CARBON FIBER COMPOSITES APPLICATIONS FOR AUTO INDUSTRIES

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Abstract

Carbon fiber composite drive shaft having crush worthiness which had been developed for rear drive passenger cars will be described. Crash load generated during head collision can be absorbed by newly developed joining technology with no adhesive between carbon fiber composite tube and steel adapter. This technology can add safety value to passenger cars in addition to conventional advantages of composite drive shaft such as weight and noise reductions. Its materials, design concept, performance data of the composite drive shaft system will be discussed in the paper.

Background

Use of carbon fiber composite tube as drive shafts have been well known and considered to be one of the promising solutions to reduce vehicle weight and NVH (noise, vibration and harshness). A lot of research and development have been carried out and it has been already proved that carbon fiber composite tube made by filament winding technology can meet basic requirements of drive shaft such as torque capability and natural frequency (critical rotational speed).

In order to make composite tube into drive shaft, a couple of issues should be taken into account in terms of fiber winding angle against longitudinal axis of the tube. Carbon fiber wound at ±45° works most effectively works in terms of torsional strength. ±90° works in terms of torsional buckling strength and 0° does in terms of critical rotational speed most effectively though both angles can not be exactly achieved by filament winding.

Thus, the most effective fiber orientation and lay-up pattern (combination of fiber orientation and winding sequence etc.) will be determined based on fundamental requirements of the shaft such as torsional strength and critical rotational speed. Torsional strength of the tube is also determined by diameter and wall thickness of the tube, so that, the first priority is usually given to critical rotational speed which very much depends on fiber angle and ratio of individual layers. In most cases, ratio of low angle layers is much to meet the requirement of critical rotational speed. However this results in the safety problems.

Safety assurance of an automobile consists in crashable body structure, in which the impact energy at the time of collision is absorbed by compressive destruction of the body, thereby mitigating the rapid acceleration applied to passengers. However, it should be noted that if the composite tube used as drive shaft is designed based on the above idea, the longitudinal shaft strength against longitudinal compressive load must be inevitably high resulting in less energy absorption.

Fig.1 and 2 show crash load comparison among conventional composite shaft, steel shaft and newly developed crashworthy composite drive shaft. As shown in these figures, load - time curve from conventional composite shaft has steep increase of the load and high maximum load, in other words, no energy absorption mechanism is observed until the shaft fails according to Euler buckling mode which is not favorable from safety viewpoint at all.

We developed unique and marginal joining technology of metal adapter (a part of yoke) to composite tube along with appropriate fiber lay-up pattern for the composite tube so that we have managed to add one more value to composite drive shaft system such as crash worthiness against head collision.

Progressive failure mechanism of the composite tube and performance of the carbon composite drive shaft system are described in this paper.

Results & Discussion

Joining method between carbon fiber composite tube and steel adapter

It is well known that carbon fiber composite shaft has been adhesively bonded to metal yoke previously. It has been proved to work, however, it is difficult to completely get rid of concern about durability of adhesive for long term usage. We have developed a unique joining technology based on press-fit concept along with serration on the outer surface of metal adapter. Figure 3 shows joining method between carbon fiber composite tube and metal adapter.

A both ends of the tube, inner hoop layers are placed to form mechanical joint between the tube ID and tip of teeth of serration generated on the outer surface of the metal adapter. The length of the joint and the amount of interference for press-fit can be determined mainly based on torque requirement.

Progressive Failure Mechanism

Figure 4 shows progressive failure mechanism. Flange located between yoke and serration initially push only hoop layer when longitudinal load applied by head collision and delamination between hoop layer and helical layer occurs as the first fracture mode and yoke continues to move into the tube as long as longitudinal load applies. Subsequently crush energy is absorbed by wedge effect during this stage and ultimately relatively large crack shown in the figure will be observed. This mechanism has been proven by FEM as shown in Figure 5 and 6. Stress concentration in the longitudinal direction at the interface between hoop and helical layer is observed which initiates delamination mechanism when longitudinal load applied to the tube. On the other hand, uniform and relatively low shear stress coming from torsional load is observed at cross section of the tube as we expected.

This progressive failure mechanism also has been proved by head collision test using actual vehicle. Figure 7 shows the comparison of load – time curve during collision and it is noted that peak load of composite system is 60% lower than that of steel system and deformation of composite system is 20 % more than that of steel system.

