An Investigation on the Preparation and Mechanical Properties of Three-dimensional Braided Composite Orthodontic Archwires

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Abstract:
Background: Traditionally, orthodontists use metallic archwires during treatment with braces; however, the use of alternative materials such as coated metals, polymers, and fiber-reinforced composites can be advantageous for esthetics or achieving different mechanical properties. The following manuscript reports a study on three-dimensional (3D) braided reinforced polymeric composite archwires. The manufacturing process of the archwires is presented, and their mechanical behavior under tension and torsional loading are investigated.

Materials and Methods: Two types of composite archwires were produced, with and without axial fibers/yarns, on a miniature 3D Cartesian braiding machine. A polyurethane-based bio compatible thermoset shape memory polymer was used as the matrix. 10 samples, with and without axial fibers, were tested in tension, and 10 samples without axial fibers were tested in torsion.

Results: The average elastic moduli of the braided composites were 21.63 GPa and 28.63 GPa for the samples without axial yarns and with axial yarns, respectively. This variation outlines the tailorability of the braiding process to obtain different properties using the same material. Shear modulus was also investigated for the samples without axial yarns, and the average shear modulus was found to be 822 MPa.

Conclusions: Properties in tension and torsion are comparable to those of existing archwires listed in the literature. In addition, the variation in elastic modulus between samples with and without axial yarns clearly indicates the tailorability of braided archwires. From the findings, it is evident that braided composite archwires offer a viable alternative to conventional archwires and should be investigated in more detail.

Key Words: Composite archwires, mechanical properties, orthodontic, shape memory polymer composites, three-dimensional braiding

Introduction

As orthodontic archwires are the active component of braces, their appropriate selection and utilization are critical to the success of treatment. Several mechanical properties will have a major impact on archwire behavior during treatment including elastic and shear moduli, which are important to the axial, bending, and torsional rigidities.¹ To satisfy the mechanical property requirements, archwires are traditionally made from metals such as stainless steel, cobalt-chromium-nickel, beta-titanium, and nickel-titanium alloys;¹ however, there has been a more recent shift toward esthetic archwires such as coated metal archwires.²

There are several disadvantages to using a coated metal archwire: They cannot be transparent, the coating can become worn or peel, and the ability to bend the wire is limited.³ A potential solution is to use other materials such as polymers and/or fiber-reinforced polymeric composite materials.³ The fiber-reinforced composite archwires that are currently available contain fibers solely in the axial (i.e., longitudinal) direction of the archwires and generally have superior axial properties compared to the non-reinforced polymeric archwires; however, they lack reinforcement in other directions important to orthodontic treatment such as torsion.³ It is proposed that using three-dimensional (3D) braiding could remedy this disadvantage since the braided fibers can provide the required stiffness and strength in torque and/or axial directions by changing the braid angle. That is, by simply altering the angle of the fibers in the archwire, its mechanical properties can be tailored to meet specific requirements. This includes altering properties along the length of a single archwire if desired.

Braiding is an old technology that was originally developed for textile materials. Later, due to the advantages, it offers - such as tailorability and fast fiber deposition - braiding was also utilized in the fiber-reinforced composites industry.⁴ Braiding is divided into two main types, being two-dimensional (2D) and 3D braiding. In a traditional 2D braiding process, single layers of tubular or flat braids are produced, whereas a 3D braiding process is capable of producing more complex shapes by interlocking between layers (e.g., solid rectangles, I-beams, and double tubes).⁵ There are two types of 3D braiding machines: Rotary as illustrated in Figure 1a and Cartesian (also known as row and column) as shown in Figure 1b.⁶ In 3D rotary braiding, the spools are attached to slots in a rotating cam, allowing the spools to either move with the cam or be transferred between cams to achieve the interlocking that creates a braid.⁷ In 3D Cartesian braiding, spools are moved across rows or columns to achieve the interlocking necessary to create a braid. The
braiding process is achieved by shifting the columns of spools in opposing directions, then the rows in opposing directions, then reversal of the directions to achieve interlocking. The most common is four-step braiding, which was used to produce 3D braided composite archwires in this study.\(^7\)

The motivation behind this study is two-fold: (a) To prove that 3D braiding technology can be utilized to obtain orthodontic archwires with mechanical properties comparable to the range of those found in existing archwires, (b) to show that the mechanical properties of 3D braided orthodontic archwires can be tailored solely by changing the braid angle of the fibers.

