STATIC AND DYNAMIC PROPERTIES OF CFRP ROLLERS

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ABSTRACT

Carbon fiber rollers combine high axial stiffness with low weight. This leads to higher bending frequencies and increased critical speed and makes them suitable for high speed machines as web guide rollers or as other functional rollers. Due to the orthotropic properties of fiber composites static deformation as well as dynamic vibration modes of CFRP rollers differ significantly from those of metallic rollers. Improved performance of CFRP rollers compared to metal rollers is not only a result of the increased critical speed but is also coming from improved damping characteristics.

If CRFP tubes are optimized for axial stiffness and high bending frequencies, static and dynamic deformation that is negligible in metal rollers become significant due to their much lower shear modulus and circumferencial elastic modulus. These deformations have to be taken into account when designing a roller for high speed machines. FRP is a design material which allows to distinctively modify materials properties differently in different direction of the material. With the filament winding process the properties of fiber composites can be modified in a very efficient and versatile way. Additional design options can be used to decrease deformation.

Energy absorption in the resin matrix as well as in the fiber material contribute to the improved damping characteristics and can increase the damping factor of the dominant modal shapes by an order of magnitude.

Composite tubes having unique combination of static and dynamic properties have been produced by filament winding. Static and dynamic properties of these CFRP tubes have been investigated by Finite Element Methods and experimental Modal Analysis.

With the results of these analysis methods complete systems of multiple rollers interacting by nip contacts or through a web can be modeled and investigated. The goal is to derive design rules for rollers that help improving dynamic aspects of web handling.

Using optimized CFRP tubes considering all aspects of their static and dynamic properties rollers can be designed that show better performance in highly productive machines.

NOMENCLATURE

δ = logarithmic decrement, describes damping
η = loss factor for viscous damping
ζ = modal damping ratio
CFRP = Carbon fiber reinforced plastics
E_x = Young's modulus in axial direction,
E_y = Youngs modulus in the circumferencial direction,
Fiber direction in tube:
  0 degree : parallel to the cylinder axis,
  90 degree parallel to the circumference of the cylinder.
FRP = Fiber reinforxced plastics,
G_{xy} = Shear modulus in the axial-circumferencial plane.

INTRODUCTION

The mechanical properties of Carbon fibers can exceed the properties of classical materials like steel or aluminum significantly. Carbon fibers have much higher strength and elastic modulus than steel while their density is lower than aluminum. The elastic modulus of pitch based carbon fiber can reach values above 900 GPa. In a bulk composite material the combination of fibers with a matrix leads to the overall material properties. Since high strength and stiffness of the fibers are only present along the fiber axis the fibers have to be oriented in the lamina in such way that the material will have the desired mechanical properties in different directions. [1]

In the final lamina fiber volume contents of 50%-60% are reached with the current manufacturing techniques. Plastic resins (i.e. epoxy) are most commonly used as matrix materials. Their mechanical properties are in the range of a few GPa for stiffness and strength. Their main purpose is to link the fibers together and to transmit forces between the individual fibers in such way that the final component will have a rigid shape and that the high mechanical properties of the fibers can dominate the bulk properties of the material. [2]

Other than in conventional materials like steel or aluminum the elastic moduli of FRP differ in different material direction and are generally independent. Static deformation of a tube under load in general is determined by its Young's modulus and its shear modulus. In conventional metals the shear modulus is about 1/3 of the Young's modulus. In many cases shear deformation can be neglected compared to conventional bending. Due to the fact that in CFRP the shear modulus can be lower by a factor of 20 or even more than the Young's modulus shear deformation has to be taken into account more carefully when designing rollers out of CFRP.

While offering a higher ratio between stiffness and weight CFRP also offers much higher damping characteristics than steel or aluminum. During the manufacturing process of CFRP the damping coefficient can be influenced by altering the properties of the matrix material as well as using additional energy absorbing fibers or introducing energy absorbing layers. Due to higher damping coefficients CRFP Rollers often offer a significant advantage to metal rollers when being excited at different frequencies in web handling machines.