Composite shaft performances

We have evaluated torque carrying capability as index of shaft performance. One of typical data have been shown in Figure 8. It is noted composite drive shaft performed as expected up to 150° C at static torsional test and showed much better fatigue resistance than steel systems shown as target.

In Figure 9, residual torque carrying capability after exposure to various environments are shown in percentage compared with control data. As shown here, reduction in performance of composite drive shaft is very minimal.

Design of Composite Drive Shaft

Another important key characteristic of drive shaft is natural frequency which can be mostly determined by fiber orientation (helical fiber winding angle) and dimension of the shaft. Figure 10 shows the natural frequency as a function of helical fiber winding angle. It is to be noted that peak of the frequency is somewhere between 5° and 15° other than 0° because bending frequency was defined by equation (1).

$$\left(\frac{\omega}{\omega_o}\right)^2 = \frac{\{1+\delta-\sqrt{(1+\delta)^2-4\varepsilon}\}}{2\varepsilon} \qquad (1)$$

$$\omega_o = \frac{\pi^2}{L^2}\sqrt{\frac{E_x I}{\rho A}} \quad , \quad f_o = \frac{\omega_o}{2\pi}$$

$$\delta = \frac{\pi^2 I}{L^2 A}\cdot\left(1+\frac{E_x}{K G_{xy}}\right)$$

$$\varepsilon = \frac{E_x}{K G_{xy}}\left(\frac{\pi^2 I}{L^2 A}\right)^2$$

$$K = \frac{E_x}{(2E_x - \nu_x G_{xy})}$$

where,

ω : resonance of composite tube to be calculated (angular velocity)

ω_o : resonance of Euler beam(angular velocity)

f_o : resonance of Euler beam(Hz)

L : support distance

A : cross section area of a tube

I : moment of inertia of a tube

E_x : longitudinal Young's modulus of a tube

G_{xy} : shear modulus of a tube

υ_x : Poison's ratio of a tube

ρ : density of a tube

Figure 11.1 to 11.3 show typical design options depending on requirements for natural frequency and torque. It is possible to determine joint distance, tube OD with a parameter of fiber Young's modulus by this kinds of chart.

Conclusion

We have developed design methodology for composite drive shaft along with new joining method between composite shaft and metal yoke so that we can add one more value to drive shaft system using carbon composite tube.

The technology is now being applied to mass production vehicles such as Mitsubisi Montero, Nissan 350Z and MAZDA RX-8.