**Materials and Methods**

Braided archwires were manufactured using 200-denier Aramid-based fiber yarns (Kevlar\(^a\) from Fiber-Line\(^b\), USA), which was chosen due to its size and availability during this preliminary work. The matrix consisted of a polyurethane based thermoset shape memory polymer (DiAPLEX SMP MP-5510 from SMP Technologies Inc., Japan) that was chosen due its biocompatibility, which is necessary for orthodontic applications, and its shape memory effect. Although the shape memory effects were not investigated in this study, they are often useful in the orthodontic treatment, and thus, a material with shape memory capabilities was incorporated. Investigation of these effects will be studied in future work.

The braids were produced on a Cartesian braiding machine, Figure 2a using a four-step braiding process as schematically illustrated in Figure 2b.\(^7\) The machine was operated manually. To investigate the tailorability of the braiding process, two different braid architecture types were produced for tensile testing. One type contained conventional Cartesian 3D braided yarns and the other had five braided yarns replaced with axial yarns (non-braided) for increased axial stiffness and strength. Both types contained a total of 25 yarns. Braids for torsion tests were also produced using the same process as the non-axial braided tensile specimens. In this experiment, only non-axial braided torsion samples were produced since the tailorability of the braiding process can be demonstrated using the two different tensile samples. Figure 3 shows one of the braided samples produced using the braiding machine.

To cure the polyurethane shape memory polymer, preparation of the components, resin, and hardener was done as per the manufacturer-supplied manual. The mixture was applied to the braid to coat it thoroughly, hand-massaged in, and then the excess resin was squeezed off. The braid was then placed in the oven to cure at 70°C for 1 h under light tension.

To perform tensile tests, 14 cm (5.5 inches) long cured braids were cut down to a length of 12.7 cm (5 inches). The ends of the samples were potted into epoxy (Loctite\(^c\) E-60hp High Strength Epoxy) as end-tabs to give sufficient surface area for the testing machine to grip without slipping.

The dimensions of the prepared samples were measured using digital calipers. Two measurements were taken at 5 points of approximately equal distance along the exposed portion.

Figure 1: (a) Labeled diagram of a functional unit of a three-dimensional (3D) rotary braiding machine (adapted from reference\(^d\)); (b) labeled diagram of a 3D Cartesian braiding machine (adapted from reference\(^e\)).

Figure 2: (a) Labeled Cartesian braiding machine; (b) four-step braiding process for a 5 × 5 square braid on a 10 rack, 10 slot Cartesian braiding machine. Green squares represent fiber carrying spools, gray squares represent empty spools, and white squares represent empty slots in a rack. The arrows show the direction to push the rack (columns) or spools (rows) for each step. Note that several iterations are required to return the fiber carrying spools to the original shape.

Figure 3: A 5 by 5 braided (non-axial) archwire sample with 1 mm tick marks to show scale (not impregnated with the matrix).
of the sample for each cross-section dimension, totaling 10 measurements for each of the two dimensions. In addition, five measurements of the length between tabs were taken. The five measurements were used to calculate strain from crosshead displacement of the machine, which could be used to confirm the measurements obtained using the extensometer.

The sample was placed between two grips that were inside a thermal chamber, manufactured in-house, to simulate the temperature of a human mouth (37°C). This thermal chamber system was calibrated to be able to hold the temperature within ±1°C of the set 37°C.

During the tests, a small pre-load of approximately 8 N was placed on the samples to remove slack. An extensometer (MTS 632.79E-01) with a 2.54 cm (1 inch) gage length was then attached to the sample at the midpoint, leaving 2.54 cm (1 inch) on either side before the grips. Before testing, the chamber was held at 37°C for 10 min to ensure the sample had achieved thermal equilibrium.

Tensile tests were conducted using a tensile testing machine (MTS Synergie 400 tensile tester) equipped with a load cell with a maximum load capacity of 500 N. Samples were loaded at a rate of 0.5 mm/min during the tests. Although 10 samples of each configuration were prepared, eight non-axial and nine axial samples were tested due to errors in the curing process of the remaining samples. The samples were not tested above 350 N as this is well outside of typical orthodontic loads and is also nearing the maximum capacity of the load cell.

Torsional test samples were prepared using the same procedure as explained above, except for the addition of end-tabs. The grip fixtures available on the torsion testing machine provided sufficient grip so that end-tabs were not required. Torsion test samples were cut to 30 mm lengths. Using a permanent marker, two marks were placed on each sample 10 mm apart, leaving 10 mm at either end. Using digital calipers, the length between the markings was measured 10 times and averaged to find the gauge length. In addition, the sides were measured 10 times each in the same way as the tensile testing samples.

