REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
3.Nov.99

3. REPORT TYPE AND DATES COVERED
THESIS

4. TITLE AND SUBTITLE
FABRICATION AND ANALYSIS OF ROUND AND RECTANGULAR PHOTOPULTRUDED COMPOSITE ARCHWIRES AND THEIR CLINICAL USE AS FLEXIBLE BONDED ORTHODONTIC RETAINERS

5. FUNDING NUMBERS

6. AUTHOR(S)
MAJ FALLIS DREW W

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF NORTH CAROLINA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
FY99-394

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

19991117 081

14. SUBJECT TERMS

15. NUMBER OF PAGES
75

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

DTIC QUALITY INSPECTED 4

FABRICATION AND ANALYSIS OF ROUND AND RECTANGULAR PHOTO-PULTRUDED COMPOSITE ARCHWIRES AND THEIR CLINICAL USE AS FLEXIBLE BONDED ORTHODONTIC RETAINERS.

Drew Wayne Fallis

A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Orthodontics of the School of Dentistry.

Chapel Hill
1999

Approved by

Advisor: Professor Robert P. Kusy

Reader: Professor William R. Proffit

Reader: Professor Robert Reeber

ABSTRACT

Drew W. Fallis: Fabrication and Analysis of Round and Rectangular Photo-Pultruded Composite Archwires and their Clinical Use as Flexible Bonded Orthodontic Retainers.
(Under the direction of Robert P. Kusy)

A previously documented photo-pultrusion process was utilized to manufacture round (0.021inch diameter) and rectangular (0.021 x 0.028inch) unidirectional fiber-reinforced composite archwires. These archwires consisited of a copolymer matrix, 2,2-Bis[4-(2-hydroxy-3-methacryloxypropoxy)phenyl] propane (Bis-GMA) with triethylene glycol dimethacrylate (TEGDMA), and S2-glass® reinforcement fibers. Reinforcement of the composites was varied according to the % volume of fiber (%V_f), twists per inch (TPI) and denier of the S2-glass® yarns.

Morphological evaluation of polished cross-sectional profiles revealed no substantial differences as a result of denier in round or rectangular samples; however, increasing the TPI of the reinforcement fibers resulted in increased yarn isolation, peripheral loading, and intra-yarn voids.

Two flexural properties, modulus (E) and flexural strength (FS), were calculated from 3-point bending tests in an Instron® universal testing machine. Moduli varied from 21.1±2.1GPa to 53.6±2.0GPa for round samples and from 19.6±0.3GPa to 45.7±0.8GPa for rectangular samples. Flexural strengths reached maximum values of 1.36±0.10GPa for round samples and 1.40±0.05GPa for

rectangular samples. Analysis of these data revealed that E's increased as a function of loading in accordance with the rule of mixtures when 1TPI fibers were utilized; whereas, when 4TPI and 8TPI fibers were utilized, E's reached an optimal level, after which additional loading was ineffective. For FS's, an optimal $\%V_f$ was reached in all materials after which additional loading was ineffective. In round profiles utilizing 1TPI and 4TPI fibers, the optimal FS coincided with optimal peripheral loading. When the denier of the reinforcement yarns was increased, the FS's of round and rectangular samples increased.

The flexural values observed were comparable to those of current orthodontic wires used in the early to intermediate stages of treatment with E's ranging from below published values for martensitic nickel-titanium (33.4-44.4GPa) to those of beta-titanium (72.4GPa). The maximum FS was observed to occur in rectangular materials at $61\%V_f$ (1.40±0.05GPa) and was comparable to beta-titanium (1.3-1.5GPa).

Rectangular materials were bonded facially to teeth with Transbond® utilizing the acid-etched technique in three orthodontic situations in which flexible bonded retainers are traditionally indicated. These indications included: retention of a closed diastema, retention of space closure following premolar extraction, and retention of a canine that had previously been severely malpositioned. The protocol included 2, 2, 4, 8, and 8 week recall appointments for a 6 month total duration of study following initial study models and photographs to ascertain patient acceptance and structural integrity of the retainer. The retainers demonstrated excellent esthetic characteristics, structural integrity and patient acceptance for the duration studied. All patients were pleased with the comfort, cleansability, and esthetics of her retainers and described no untoward intra-oral effects from the retainer's presence.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to everyone who contributed to the completion of this thesis, with special recognition to:

Dr. Robert P. Kusy, my research advisor, for not only teaching a hard-work ethic but demonstrating it daily.

Dr. William R. Proffit, for giving me the opportunity to pursue a career in orthodontics and teaching me the importance of "Pooh Logic".

Dr. Robert Reeber, who reviewed this thesis and provided the input of a respected researcher in material science.

Many thanks to John Whitley and Deborah Price for bestowing their knowledge of illustrations and graphs.

I would like to thank the members of the Class of 1999 who made this educational experience thoroughly enjoyable: Dr. William Engilman, Dr. Andy Hass, Dr. Steve Austin, and Dr. Jackie Malone. You have been "true friends" in every way and your advice has helped me on numerous occasions.

Lastly, I would like to dedicate this work to the most important person in my life, my wife Rochelle Fallis, without whom I would be lost. Your love, patience and encouragement have made my professional endeavors possible.

