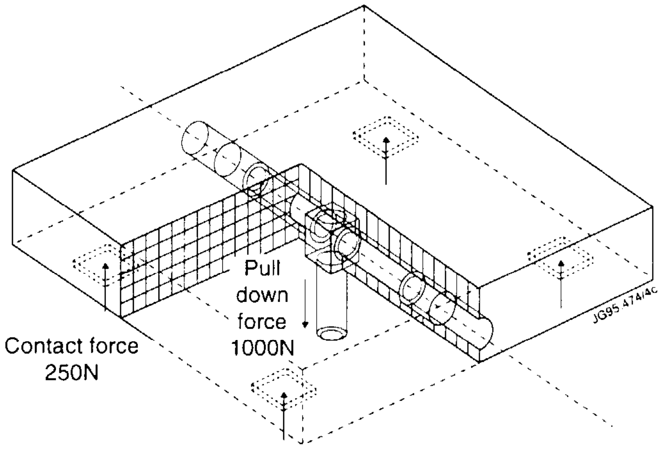

Fig.4: Dumbbell tile fixing.

Construction of a carrier requires a different joining technique. Tapping threads directly into CFC is feasible but the fibrous, anisotropic nature of the material leads to chipping of the threads. Consequently a barrel nut and bolt system, as shown in figure 5 has been tried successfully. In general an M6 bolt is made from Nimonic 80A and a barrel nut from aluminium-bronze, torqued to 10Nm, to produce a non-seizing combination. Certain areas under high thermal load can reach temperatures above the safe value for al-bronze and alternative materials such as Inconel and CFC are being tested.

THERMAL AND MECHANICAL TESTING

Tile material from 4 European manufacturers was subjected to high power load testing in the JET Neutral Beam Test Bed [1]. The 2-D materials developed cracks in the fibre planes at temperatures in excess of 2000°C but this did not affect the tile performance with the tie-rods maintaining the tile geometry. The 3-D materials remained crack-free but were not tested to the same level as the 2D material. Mechanical testing of the dumbbell fixing system was carried out to

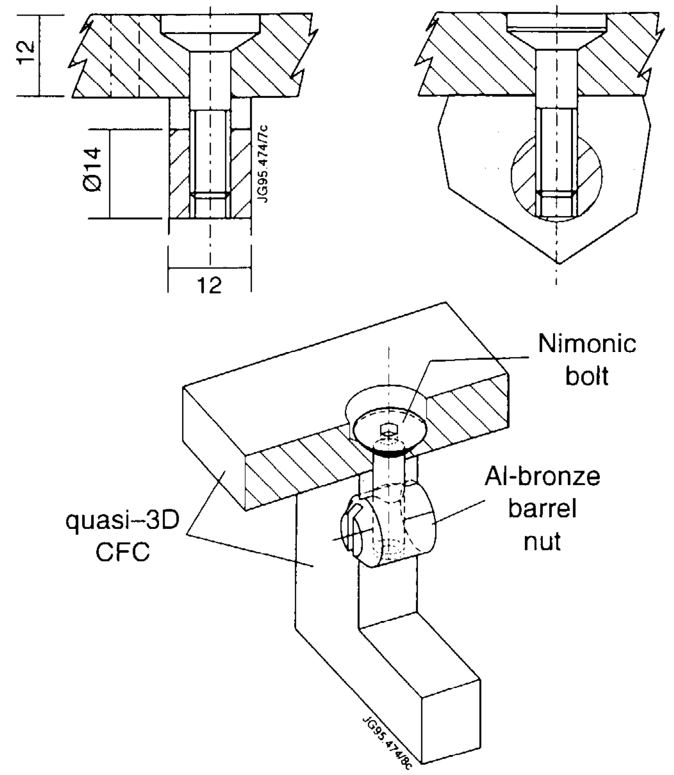

Fig.5: Barrel nut and bolt fixing.