Torsion tests were conducted on a torsion testing machine (MTS-Torsion Master testing machine - MTS Systems Corporation Eden Prairie, MN, USA) equipped with a load cell with a maximum load capacity of 2 Nm. The tests were conducted at a loading rate of 0.1 rad/s. 10 samples were tested under these conditions, and testing was ended at approximately 7 radians to ensure the samples were well outside of the elastic range.

**Results**

**Tensile testing**

For the eight non-axial tensile test samples, the average elastic modulus was found to be 21.63 GPa with a standard deviation of ±1.80 GPa; for the nine axial tensile test samples, the average elastic modulus was found to be 28.63 GPa with a standard deviation of ±3.67 GPa as shown in Graph 1a. In all stress-strain curves, the linear fit of the elastic region had a correlation coefficient above 0.99. Representative stress-strain plots are shown in Graph 1b.

An independent sample t-test was conducted to determine if the axial samples had a statistically significant higher elastic modulus compared to the non-axial samples at the 95% confidence level. The null hypothesis was that the two means are equal, versus the alternative hypothesis where the axial mean was greater than the non-axial mean (one-tailed). Unequal variances were assumed since the standard deviation for the axial samples is over twice that of the non-axial samples. This resulted in \( P = 0.0002 \), which provides very strong evidence to reject the null hypothesis and concludes that the axial samples have a significantly higher elastic modulus at the 95% confidence level.

**Graph 1:** (a) Bar graph of the average elastic moduli for axial and non-axial samples with standard deviations; (b) representative tensile engineering-stress versus strain curves for axial and non-axial braids.
Torsion testing
The torque values in the torsion test were under 20 Nmm. Since the available load cell was 2000 Nmm, the data had significant noise. To mitigate some of this noise, a moving average filter was developed. This filter first found the average torque, $T_i$, of five values for each data point after 2 and before $n−2$ using:

$$T_i = \frac{T_{i-2} + T_{i-1} + T_i + T_{i+1} + T_{i+2}}{5}$$

This evenly weighted average was used since the data points are equally spaced by 0.1 s, making the time-weighted average identical. This average value was compared to the original value, $T_i$, by taking the absolute value of the difference between them. If this difference was greater than a set tolerance, the data point would be removed as it is assumed to be an outlying value due to noise. To set this tolerance, an approximate range for the slope of the linear portion was first estimated to be 10-15 Nmm/rad. Given the loading rate of 0.1 rad/s, this would make the data points increase by approximately 1-1.5 Nmm/s. Furthermore, with a data acquisition rate of 10 Hz, the points increase by approximately 0.01-0.015 Nmm. A “factor of safety” of 3 was set on this increase to ensure the removed points would be spikes due to noise as opposed to scatter about the average increase. Graph 2a and b show the representative torque versus angle of twist curves for the unfiltered and filtered data, respectively.

For the 10 torsion test samples, the slopes from the linear elastic portion of the graph were found and used to calculate the shear modulus, $G$, using:

$$G = \frac{T_θ \cdot L}{β \cdot a \cdot b}$$

In the above formula, $T_θ$ corresponds to the slope, $L$ is the length of the braided sample tested, $a$ is the largest of the two sides of the cross section, $b$ is the smallest of the two sides of the cross section, and $β$ is a factor determined based on the ratio of $a$ to $b$. An $a$ to $b$ ratio of 1.0 corresponds to a $β$-value of 0.141, and a ratio of 2.0 corresponds to a value of 0.229. The $β$-values were interpolated linearly between these two values to calculate the shear modulus. An average shear modulus of 822 MPa with a standard deviation of ±102 MPa was obtained.

Discussion
The elastic modulus for the axial samples is significantly larger than that of the non-axial samples at the 95% confidence level. This difference proves the tailorability of the braided composite archwires. If an archwire with greater tensile modulus is required, more axial fibers can be added, or the braid angle can be moved closer to 0°, which aligns the axis of more fibers with the direction of loading for tension. Conversely, if an archwire with greater torsional or lower tensile stiffness is required, the braid angle of the fibers can be rotated to off-axis.