STATIC DEFLECTION OF CFRP ROLLERS

Figure 1 shows the main deformation modes of a roller under a uniform load applied in a contact nip or resulting from the change of direction of a web. In figure 1a) the classical bending deformation is shown. The lower wall of the roller tube is under axial tension while the upper wall of the roller tube is under axial compression. The axial Young's modulus E_x of the roller tube determins the deformation in this mode. Figure 1b) illustrates the deformation of the roller due to shear. There is no axial tension or compression in the roller wall but there is shear deformation between each roller ring segment and its neighboring ring segment. The in plane shear modulus G_{xy} of the wall of the roller tube determines the deformation in this mode. Figure 1c) shows deflection of the roller due to buckling (Brazier) This mode is also described as ovalization mode since the cross section of the roller in the center shows an oval form. The diameter in the drawing plane is reduced while the diameter perpendicular to the drawing plane is extended. The deformation in this mode is determined by the combination of the axial Young's modulus E_x as well as the Young's modulus in circumferencial direction E_y and the in plane shear modulus G_{xy} of the roller wall.

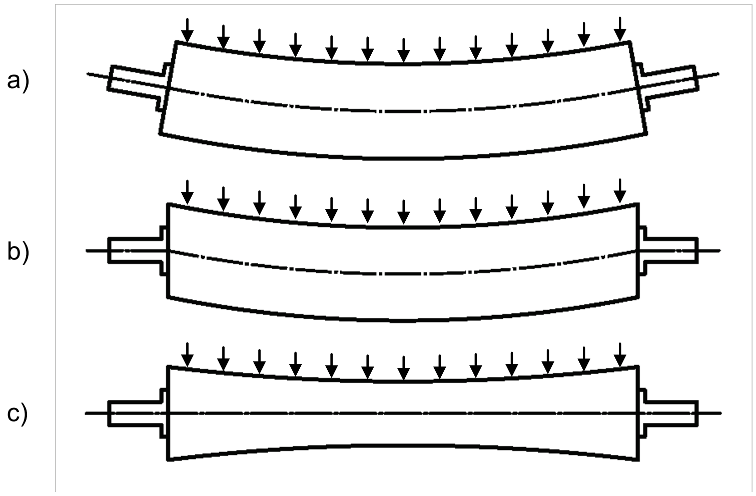

Figure 1 – Deformation modes of a roller under load

<u>Optimization of Lamina for Static Deflection</u>

Figure 2 to Figure7 show the deformation of CFRP rollers having the same fiber content but different lamina designs. For this comparison a roller geometry with a outer diameter of 150 mm and a face length of 2000 mm was used. The distributed load used in the calculation was 2N/mm. The calculations were done using pitch based carbon fiber with a Young's modulus of 640 GPa and a fiber content of 55%

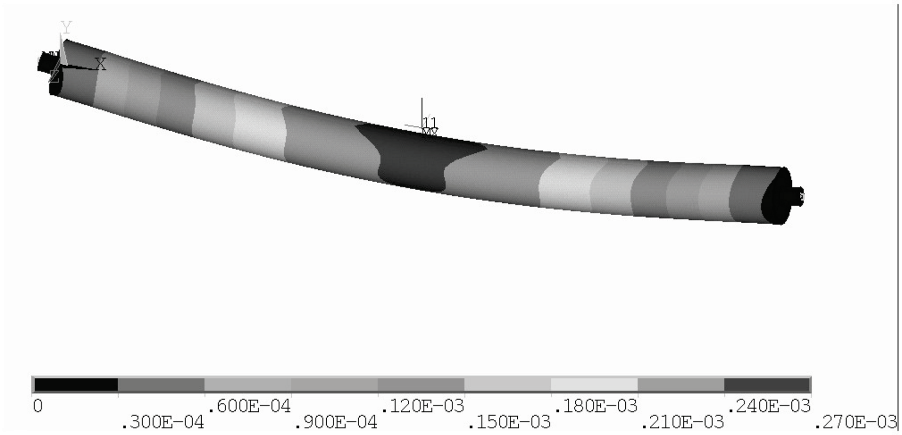

Figure 2 – Contour map of deflection of roller under a linear load from the top.

Figure 2 shows a typical contour plot of the deflection of the roller analyzed by finite element analysis. For this analysis the deflection only due to the linear load was considered and the deflection due to gravity was neglected. In figure 3 to 7 the deflection of the line along the applied load at the face of the roller is plotted and also the deflection along the face of the roller opposite to the applied load. The difference between the two curves shows the deformation due to ovalization.

