FLEXURAL STIFFNESS OF GFRP COMPOSITE ORTHODONTIC ARCHWIRES

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1 Introduction

Tooth movement for correcting functional occlusion is clinically obtained through the application of light, but continuous forces imposed by an orthodontic system composed by archwires and brackets, which are attached to the teeth. The load-release system should behave elastically over the period of the treatment, from weeks to months.

The introduction of new archwire materials led to a growing interest on mechanical properties comparison for since the 80s. Stainless steel, the traditionally material of choice in the clinical practice since the 40s, was increasingly substituted by nickel and titanium alloys in the 70s, and by titanium-molybdenum alloys a decade later [1] [2].

Currently, the orthodontic treatment has become more common in adult patients, and the demand for improvement in the esthetic quality has been increasing [3]. As a result, composite materials archwires are commercially available as an important option for orthodontists. These materials associate superior properties of stiffness and strength with the esthetic appearance, which is an important concern of the patient. Glass fiber reinforced plastics (GFRP) are particularly suitable for this application, due to its relatively high specific stiffness and strength and almost transparent appearance [4]. Esthetic differences between metal and GFRP orthodontic archwires can be observed in Fig. 1.

However, very few information on mechanical behavior of composite archwires is available in the literature. The flexure stiffness is the most important mechanical property, directly related to the level of load released after a displacement is imposed to the system by the orthodontist. Manufacturers claim that composite mechanical performance is comparable to metallic archwires in terms of flexural stiffness.

In this work, a three-point bending test program was conducted according to the ISO Standard 15841 [5] in commercially available orthodontic archwires, in order to evaluate their flexural stiffness. Test specimens were cut from circular cross section GFRP archwires. Results were compared to stainless steel archwires data obtained from the literature.

Fig. 1. Esthetics of metal (top) and GFRP (bottom) orthodontic archwires.

2 Materials and Methods

The commercially available GFRP composite orthodontic archwire used in this study was the OPTIS™ (TP Orthodontics), with circular cross section diameters of 0.014” (0.36 mm), 0.016” (0.41 mm) and 0.018” (0.46 mm). Two GFRP test specimens with 32 mm length were cut from the linear portions at the back of each orthodontic archwire (Fig. 2).

Flexure stiffness was evaluated using three-point bending quasi-static tests (Fig. 3) conducted according to ISO 15841 [5] on a Dynamic Mechanical Analyzer (DMA) Model Q800 (TA Instruments).

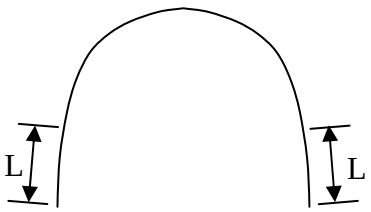

Fig. 2. OPTIS™ Superior Straight Arch and regions where specimens were cut.

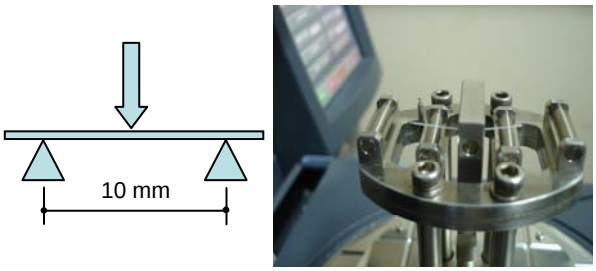

Fig. 3. Three-point bending creep test schematic view (left) and test setup (right).

GFRP archwires stiffness was measured from the linear portion of the load-displacement diagrams. The Young's Modulus was calculated from Eq. (1) obtained from the expression for midspan deflection in a three-point bending simply supported beam:

$$E = \frac{P L^3}{48 \delta I} \qquad (1)$$

where P is the applied load, L is the bending span, δ is the midspan deflection and I is the moment of inertia.

Stainless steel data was obtained from the work of Andreasen and Hillerman [6] also for 0.014" (0.36 mm), 0.016" (0.41 mm) and 0.018" (0.46 mm) archwires.