A previous study reported the flexural moduli of 0.45 mm diameter glass-fiber-reinforced plastic archwires produced using pultrusion to range from 25.4 to 34.77 GPa depending on the size of the glass fibers used. The range of values obtained in our study for the 1 mm by 1 mm 3D braided composite archwires, 21.63-28.63 GPa, is in a comparable range to the pultruded archwires. Another study examined the mechanical properties of metal alloy archwires, obtaining elastic moduli ranging from 53.4 to 241.5 GPa for stainless steel, cobalt-chromium-nickel, beta-titanium, and nickel-titanium archwires with a 0.41 mm × 0.56 mm (0.016 inches × 0.022 inches) cross section. The 3D braided composite archwires are comparable with the lower end of this range, and if the amount of axial fibers or braid angle is adjusted, the values may become closer.

A study examining the torsional properties of various steel and nickel-titanium archwires found the average torque values at a 20° twist angle to range from 1.7 to 43.8 Nmm. In this study, the average value at 20° of twist for the 3D braided composite

Graph 2: Representative torque versus angle of twist curve with (a) Unfiltered and (b) filtered data.
Archwires was found to be 5.8 Nmm with a standard deviation of 1.1 Nmm; this value falls within the range of the metal archwires currently available on the market. Furthermore, it has been suggested that a minimum torque of 5 Nmm is necessary to generate orthodontic tooth movement, and at 20° of archwire twist, it was found that these wires exceeded this value. Moving forward, this is a promising result as it suggests that these wires are certainly capable of generating rotational tooth movement during treatment.

In terms of the future clinical application of braided composite archwires, the results from this study are promising. Having the ability to tailor properties of the archwire by solely varying the braid angle of yarns would allow for the production of archwires with different behaviors around the arch. For instance, the wire could be designed to be more rigid in posterior sections for anchorage units while altering the fiber angle in a given section to have more torsional rigidity for third-order torque correction. Current composite archwires are unable to offer the same level and ease of tailorability. Switching materials along the archwire would allow for tailoring of properties (e.g., composite to metal); however, this is substantially more complicated to manufacture and introduces more potential for failure at the joint. The potential for using other composite archwire manufacturing techniques such as pultrusion, extrusion, or similar processes to vary properties along a wire has been discussed previously. While this may be possible to some extent without the use of a braided preform, the addition of braiding allows for more precise control over fiber orientation simply by altering input parameters such as braiding speed.

The tensile and torsional mechanical properties of the braided composite archwires studied here were comparable to the lower end of the spectrum of conventional metallic archwires studied in the literature. Current literature has suggested that lower continuous forces are better suited to provide physiologic tooth movement, and more work is currently being completed to determine an optimal range of forces. As more research begins to elucidate debate surrounding optimal loads for treatment, it will be important to have appliances that can accommodate such loads. The tailorability of braided composite archwires offers the potential to meet changing needs in applied loading during treatment in addition to their lower magnitude force delivery.

While the tailorability of the 3D braided archwires provides a significant advantage over existing archwires, there are several limitations of this study. One of these limitations is the cross-section definition. The non-axial braids had a well-defined square cross section, whereas the axial braids had a noticeable but slightly less defined square cross section. As the size of the yarn is decreased relative to the cross-sectional area, the definition of the shape increases. A mold may be used in the future for curing which will aid in generating the desired cross section. The wires that were produced in this study were larger than conventional ones used in practice. To obtain a smaller cross-sectional area that is necessary to produce a smaller archwire, smaller yarns that are available on the market can be used in future studies. In addition, the yellow Kevlar fibers would not generate an esthetically pleasing archwire; however, these fibers were readily available for this proof of concept study, hence their use. Esthetics of braided archwires could easily be improved through the use of transparent or opaque fibers, which are available on the market.

**Conclusions**

In this study, a miniature 3D Cartesian braiding machine was developed and utilized to produce orthodontic archwires that were impregnated with a shape memory polymer. Elastic moduli for 3D braided archwires both with and without axial yarns were characterized, in addition to torsional characterization for 3D braided archwires without axial yarns. From the work conducted in this preliminary study, the following conclusions can be made regarding the developed 3D braided composite wires:

- Differences in the elastic moduli of archwires with and without axial yarns are statistically significant, demonstrating that the 3D braiding process can be used to produce archwires that have tailored properties by adjusting the braid angle of the yarns.
- In comparison with the existing archwire properties in literature, the 3D braided composite archwires can be produced with tensile and torsional properties in a similar range.

Based on the findings of this study, it is suggested that braided composite orthodontic archwires offer a promising alternative to existing archwires and are worthy of further investigation. Future work will involve automation of the manual braiding machine and the detailed testing of dimensionally accurate samples.

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