For the calculation of the deflection shown in figure 3 a lamina design was used having 80% of the fibers at 0 degree and 20% of the fibers at 90 degree. For the calculation shown in figure 4 the angle of the 80% of the fibers being oriented at 0 degree was changed to 12.5 degree. The maximum deflection is reduced compared to the result in figure 3. Even though the axial stiffness is lower for this roller than for the roller with the fibers at 0 degree, the much higher shear stiffness overcompensates for the lower axial stiffness. For the calculation in figure 5 a fiber direction of 45 degree was used for the whole lamina. The deflection is roughly 10 times bigger than for the rollers in figure 3 or 4. The reason is a reduction of the axial stiffness by a factor of over 18 compared to the roller calculated in figure 3. Due to the increase in shear modulus the deflection due to ovalization is cut in half. For the calculation in figure 6 the sequence of fiber direction of the layers within the lamina was optimized in order to allow for a minimum deflection of the roller. In this design the deformation due to ovalization could be reduced also while keeping the deflection due to bending and shear deformation at the level of figure 4.

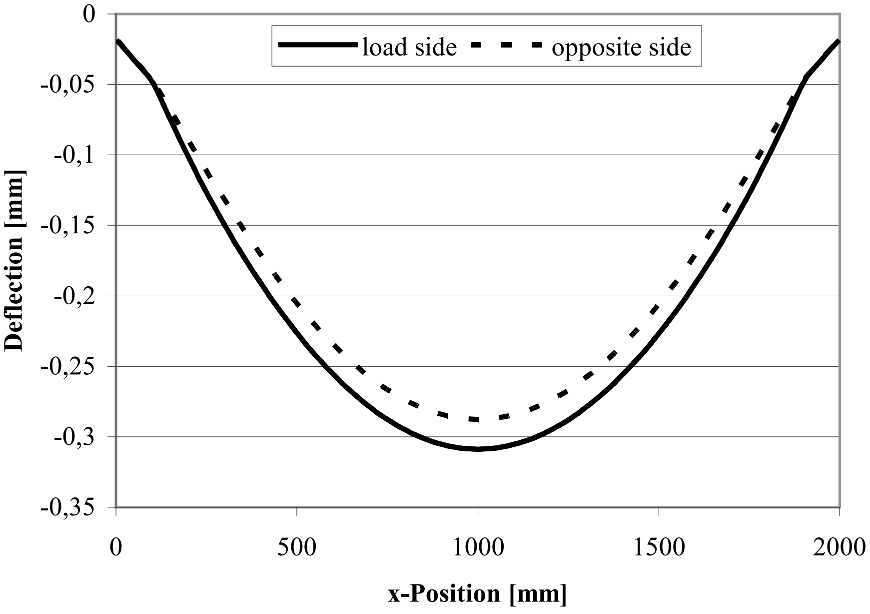

Figure 3 – Deflection of a roller with 80% of the fibers at 0 degrees.

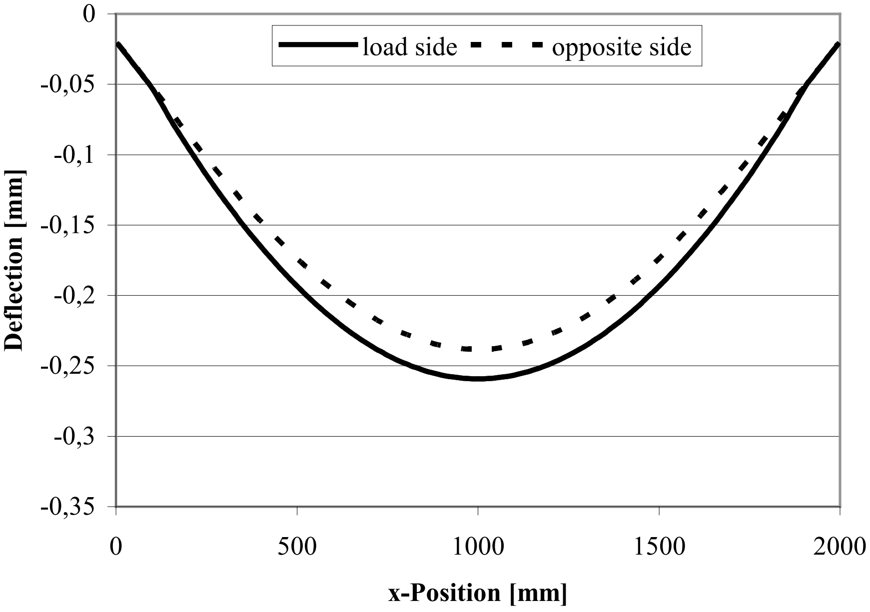

Figure 4 – Deflection of a roller with 80% of the fibers at 12.5 degrees.

