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# Through-thickness compressive strength of carbon–phenolic woven composites

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**Abstract**

Carbon–phenolic woven composites are increasingly employed as the material for the heavy-duty journal bearings. Since the through thickness compressive strength (TTCS) is important for the heavy-duty bearing, in this paper, the effects of lay-up angles and specimen thickness of woven composites on TTCS were investigated for the efficient design of carbon–phenolic woven composite bearings. From the experiments and FEM analysis, it was found that the TTCS of the carbon–phenolic woven composite is much dependent on the stacking sequence rather than composite thickness because different stacking sequence produced much different interlaminar stresses.


*Keywords:* Through thickness compressive strength (TTCS); Carbon fiber; Rayon; PAN; Phenol; Composite bearing

## 1. Introduction

Carbon fiber reinforced phenolic composites are increasingly employed for heavy duty bearings, which are subjected to not only high pressure, but also under oil-less environment frequently because they have good heat-resistant and self-lubricating properties. They are used as the material for journal bearings of marine engine propeller shafts [1] and the hemi-spherical bearing of military tracked vehicles.

In order to design the heavy duty carbon–phenolic composite bearing efficiently, the mechanical and thermal properties of carbon–phenolic composites are required. The through-thickness compressive strength (TTCS) of the carbon–phenolic composite material is one of the important properties for heavy duty composite bearings. Zhang [2] reported that the TTCS of unidirectional carbon-epoxy composite had the values in the range of 171–194 MPa depending on the specimen width, while the TTCS of cross-ply laminate increased up to 1000 MPa. He also showed with the finite element analysis that the interlaminar shear stress was increased when the friction coefficient between the specimen and loading plate was increased, from which he concluded that the interlaminar shear stress affected the TTCS. But, the effect of stacking sequence on the TTCS of woven composite was not considered. Laramee et al. [3] reported that the TTCS of carbon–phenolic woven composite was about 500 MPa at 0 °C. Lodeiro et al. [4] reported that the TTCS of glass-epoxy woven composite was about 588 ± 29 MPa. Goeke [5] investigated the factors affecting the TTCS of glass fiber–polyester composite and carbon/Kevlar–polyester composite, from which he concluded that the through-thickness strength and modulus did not depend on the specimen

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width when the specimen thickness was constant. But, all the previous investigations did not consider the effect of stacking sequence on the properties of woven composites.

As mentioned above, there has not been enough investigation on TTCS of the carbon–phenolic woven composites for the design of composite bearings. The TTCS of carbon–phenolic woven composites depends on the kind of carbon fiber, stacking sequence of the woven composite, and specimen thickness: For example, there is a considerable difference between the TTCS of PAN based carbon–phenolic woven composite and TTCS of rayon based composite. Since the thickness of composite heavy duty bearing is usually very thick, it is also necessary to investigate the thickness effects on the TTCS of carbon–phenolic woven composite.

Therefore, in this paper, the effects of stacking sequence, specimen thickness, and kinds of the reinforcing fiber on the compressive characteristics of carbon fabric–phenolic composites were investigated.

## 2. Experiments

### 2.1. Specimen preparation

In this work, two kinds of the carbon–phenolic woven composites were used. The first one is rayon based carbon–phenolic woven composite of which woven structure is twill weave. The other one is PAN based carbon–phenolic woven composite with 8-harness satin weave structure. For the rayon composite specimen, 56 plies were stacked to make 24 mm thick specimen because the ply thickness was 0.43 mm. The stacked prepregs were cured in an autoclave under the pressure of 0.6 MPa at 155 °C. The cured thick plates were cut to the specimen size by a diamond wheel cutter. The length, width, and thickness of the specimen were 12 mm, 12 mm, and 24 mm, respectively according to the ASTM D695 [6]. The depth of cut during cutting operation was maintained less than 0.25 mm under sufficient cooling water to minimize the damage on the machined surface. The specimens with short thickness of 12 mm were also tested to investigate the thickness effect on the TTCS of carbon–phenolic composite. The 12 mm thickness was recommended by the British Standard BS 2782: Method 345A: 1979 [7], which was revised by BS EN ISO 604:2003 [8]. But this new standard is not applicable to the materials reinforced by textile fibers [8]. The other standard, ISO 14126:1999 [9] is only applicable to the compressive tests in the in-plane direction.

The designation and stacking sequences of the specimens are shown in Table 1, in which, two letters 'S' and 'T' were used to represent the 12 mm thick specimen, and the 24 mm thick specimen, respectively. For example, RAS represents the specimen of 12 mm thick with $[\pm45]_{14}$ rayon based carbon–phenolic woven composite. Table 2 shows the ply properties of PAN based carbon–phenolic and rayon based carbon–phenolic woven composites.

### 2.2. Test methods

The prepared specimens were compressed between two steel collars to measure TTCS (through-thickness compressive strength). Grease was pasted on the interface between the specimen and the collars to reduce the interfacial friction. The testing machine was INSTRON 5208 with 150 kN load cell, and the cross-head speed was maintained at 1.3 mm/min according to the ASTM D695. In another test method according to British Standard BS 2782 [7], a self-aligning device as shown in Fig. 1 was employed to remove the stresses which might be induced due to the bending of the specimen.

Table 1
Stacking sequences and designations for the compression test specimen

| Material stacking sequence | PAN based carbon–phenolic woven composite | | Rayon based carbon–phenolic woven composite | |
|---|---|---|---|---|
| | 12 mm thick | 24 mm thick | 12 mm thick | 24 mm thick |
| $[0]_{2n}$ | PZS $[0]_{32}$ | PZT $[0]_{64}$ | RZS $[0]_{28}$ | RZT $[0]_{56}$ |
| $[0/90]_n$ | PCS $[0/90]_{16}$ | PCT $[0/90]_{32}$ | RCS $[0/90]_{14}$ | RCT $[0/90]_{28}$ |
| $[\pm45]_n$ | PAS $[\pm45]_{16}$ | PAT $[\pm45]_{32}$ | RAS $[\pm45]_{14}$ | RAT $[\pm45]_{28}$ |
| $[-45/0/45/90]_{(n/2)s}$ | PQS $[-45/0/45/90]_{4s}$ | PQT $[-45/0/45/90]_{8s}$ | RQS $[-45/0/45/90/45/0/-45]_{2s}$ | RQT $[-45/0/45/90/45/0/-45]_{4s}$ |

Table 2
Mechanical properties of the carbon–phenolic woven composites

| Properties materials | $E_{11}$ (GPa) | $E_{22}$ (GPa) | $E_{33}$ (GPa) | $v_{12}$ | $v_{13}$ | $v_{23}$ | $G_{12}$ (GPa) | $G_{23}$ (GPa) | $G_{13}$ (GPa) |
|---|---|---|---|---|---|---|---|---|---|
| PAN based carbon woven | 61.5 | 61.4 | 6.2 | 0.039 | 0.46 | 0.46 | 5.8 | 3.8 | 3.8 |
| Rayon based carbon woven | 11.8 | 6.8 | 8.4 | 0.116 | 0.21 | 0.32 | 7.8 | 4.3 | 4.3 |