3 Results

Stiffness. A three-point bending test program was conducted to evaluate the GFRP archwires stiffness. Results are presented in the form of load vs. displacement plots in Figs. 4, 5 and 6, respectively for archwires with diameters of 0.014" (0.36 mm), 0.016" (0.41 mm) and 0.018" (0.46 mm). Five test specimens were cut from three 0.014" (0.36 mm) diameter archwires, and they were later submitted to three-point bending tests until midspan deflection of 2 mm (Fig. 4). For archwires with diameter of 0.016" (0.41 mm), four specimens were cut from two archwires, and flexural tests were conducted up to a maximum midspan deflection of 1 mm, reduced in order to avoid damage (Fig. 5). This same 1 mm maximum midspan deflection was used to test the five test specimens cut from three 0.018" (0.46 mm) diameter archwires (Fig. 6). A relatively high scatter is observed in Figs. 4, 5 and 6 with respect to the stiffness (slope of the load vs. displacement curves).

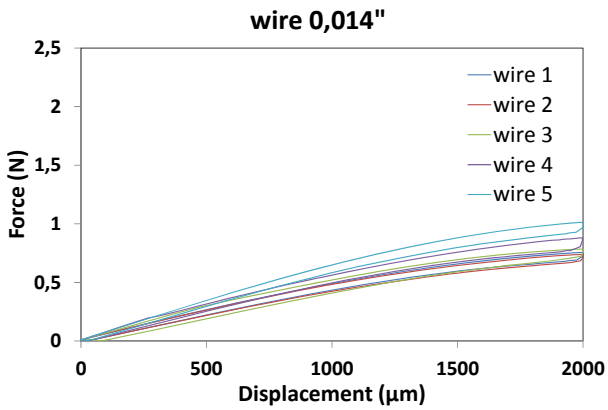

Fig. 4. Load vs. displacement results for 0.014" (0.36 mm) diameter archwire test specimens.

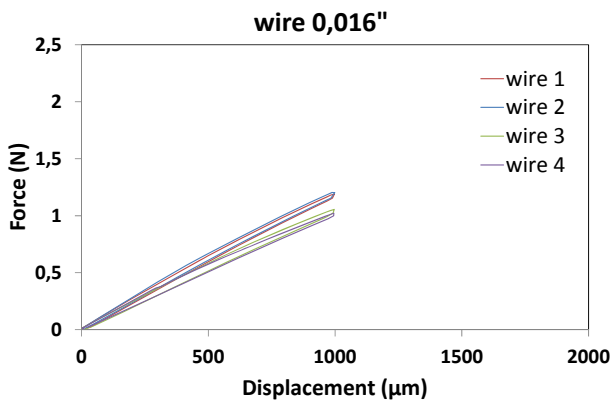

Fig. 5. Load vs. displacement results for 0.016" (0.41 mm) diameter archwire test specimens.

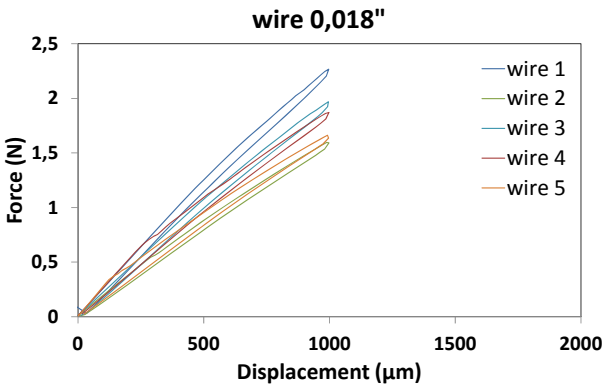

Fig. 6. Load vs. displacement results for 0.018” (0.46 mm) diameter archwire test specimens.

Fiber distribution. Further investigation on the fiber distribution along the archwire length showed severe non-uniformity of fiber distribution with large resin rich areas, probably due to the manufacturing process. Samples from archwires, for each diameter, were cut in three points (I, II and III) as shown in Fig. 7. Cross sections were polished and photographed using an optical microscope.