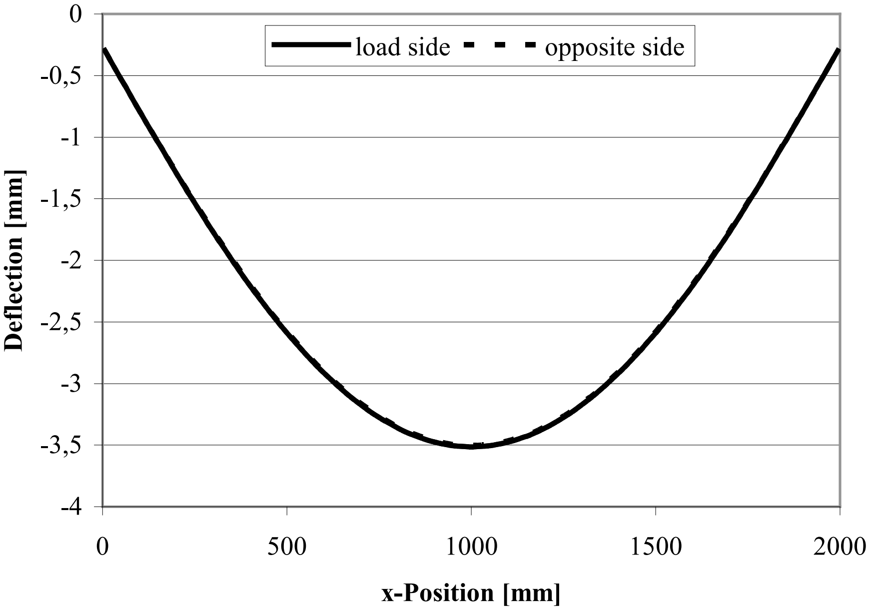

Figure 5 – Deflection of a roller with 100% of the fibers at 45 degrees.

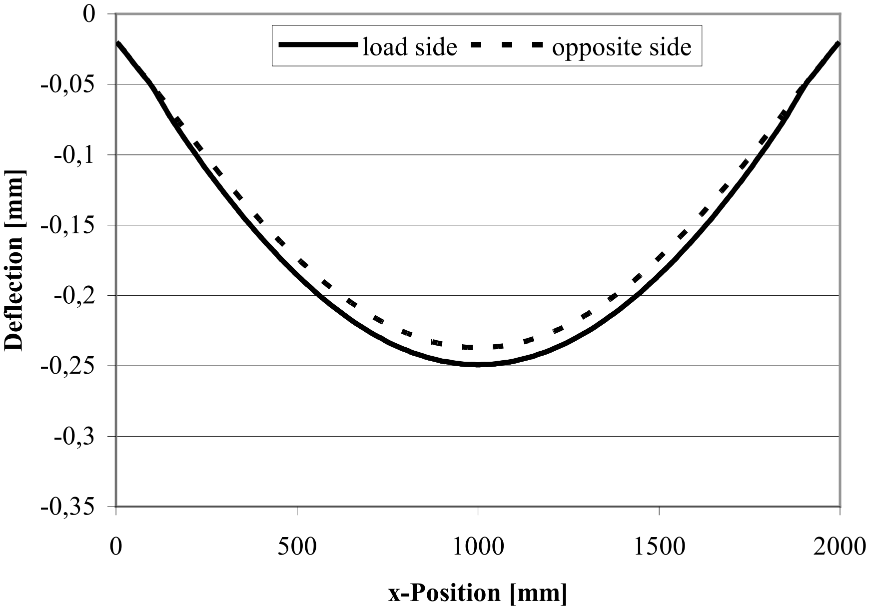

Figure 6 – Deflection of a roller with optimized layered fiber design.

Deformation due to shear and buckling becomes more dominant as the ratio between diameter and length of the roller tube increases and as the wall thickness is reduced compared to the circumference of the roller tube.

Other lightweight design techniques for deflection optimization

In light weight design other techniques are used to reduce the deflection of a shell. With sandwich designs the section modulus of shell wall can be increased by increasing the wall thickness with minimal impact on the weight. Sandwich construction can also be used for rollers reducing deflection due to shear and ovalization. In most cases the cost in manufacturing the sandwich tube is higher than the cost savings due to reducing the usage of carbon fiber. Also other concepts for reducing buckling like fins for stiffening can be transferred to CFRP rollers.