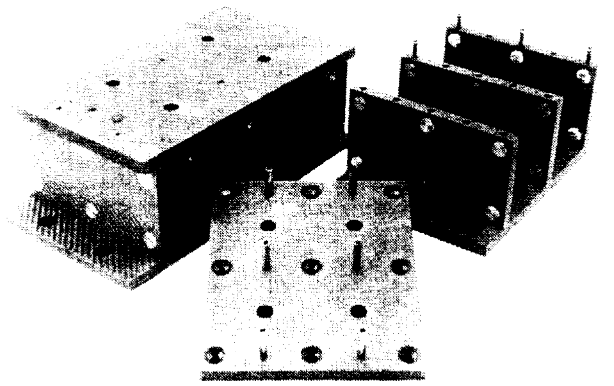

Fig.6: Prototype model structure.

check the tile behaviour under halo current loads. At a load of 13.7kN the dumbbell deformed plastically but the tile remained intact. Mechanical testing of a prototype model structure from Sepcarb A11 was carried out to study the behaviour of the barrel nut bolting system under bending and tensile loads. Figure 6 shows the model in component and assembled form. The first bending test applied equal and opposite forces to the upper and lower plates to induce an S-bend in the vertical ribs. The second bending test applied a bending moment about the lower barrel nut joints. Figure 7 shows the load/deflection curves for the two cases. An approximately linear behaviour is seen up to forces of 6KN and 3KN respectively, estimated to be about 7 times greater than for the worst-case disruption. A third test to failure checked the pull-out force for a barrel nut in a 12mm CFC plate. The result is shown in figure 8. The material failed in tension across the minimum section above the insert.

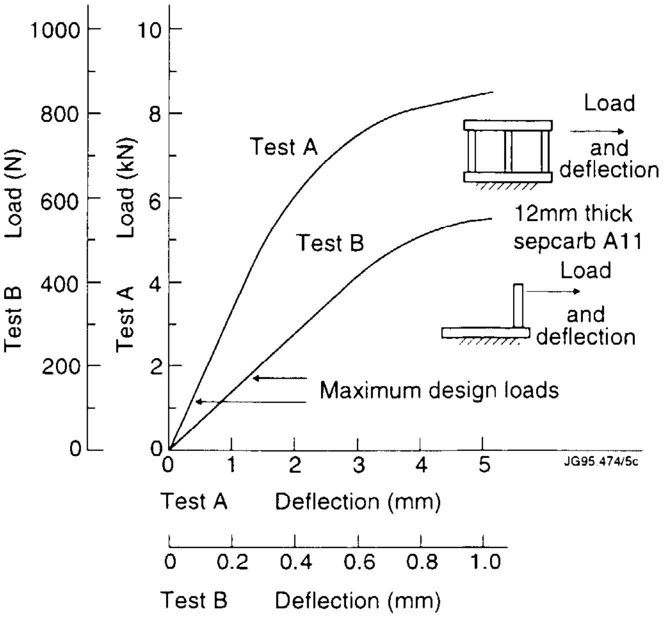

Fig.7: Bending test on bolted assemblies.

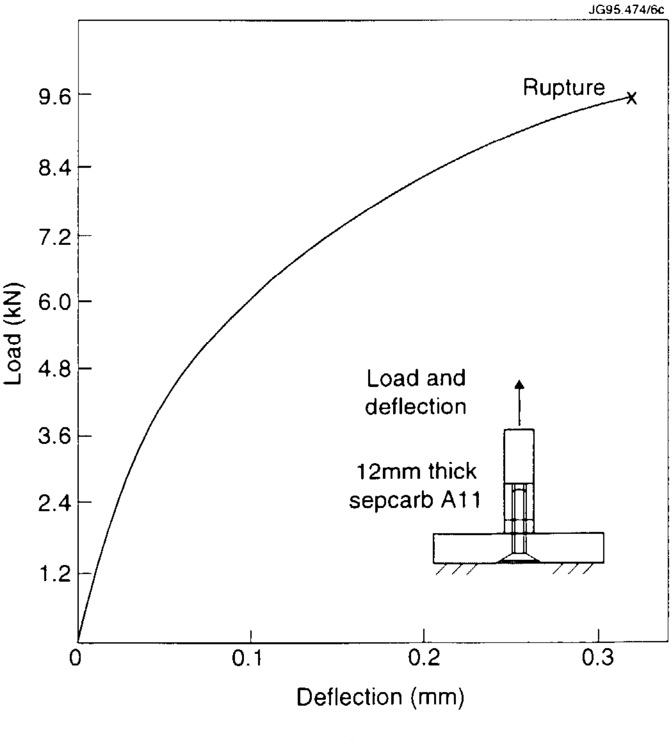

Fig.8: Pull-out test on barrel nut/bolt fixing.

REFERENCES

[1] M.A.Pick et al, "Large carbon fibre reinforced carbon tiles for a Mark II divertor in JET", Journal of Nuclear Materials 220-222 (1995) 595-600.

[2] M.A.Pick, P. Noll, P. Barabaschi, F.D. Marcus, L. Rossi, "Evidence of halo currents in JET", 14th SOFE, San Diego 1991, pp. 187-190.