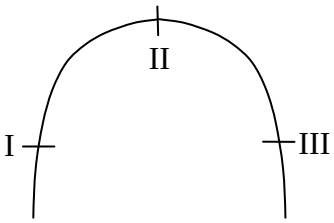

Fig. 7. Archwire cut sections.

Figures 8, 9 and 10 show cross section microscope photographs of cross sections respectively for samples of GFRP archwires with diameters of 0.014” (0.36 mm), 0.016” (0.41 mm) and 0.018” (0.46 mm). It can be observed from these figures that fiber distribution is not uniform at different cross sections along the archwires, which can explain the scatter found in the bending test results. Fiber concentration and resin rich areas drastically affect the cross section flexural behavior.

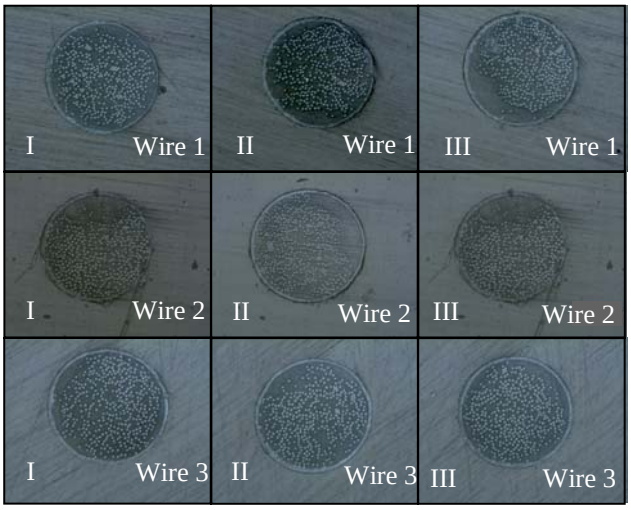

Fig. 8. Cross section images for three samples of 0.014” (0.36 mm) archwire.

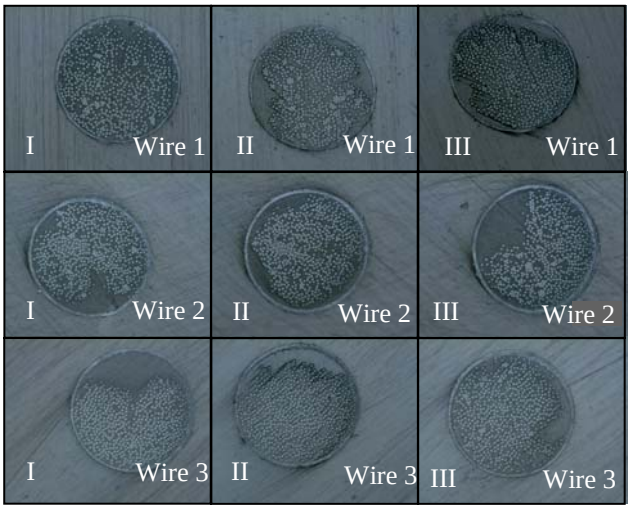

Fig. 9. Cross section images for three samples of 0.016” (0.41 mm) archwire.

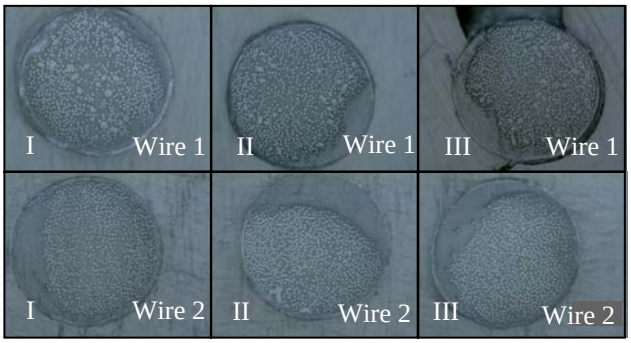

Fig. 10. Cross section images for two samples of 0.018” (0.46 mm) archwire.