DYNAMIC PROPERTIES OF CFRP ROLLERS

The stiffness to weight ratio of CFRP can be higher by a factor of over 10 than in the case of steel or aluminum. This leads to significantly higher natural frequencies of CFRP components compared to metal components and thus to higher critical speed of CFRP rollers compared to metal rollers [3]. Due to the low weight of CFRP, dynamic imbalance of CFRP rollers is naturally lower than that of metal rollers. Last but not least CFRP offers much higher damping than steel or aluminum. The main advantage of a higher damping factor is reduced vibration amplitudes when excited at a frequency close to a natural frequency. The damping of a component is often measured in the loss factor η or the logarithmic decrement $\delta=\pi\eta$. The loss factor η indicates what fraction of the vibratory mechanical energy is dissipated in one cycle of vibration. The damping coefficients reported in this paper are measured using experimental modal analysis. The values given are representing the modal damping ratio ζ (=fraction of critical damping) which is the ratio between the actual damping coefficient (viscous damping) and the damping coefficient in case of critical damping. $\zeta=\eta/2$ [4], [5]

Modal Analysis of CFRP Tubes

The modal analysis was performed on just the roller tubes without any headers or journals. The tubes were hung vertically in order to have as little influence as possible from the support structure. The modal analysis was performed by exciting the tube with a modal hammer and measuring the frequency response function between the excitation spectrum and the resulting vibration spectrum of the tube. By measuring many frequency response functions of a single tube the modal parameters can be extracted from the measurements using a curve fitting algorithm. For each vibration mode the modal shape and the modal damping ratio can be extracted.

Figure 7 to 10 show some basic modal shapes of a single tube. Since we measured only tubes with a ratio of length to diameter of over 4 the modal shape with the lowest modal frequency was always the first bending mode. This mode also always showed the smallest modal damping ratio. Therefore we concentrate on the first bending mode in the following discussion.

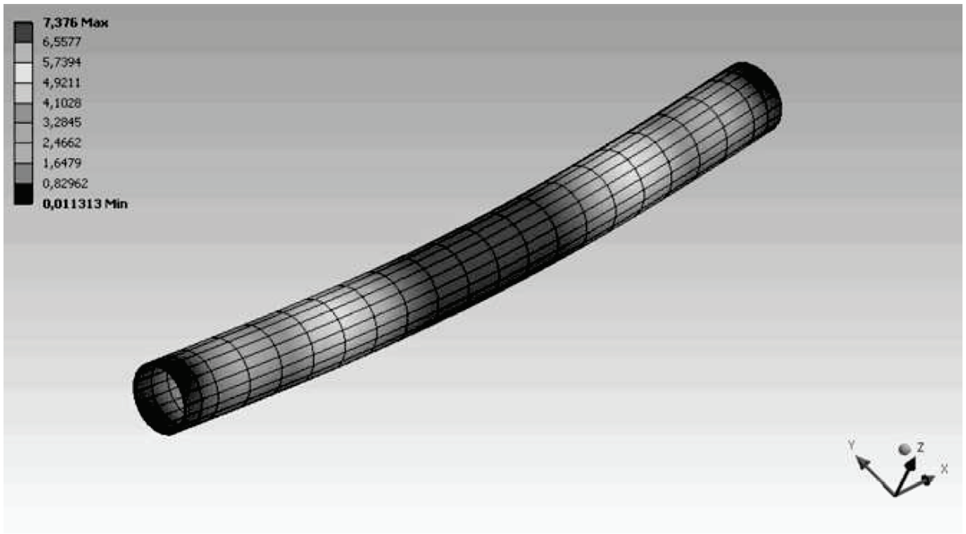

Figure 7 – 1st bending modal shape of a tube.

