MICROSTRUCTURE AND MECHANICAL BEHAVIORS OF THICK-WALLED JOURNAL BEARING GFRP RINGS

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1 General introduction
A journal bearing is a cylindrical component that rides on a rotating shaft, mostly floating on a layer of oil or grease. Metal journal bearings are the classic, but now, more journal bearings are made of thermoset plastics. In addition to standard formulations, custom thermosets can be designed to meet specific bearing related design requirements: be able to support high compressive loads and extend bearing life by use of self-lubricating modifiers in open porosity.

The best variant now is wound high porous glass-fabric reinforced plastic (GFRP) [1, 2]. But the most problem for wound thick-walled tubes/rings is the variation of mechanical behaviors of GFRP layer during winding of prepreg on mandrel with tension and presence of transversal macrocracks [2] just at the cooling stage of curing procedure.

The fabric-based prepreg is soft enough and compressible in transversal direction and can vary microstructure, elastic behaviors, thermal expansion, fiber volume fraction and porosity due to pretension at winding. So, investigation of microstructure and mechanical behaviors of thick-walled GFRP’s bushing ring plies is the subject of this paper.

2 Material and technology
The material used in this study is plane-weave glass fabric of thickness about 0.24 mm preimpregnated with epoxy/phenolic resin as matrix and acetone as a solvent and open porosity producer. The steel mandrel (d=90 mm of diameter) was used to wind tube with permanent prepreg tension of 10-12 N/cm.

The curing process consists of three parts: gelation (90°C, 2hrs), polymerization (120°C, 2hrs + 160°C /8hrs) and cooling (5-10°C/hr) down to room temperature. Mechanical tooling was used to get outer diameter of tube D=110 mm. And final procedure was cutting tube into rings with h=15 mm of width.

The average density of GFRP rings is 1.48 g/cm³, radial compressive strength is 350 MPa, glass fiber volume fraction is about 46%, voids are about 23% and matrix is about 31%. Microstructure of wound ring is shown on Fig.1 (0.3 mm slice thickness).

There are voids lines, curved and thickened inner layers and tightened outer layers of fabrics. So, the micro structure is different in radial direction and mechanical behaviors (elastic moduli and thermal expansion) will be different too.

3 Experimental procedures
It is clear, that voids distribution into GFRP will have influence on its mechanical behaviors. Because the voids distribution is very hard controlled during production technology it needs to develop ‘postmortem’ methods to determine real micro geometry and circumferential elastic moduli of fabric layers into GFRP ring. After that it is possible to estimate all other physical features by using, for example, FEA micromodeling.

3.1 Determination of volume fraction of fibers, matrix and voids
For this purposes we cut out 45⁰ segment of the ring and split it onto several layers. After initial weighing and measuring of volume each layer was put into furnace (700°C/12 hrs) to burn matrix out and weighing again. Using known values of fiber and matrix density, density of GFRP we could determine volume fraction of fibers, matrix and voids and its distribution into ring’s thickness, Fig.2-4. The average density of GFRP rings is 1.48 g/cm³, glass fiber volume fraction is about 46%, voids are about 23% and matrix is about 31%. Here we can say that inner layers are enriched by matrix and depleted by voids and glass fibers. It can be only if thickness of the inner layers is increased and matrix was migrated from outside due to compression under tension winding. In the middle of thickness volume fraction of fibers is increased up to \( V_f = 47\% \). Because of warp’s straightening under tension the fabric becomes as 0/90 composite with straight fibers. Using ‘mixture rule’ for \( E_i \) (modulus of elasticity in 0⁰ di-
For [0/90] composite) we can estimate this value: $E_s/E_l V_l = 70 \text{GPa} \times 47\% / 2 \approx 16.5 \text{ GPa}$.

For inner layers this modulus must be less.

3.2 Determination of average circumferential and shear moduli of GFRP’s layers

Here we used the segment of ring (10 mm thickness) and 3-point bending fixture, Fig.5, to calculate $E_s/G_{xy}$ by using the variation of support distance from 80 to 50 mm and FEA, Fig.6, as the instrument to fit theoretical and experimental stiffness of segments. Also we assumed frictionless support. As the result we have $E_s/G_{xy} \approx 4.4$.

3.3 Determination of elastic modulus of layer

We used INSTRON 5882 universal testing machine with standard pin’s fixture to have “load – displacement” diagrams of entire rings. The diametrical tension (Fig.7) of ring with different thickness $H$ was used to get ring’s stiffness $S$ for each value of $H$:

$$S(H) = \frac{AP(H)}{AU},$$

where $\Delta P(H)$ and $\Delta U=1 \text{mm}$ – increments of load and displacement on linear part of loading diagrams. Different thickness was made by decreasing of outer ring diameter with unwinding of several GFRP layers out.

Using the assumptions of homogeneity of ring's material at diametrical tension [3] we get

$$U = 0.149 S r^3 \left[ 1 + 0.44 \frac{H^2}{r^2} (1+E/G) \right]/E J,$$

where $r$ is mid-radius of ring, $E$, $G$ – modulus of elasticity and shear, $J$ – moment of inertia of cross section under bending $(bh^3/12, \text{where} \ b – \text{width of ring}, \ S – \text{stiffness (1)}$. For this GFRP $E/G\approx4.4$, so the biggest value 'of anisotropy' in square bracket is only 1.095 (thickest ring). Therefore we can consider GFRP as an isotropic material (less than 10% error).

Experimental function of $E(H)$ is shown on Fig.8 (line – cubic approximation of experiments). Arrow shows the direction of an experimental data sequence.

4 Theory

We used finite element analysis (FEA, Fig.9) and the approach based on mechanics of materials [4] (variable ply elasticity through thickness of beam) to inverse calculation of ply elastic modulus with taking into account of experimental values of average bending ring modulus of elasticity (schematization of cross section of ring as thin beam shown on Fig.10).

Results of calculations of ply elastic modulus vs radius of ring are shown on Fig.11.

Conclusion

Experimentally shown that winding of plane-weave glass fabric prepreg with tension can lead to decrease of circumferential modulus of elasticity of inner layers of wound ring down to 11.0 GPa of average 16.0 GPa. Approximately 30-35% of thickness has lower modulus than maximum one. Microstructural analysis showed that thickness of inner layers and curvature of warp threads were increased in comparison with outer layers. It can lead to increased circumferential thermal expansion coefficient of plies and possibility to have significant transversal tensile stress or even cracks after curing.

References

Fig. 2. Volume fraction of glass fibers vs thickness.

Fig. 3. Volume fraction of matrix fibers vs thickness.

Fig. 4. Volume fraction of voids fibers vs thickness.

Fig. 5. Short beam bending/shearing (segment of ring) with roller support.

Fig. 6. FEA-schematization of 3-point bending of ring's segment.

Fig. 7. Loading scheme and bushing ring in the fixture.
Fig. 8. Average value of elastic bending modulus $E$ vs thickness $H$ of ring.

Fig. 9. FE model for entire ring (1/8 of whole ring).

Fig. 10. Schematization of cross-section of beam.

Fig. 11. Distribution of ply elastic modulus vs radius. Solid line – mechanics of materials method, dot line – FEA.