Young's Modulus in fiber direction (E_1). GFRP Young's Modulus was evaluated from test data using Eq. (1), and predicted using fiber volume fractions considering micromechanics rule of mixtures with typical values for E-Glass/Epoxy systems (fiber modulus E_f = 72 GPa, and lamina modulus on the fiber direction E_1 = 38 GPa for a fiber volume fraction of v_f = 50%). Fiber volume fractions (v_f) for the GFRP archwires were evaluated using computer image processing tools for the microphotographs of the cross sections. Fiber volume fractions were consistently constant for each one of the diameters, indicating a finite number of continuous fibers along the archwire. Figures 11, 12 and 13 show microscope photographs of cross sections with fiber volume fractions evaluated for archwires respectively with diameter of 0.014" (0.36 mm), 0.016" (0.41 mm) and 0.018" (0.46 mm).

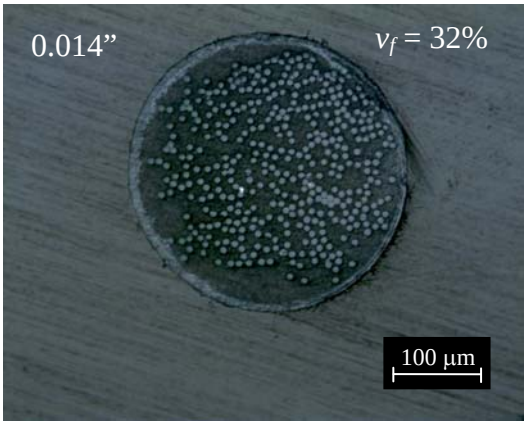

Fig. 11. Cross section image of 0.014" (0.36 mm) archwire with measured fiber volume fraction.

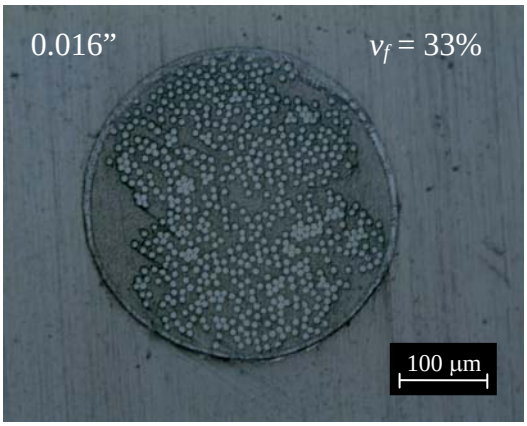

Fig. 12. Cross section images of 0.016" (0.41 mm) archwire with measured fiber volume fraction.

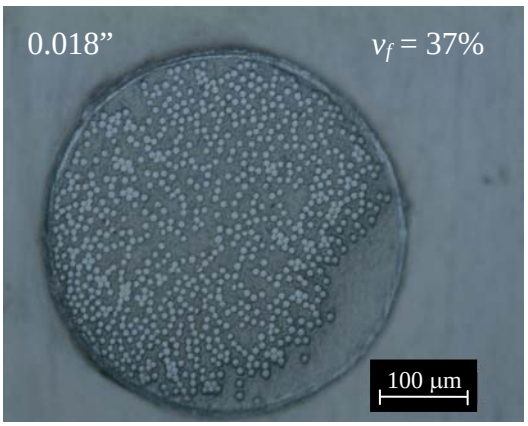

Fig. 13. Cross section image of 0.018" (0.46 mm) archwire with measured fiber volume fraction.

Table 1 shows the comparison for the Young's Modulus in fiber direction (E_1) evaluated from test data and predicted using micromechanics. These results are plotted in Fig. 14. It can be observed that micromechanics over predicted the Young's Modulus in the fiber direction. The large difference between the prediction and test values can be attributed to the non-uniform distribution of the fibers in the cross sections along the archwires, as previously commented. Flexural results are very sensitive to the cross section inertia and consequently to the fiber distribution.