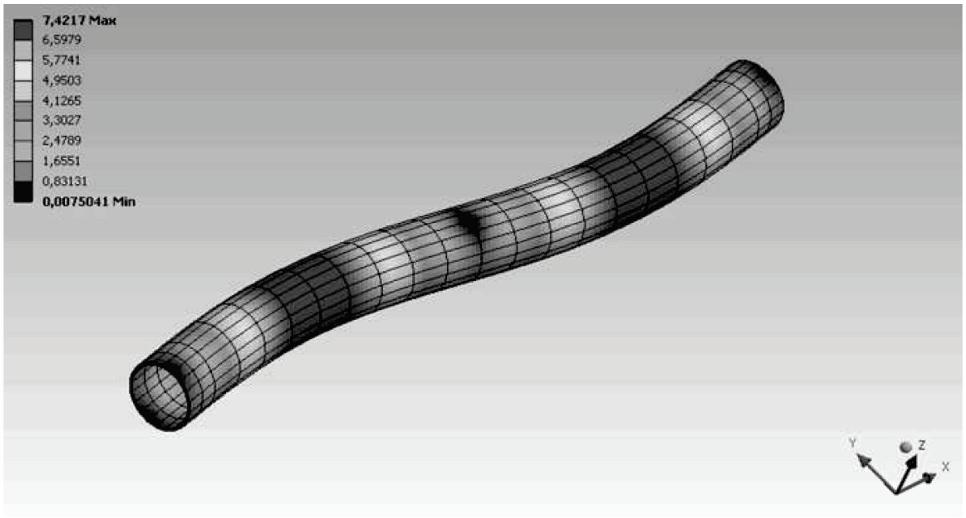

Figure 8 – 2nd bending modal shape of a tube.

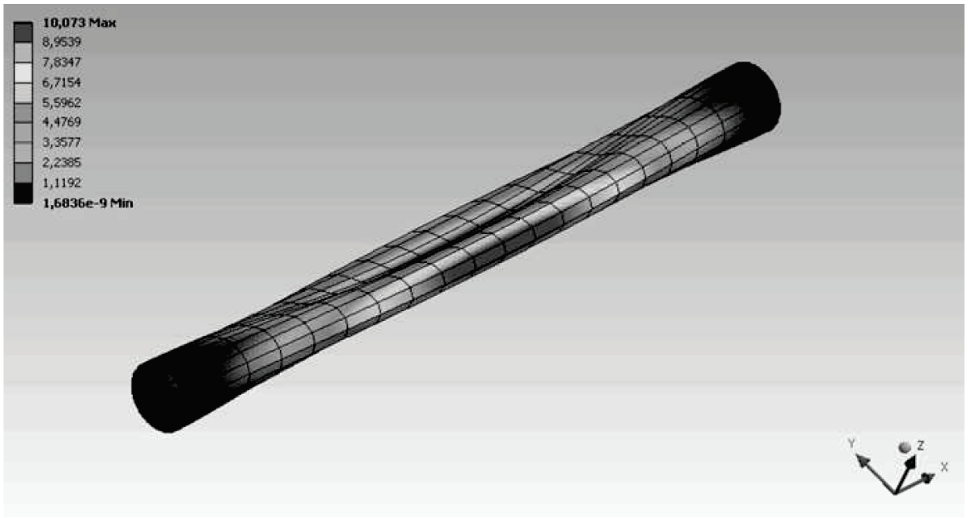

Figure 9 – 1st ovalization modal shape of a tube.

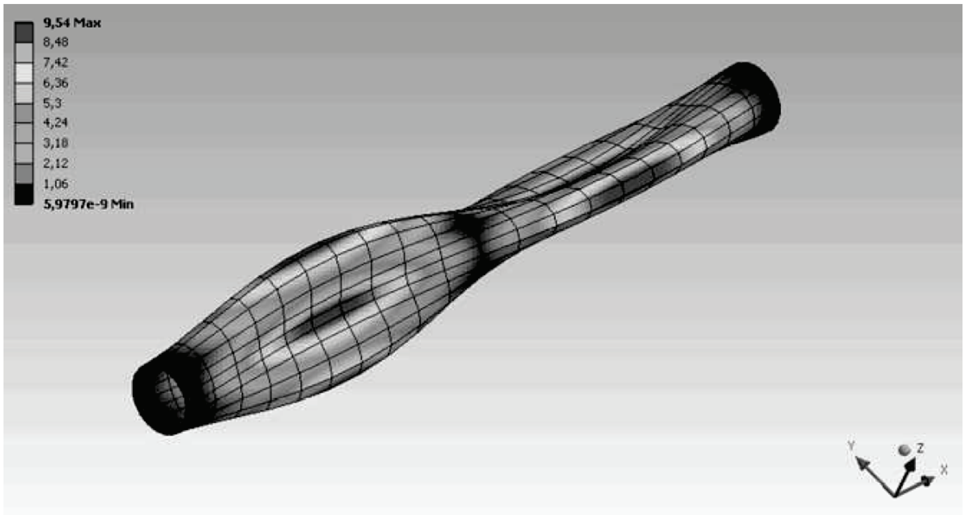

Figure 10 – 2nd ovalization modal shape of a tube.

Increasing of Damping properties in CRFP Laminas

Figure 11 shows the modal damping ratios for a steel tube, an aluminum tube, a standard CRFP tube and a damping optimized CFRP tube measured by modal analysis.