Figures

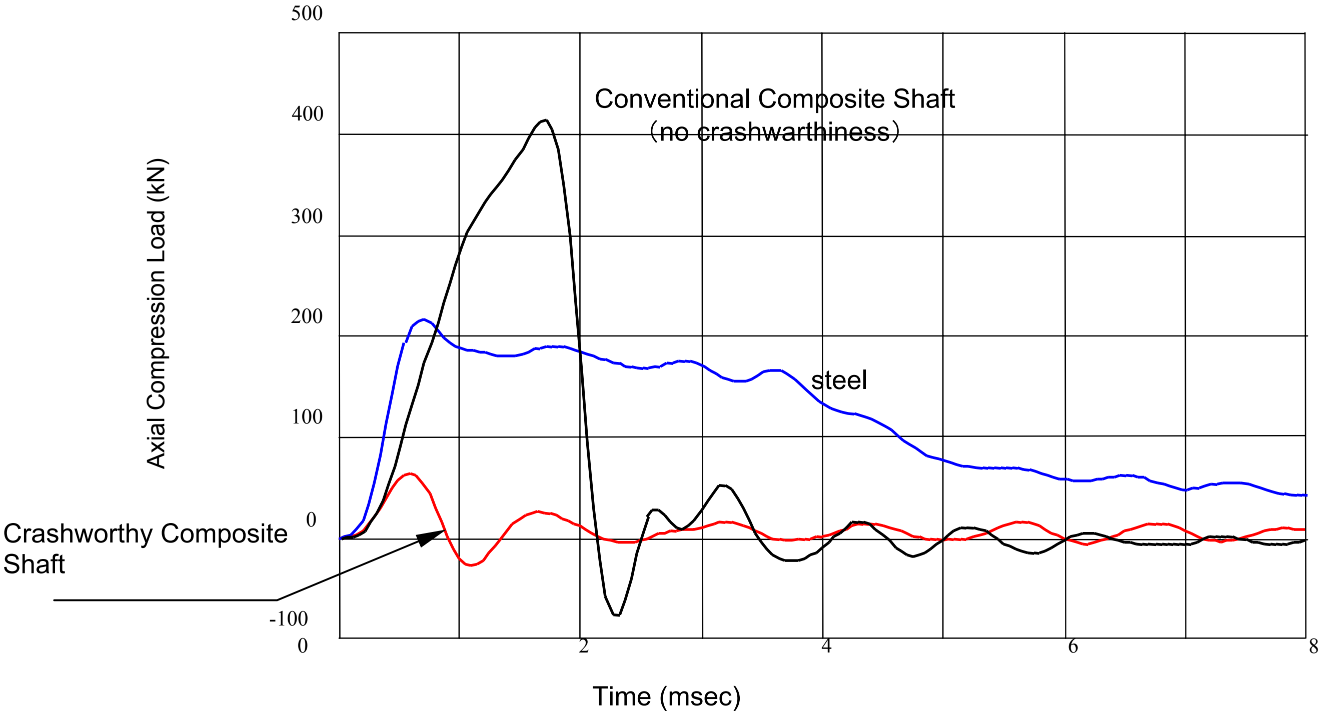
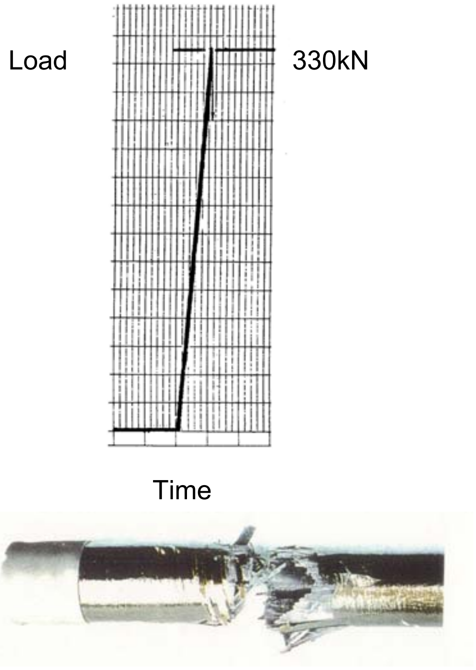
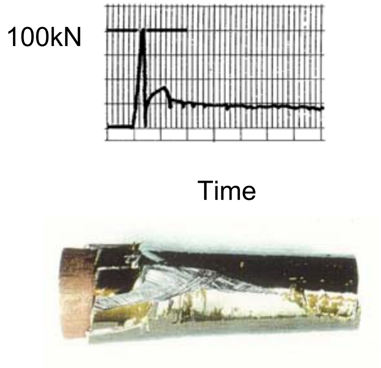


Figure 1: Comparison of Axial Crash Load (35 km/hour Crash Test)

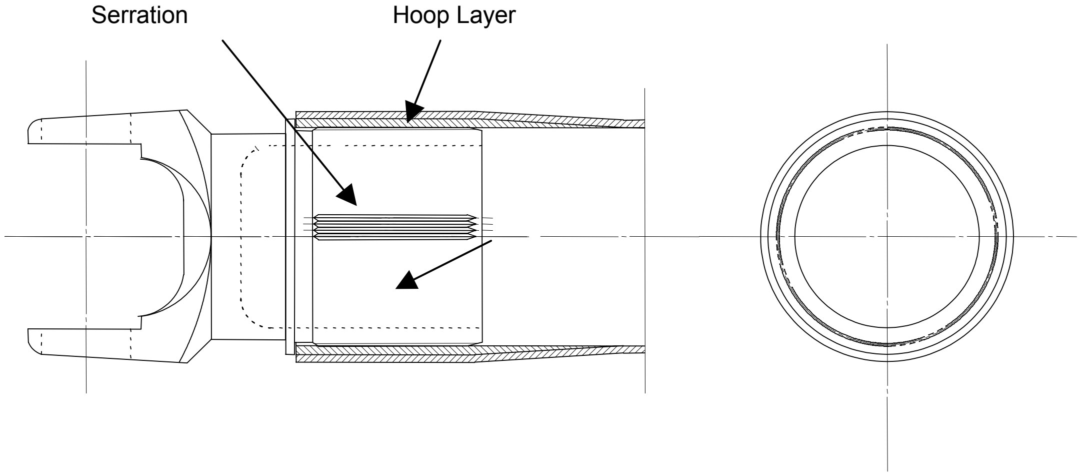


Euler Buckling Mode
(conventional technology)



Progressive Failure Mode
(new technology)