Archwire Diameter	Eq. (1)		Micromechanics prediction	
	E_1	σ	E_1	v_f
0.014" (0.36 mm)	15.94	1.73	25.76	0.32
0.016" (0.36 mm)	19.26	1.39	26.44	0.33
0.018" (0.36 mm)	20.39	2.65	29.16	0.37

E_1 – Young's Modulus in fiber direction (GPa)
σ – Standard deviation (GPa)
v_f – Fiber volume fraction

Tab. 1. Three-point bending test flexural stiffness.

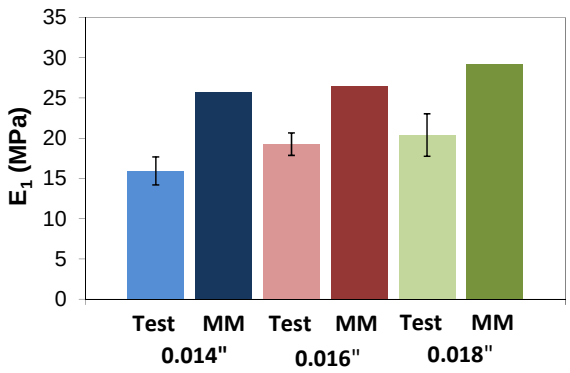

Fig. 14. Young's Modulus in fiber direction (E_1) considering test results (Test) and micromechanics prediction (MM).

GFRP vs. stainless steel. Stiffness results for GFRP and stainless steel orthodontic archwires were compared in order to establish a baseline for clinical decisions.

Table 2 shows the average bending stiffness evaluated from load vs. displacement curves for stainless steel and GFRP archwires. Stainless steel data was obtained from the work of Andreasen and Hillerman [6].

Archwire Diameter	Stainless Steel		GFRP	
	k_{av}	σ	k_{av}	σ
0.014" (0.36 mm)	4.49	0.29	0.54	0.07
0.016" (0.36 mm)	6.45	0.50	1.11	0.10
0.018" (0.36 mm)	8.00	0.53	1.84	0.30

k_{av} – Average bending stiffness (N/mm)
σ – Standard deviation (N/mm)

Tab. 2. Three-point bending test flexural stiffness.

Data from Tab. 2 is plotted in Fig. 15. It can be observed that GFRP archwires presents lower stiffness levels as compared to stainless steel archwires.

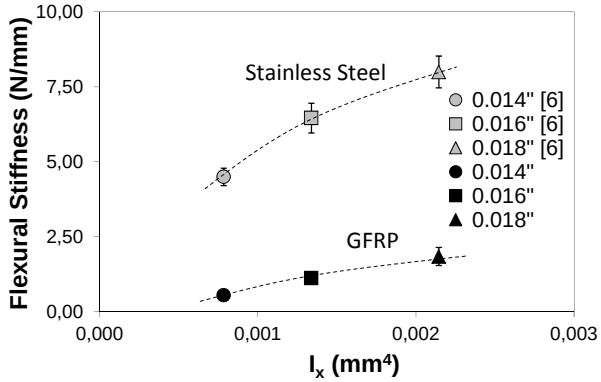

Fig. 15. Flexural stiffness vs. cross-section inertia for stainless steel and GFRP archwires.

4 Conclusions

Flexure stiffness was evaluated for GFRP orthodontic archwires with circular cross section diameters of 0.014" (0.36 mm), 0.016" (0.41 mm) and 0.018" (0.46 mm) by means of three-point bending tests. Non-uniform fiber distribution in cross sections along the archwires was observed and resulted in large scatter in the test results and in over prediction of Young's Modulus on the fiber direction using micromechanics rule of mixtures. GFRP archwires also presented lower stiffness level compared to stainless steel. Clinical decisions should balance esthetics with adequate mechanical performance in terms of stiffness. Better controlled manufacturing procedures for GFRP archwires should be attempted in order to produce more uniform fiber distribution on the cross sections.

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