Modification to the polymer matrix of the lamina allowed a significant increase in the damping coefficient compared to a standard CFRP tube [6]. The modal damping ratio of the standard CFRP is higher by a factor of 10 than the measured aluminum or steel tube. First test with prototype rollers with increased damping are currently running.

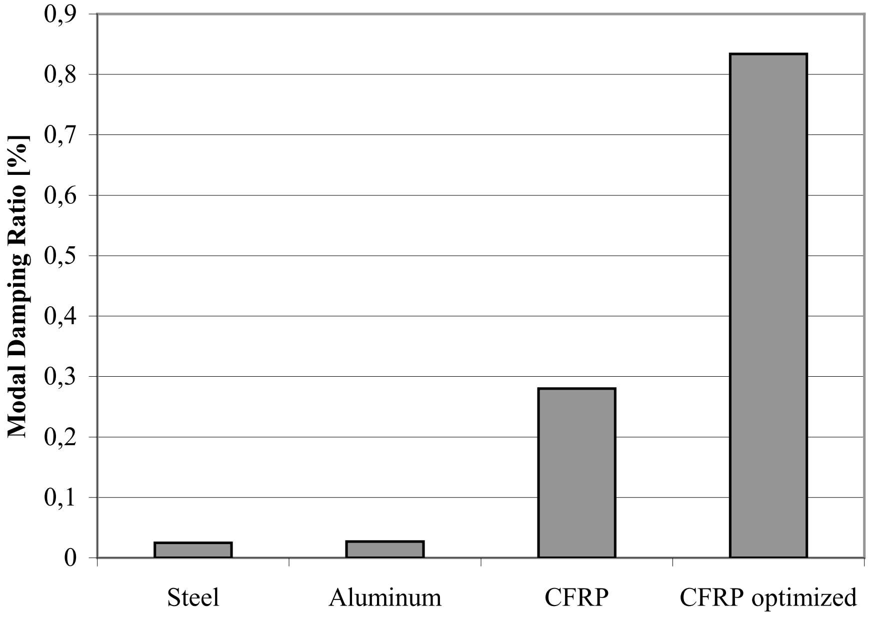

Figure 11 – Modal damping ratios of different tube materials.

Damping Influence on Dynamic Deflection and Dynamic Imbalance

Reduced dynamic imbalance and increased damping leads to significant lower dynamic runout of CFRP rollers than we see with steel rollers. Figure 12 shows a comparison between a steel roller and a standard CFRP roller. Both are rollers for the same position in a paper mill. The dynamic runout of the rollers is plotted against the surface speed. The first peek in each curve shows the dynamic runout at half critical speed of the roller. The second peek in each curve shows the dynamic runout at critical speed. Due to the higher ratio of stiffness to weight the critical speed of the CFRP roller is higher by 50% but also the dynamic runout is quite a bit lower. In this case the CFRP roller can be used up to almost its critical speed because at half critical speed the dynamic runout still stays within the specification. A similar effect can be seen when using a CFRP roller for web tension measurement. Due to the lower dynamic imbalance the noise of the signal can be dramatically reduced especially at half critical speed.