Figure 2: Comparison of Failure Mode



cross section

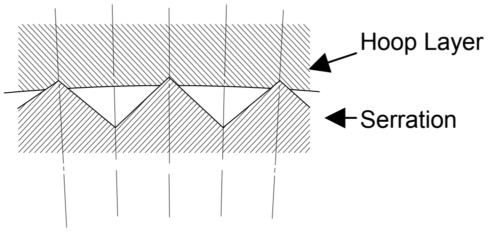


Figure 3 : Joining Method (serration + press fit)

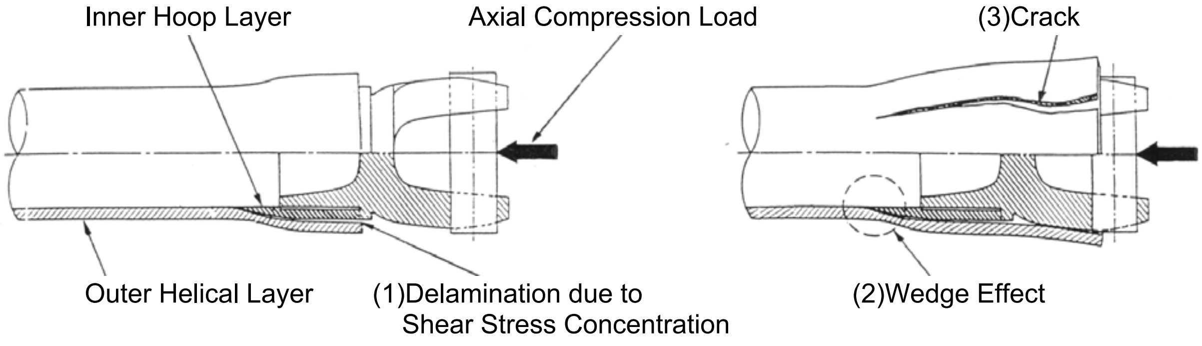


Figure 4 : Progressive Failure Mechanism