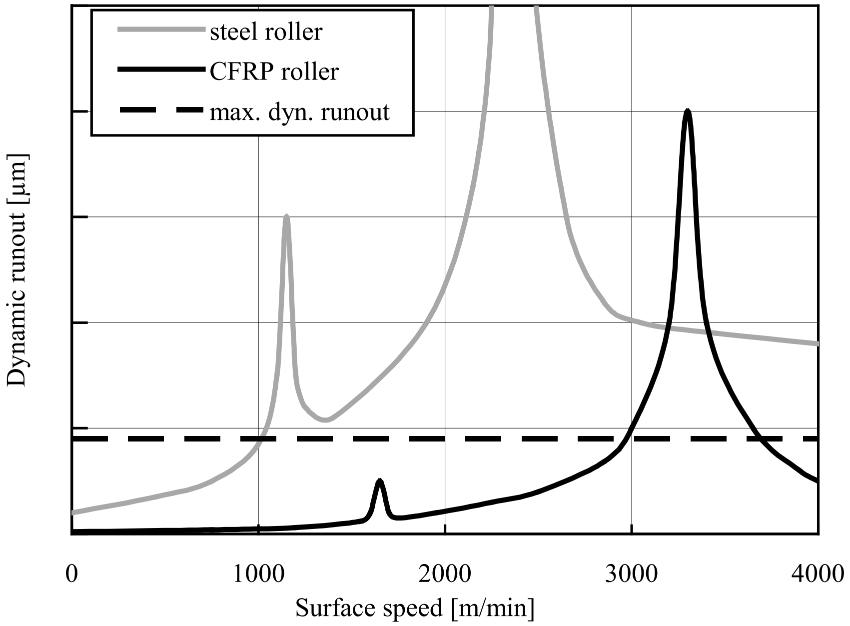

Figure 12 – Dynamic rounout as a function of surface speed

SUMMARY

The main reason for using CFRP rollers in high speed machines is their superior dynamic behavior. Due to the orthotropic properties of the material CFRP rollers behave quite different than metal rollers under static load. When designing a CFRP roller the directional Young's moduli and the shear moduli have to be taken in to account in order to optimize the lamina for the desired performance. The external load and the geometry of the roller define the optimum angle for each fiber layer. With the filament winding process CFRP tube manufacturing can be tailored to the application since the winding angle of each fiber layer can be individually controlled in an easy way. Measurements of rollers manufactured with the filament winding process are in very good agreement with the presented deflection calculations.

Reason for the superior dynamic properties of CFRP rollers is not only the increased critical speed but also the lower dynamic imbalance and the improved damping characteristics. It has been shown that the damping coefficient of a CFRP tube can be further improved over standard CFRP tubes. We expect a further improved dynamic behavior especially in cases where the roller sees excitation at its natural frequency. This technology is also a good candidate for reducing noise in high speed machines.

OUTLOOK

The next step is to build a model of a complete system of rollers interacting by nip contact or through a web. Using the measured damping coefficients for each roller in such a system the vibration response to external excitations can be calculated. These results shall be compared to measurements in real machines and linked to the performance of the machine.

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3. Yoshiya, A., "Characteristics and Applications of Pitch-based Carbon Rollers," Paper, Film & Foil Convertech Pacific, July 2001.
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Carbon Fiber Rollers

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Name & Affiliation	**Question**
Jason Mitchell, Mitsubishi Polyester Film	In the table of deflection data shown I am wondering why the second mode of bending has higher deflection than the first mode of bending.
Name & Affiliation	**Answer**
Ulrich von Hülsen, Inometa Technologie GmbH & Co.	This is affected by the damping ratio. Generally the first bending mode has the lowest damping ratio. So in all the tubes we have looked at, that was the case which means the first bending really is the dominant vibration that we have to take into account.
Name & Affiliation	**Question**
Unknown	For the case shown in Figure 3 where 80% of the fibers were oriented at 12.5 degrees: Is this a common web handling application or is this just an example?
Name & Affiliation	**Answer**
Ulrich von Hülsen, Inometa Technologie GmbH & Co.	It is just an example. For this example, the dimensions had been calculated. For each roller design you must determine an optimum fiber angle. That optimum depends on length to diameter ratio.
Name & Affiliation	**Question**
Unknown	For a roll of significant diameter, 10 inches for example, what is the thinnest wall thickness that can be produced?
Name & Affiliation	**Answer**
Ulrich von Hülsen, Inometa Technologie GmbH & Co.	If you have a long roll with a large diameter and a thin wall thickness a lot of buckling deformation may result. This can particularly troublesome when you try to balance the roll. You can certainly make such rollers. The issue which should be addressed is how the rolls will perform as a result of steady state and dynamic loads. This will dictate the minimum wall thickness.
Name & Affiliation	**Question**
Unknown	It's been known for years that a curved axis roller can be an effective spreading roller. Typically these rollers are produced by producing a curved axis dead shaft which has several roller bearings mounted across the width. An elastomeric cover the width of the roller is forced over the outer races of these bearings. Carbon fibers themselves have tremendous strength but they are embedded in matrices of epoxy which have very low strength. So comparatively the bending stiffness (EI) might be pretty low compared to a roller with a metal shell cover. If you have a 180 degree web wrap of a carbon fiber roll you have twice the web tension acting to deform the carbon fiber roller in the worst possible orientation of a curved axis roller, it will wrinkle the web rather than spread it in this

orientation. My question is do you limit the bending deformations of your rollers to prevent them from wrinkling the web? This seems like a typical design problem. You want the wall thickness as thin as possible to yield a low rotational mass moment of inertia for tension dynamics and control issues. But you don't want the wall thickness too thin so that the roller would wrinkle the web.

Name & Affiliation	**Answer**
Volker Traudt, Inometa Inc.	Typically our customers tell us how much roller deflection their webs can tolerate without wrinkling and we design the roller accordingly.