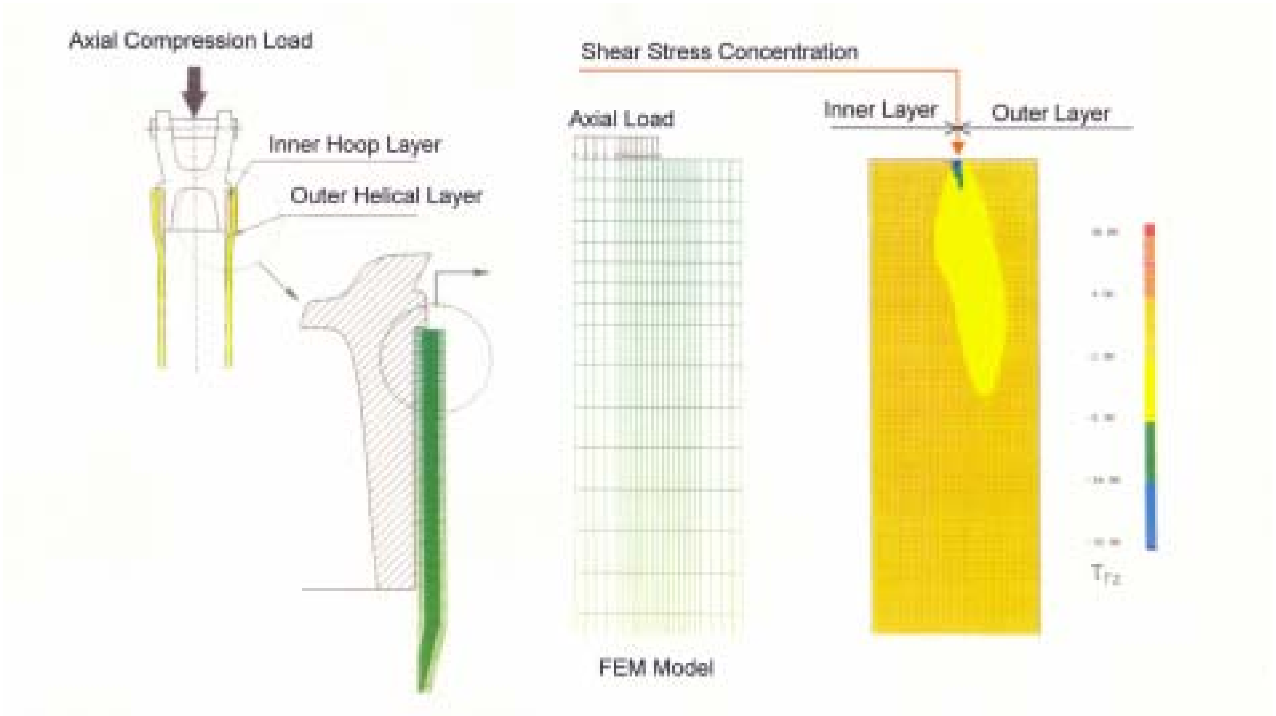


Figure 5 : Stress Distribution in longitudinal Cross Section

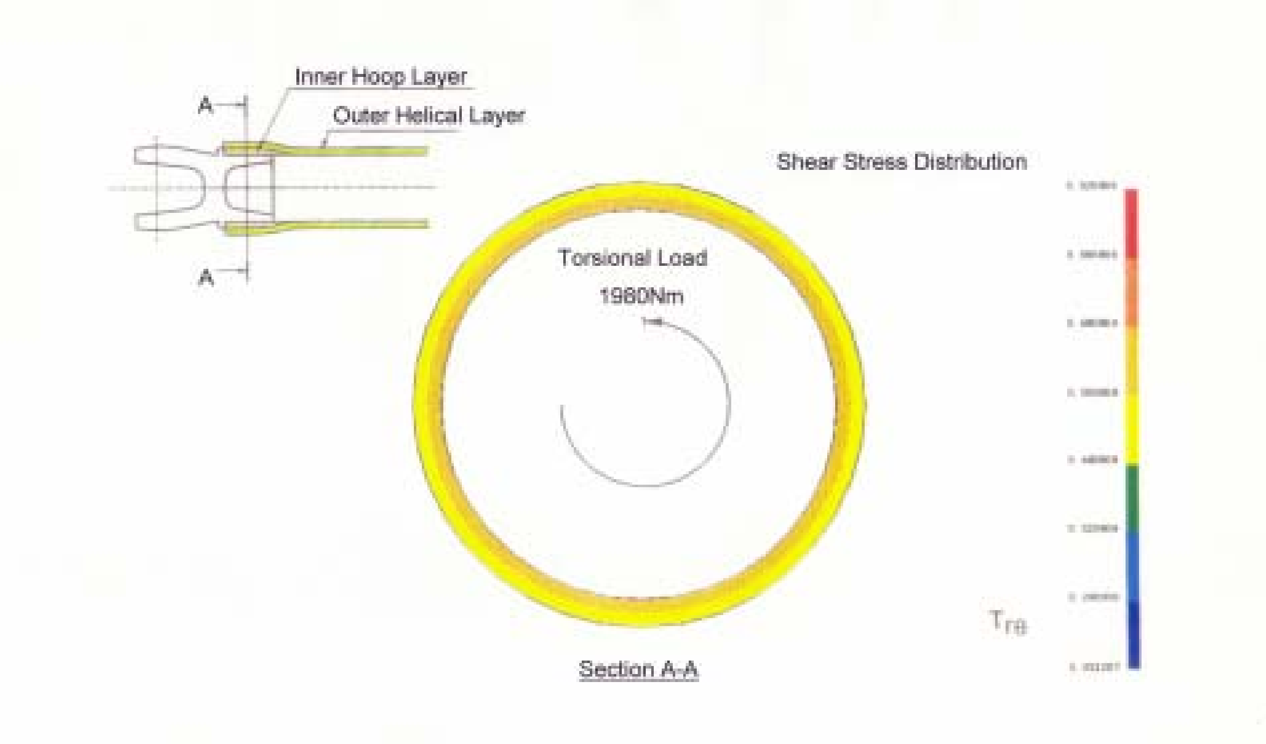


Figure 6 : Stress Distribution in Transverse Cross Section (A-A)

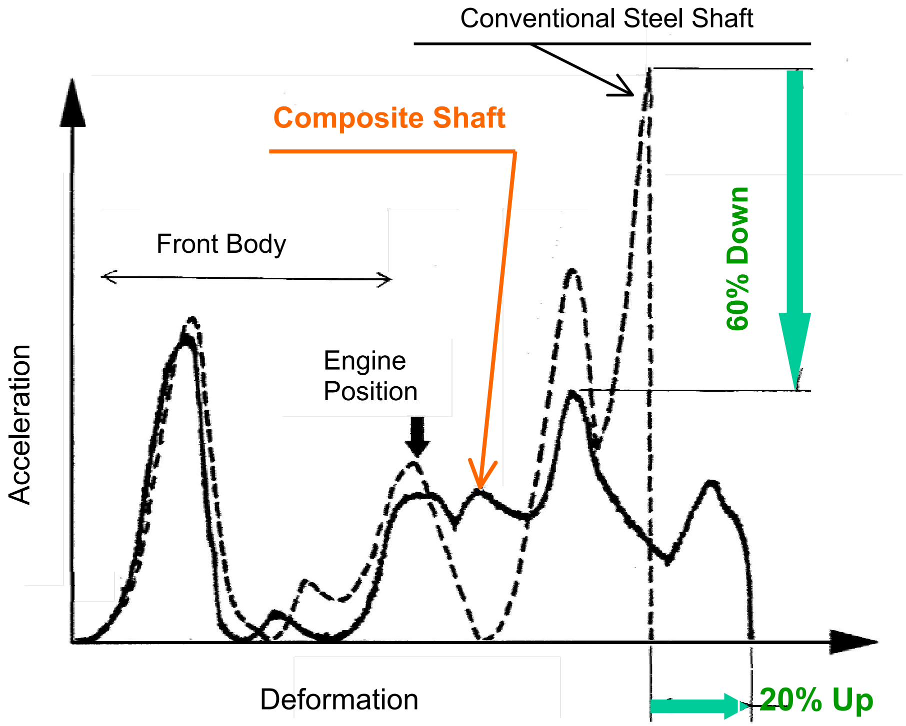
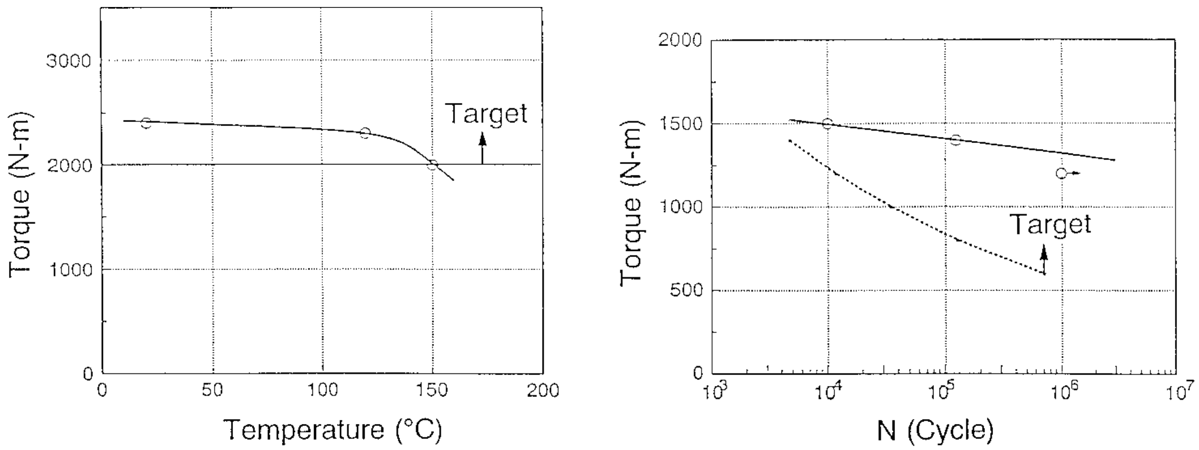


Figure 7 : Deformation Comparison Composite Shaft VS Steel Shaft



Torsional Static Strength

Torsional Fatigue Strength at 120 ° C

Figure 8 : Torsional Strength of Drive Shaft for 2000 Nm class

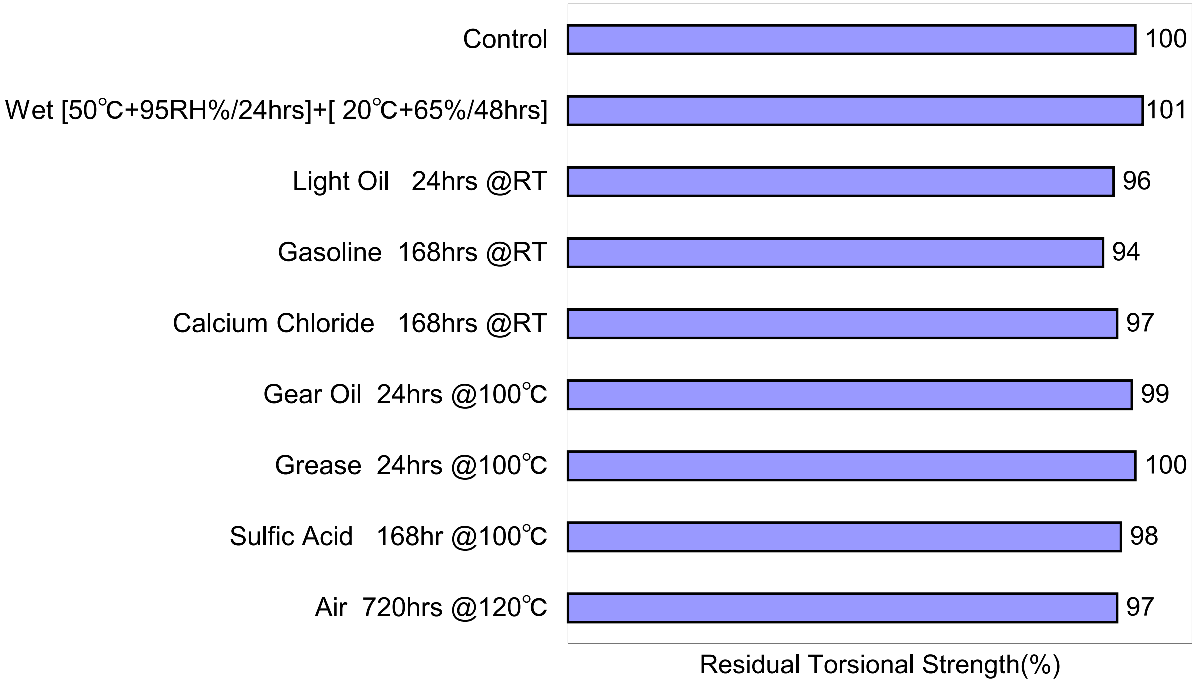


Figure 9 : Residual Torsional Strength (%) after Environmental Testing

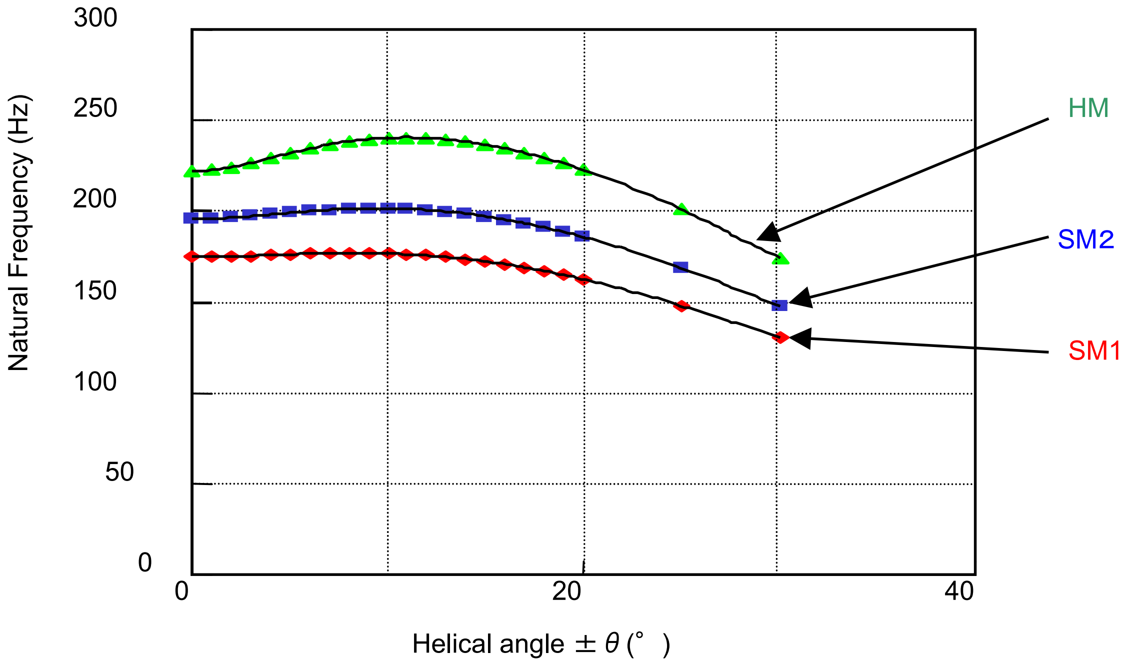
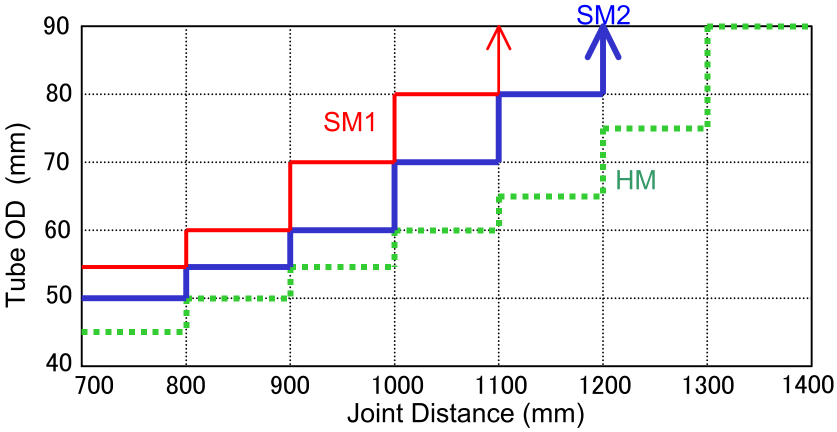


Fig 10 : Natural Frequency of Filament Wound Composite Shaft
-[90/± θ](0.3 / 2.0mm thick)
-OD:70.1mm / ID:65.5mm / Length:1300mm



SM1 : 230 GPa (TORAYCA T700S)
SM2 : 260 GPa (TORAYCA T710S)
HM : 377 GPa (TORAYCA M40J)

Figure 11.1 Design Option#1 200Hz/1400Nm

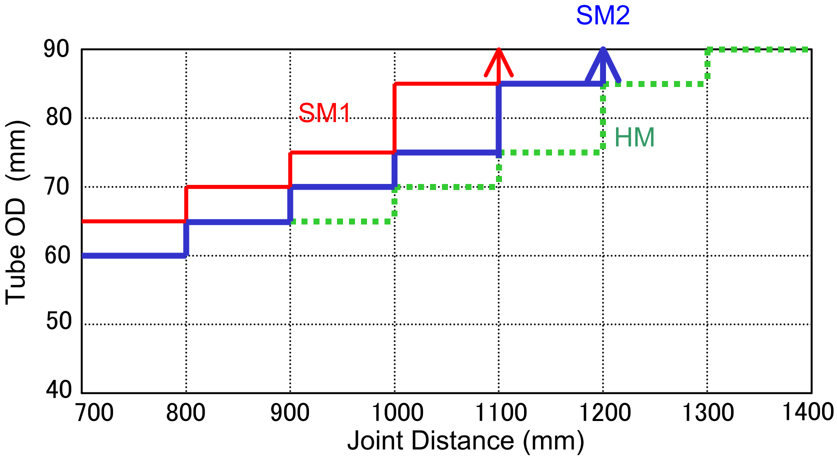


Figure 11.2 Design Option#2 200Hz/4500Nm

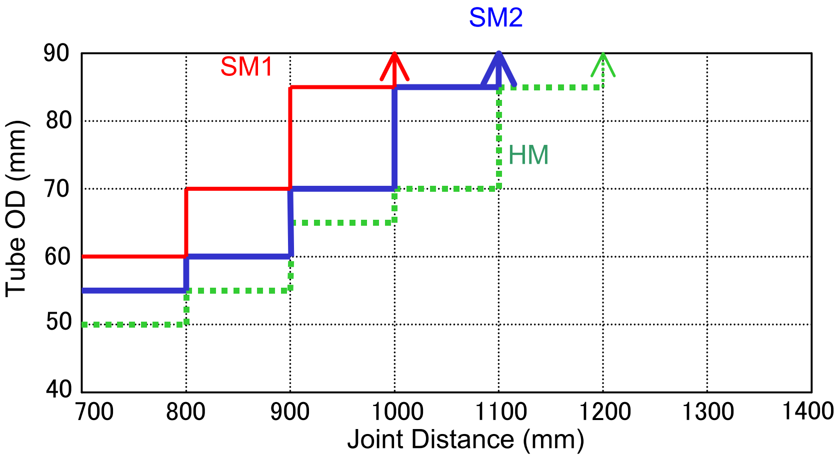


Figure 11.3 : Design Option#3 240Hz/1400Nm