TABLE OF CONTENTS

Chapter **Page**

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

TPI	twists per inch
$\%V_f$	percent volume of fiber
GPa	giga-pascal
NiTi	nickel titanium
UFRP	unidirectional fiber-reinforced plastic
CG150	continuous g-fibers @ 150 denier equivalent
CG75	continuous g-fiber @ 75 denier equivalent
UV	ultra-violet
E	modulus
FS	flexural strength
δ	deflection
P	applied load
L	span length
I	area moment of inertia
D	diameter of composite
b	base dimension of composite
h	height dimension of composite
M	maximum bending moment
c	sectional dimension

1. INTRODUCTION

1.1 Background, significance, and statement of overall goal

From the straw-reinforced bricks of Egypt to the structural components of advanced aircraft, the belief that a combination of different classes of materials can be combined to achieve properties greater than their individual components has been widespread. Composite materials have been used since antiquity, and applications for their uses have continued to be developed throughout the 20th century, resulting in continued research into their design and processing.

In 1951, W. B. Goldsworthy patented a continuous process for making fiber-reinforced composites called pultrusion [1]. This manufacturing process consisted of polymer-impregnated fibers that were "pulled-through" a heated die that shaped the material and cured the polymer. Although, the first application of pultrusion was in the manufacture of fiberglass fishing rods, uses were soon discovered in the hardware, aerospace, defense and medical fields. In the past decade, two patents have been issued for applications of thermal pultrusion in the field of dentistry [2,3]. This pultrusion process is ideally suited for the fabrication of small profile composites and has been recommended for use in dentistry to fabricate frameworks for provisional bridges, splints, retainers, space maintainers and orthodontic archwires [4]. Although these materials have mainly utilized thermoplastic polymers, numerous polymer matrices and reinforcement fiber combinations have been documented [5,6]. Studies have documented the flexural properties [7], hydrolytic stability [8], and the effect of moisture on the flexural properties [9].

Recently, a novel pultrusion process has been patented [10] utilizing photo-polymerization rather than the conventional thermal-polymerization and has several documented advantages [11,12]. This photo-pultrusion process has been utilized to fabricate small diameter fiber-reinforced composites with superior flexural properties to previous thermally-pultruded materials [13,14]. Studies have also been conducted to characterize the hydrolytic stability [15] and steady-state sorption [16] of these materials to determine their clinical viability.

When compared to conventional thermal protrusion, the photo-pultrusion process allows greater control over the polymerization initiation reaction; therefore, increasing the versatility of the process. By limiting the initiation reaction, these materials can be incompletely polymerized and post-formed into a desired shape. In this way, rectangular materials have been fabricated demonstrating excellent flexural properties [17].

Utilizing the photo-pultrusion process, composite materials can be manufactured with flexural properties that are comparable to conventionally used orthodontic materials but with superior esthetics. In fact, the moduli of the material can be tailored for specific applications by varying the % loading of the reinforcement fibers [13,14], creating an esthetic alternative to alloys in many orthodontic applications.

One such application is a flexible bonded orthodontic retainer, which is used to maintain the position of a tooth following orthodontic treatment while waiting for reorganization of the periodontal ligament and gingival fiber network. Histological studies have shown that this reorganization process takes in excess of 7 months to occur [18] and requires that the retained teeth be allowed to move independently [19].

A review of the current literature reveals that the most common wire used for the fabrication of a flexible-bonded retainer is a round stainless steel multistrand wire varying from 0.015 to 0.0215 in. in diameter [20,21]. This multistrand wire is most commonly bonded with a conventional restorative composite based on Bis-GMA (19) to the lingual of the two or more teeth to avoid the poor esthetic display of the metal wire. The use of a multistrand wire is recommended to achieve some degree of flexibility of the wire to allow physiologic movement of the teeth while maintaining the strength necessary to withstand forces from occlusion.

Photo-pultruded composite materials have moduli that range from nickel titanium (33.4 GPa) to near beta-titanium (72.4 GPa), producing about one-quarter the force of a stainless steel wire per unit of activation. Their reported flexural strengths are comparable to beta-titanium (1.3-1.5GPa). Therefore, these composite materials have the flexural properties necessary to fulfill the requirements for a flexible orthodontic retainer while demonstrating superior esthetic properties over conventional alloys.

1.2 Statement of generalized hypotheses and specific objectives

The **first hypothesis** of this work was that continuous rectangular fiber reinforced composites could be fabricated utilizing a recently patented photo-pultrusion apparatus into profile sizes approximating those of currently used orthodontic archwires.

Specifically, the objectives to be accomplished in analyzing this first hypothesis were to design, fabricate and test forming dies with internal rectangular geometry and incorporate these dies into a continuous photo-pultrusion apparatus. Although this photo-pultrusion process had previously been used to fabricate fiber-reinforced composite materials with circular cross-sections, the ability to generate geometrically acceptable rectangular composites had not been reported.

The **second hypothesis** of this work was that the flexural properties of both round and rectangular photo-pultruded composites could be altered by changing fiber-reinforcement parameters.

Specifically, the objectives to be accomplished in analyzing this second hypothesis were to: 1) fabricate round and rectangular S2-glass® reinforced composites with consistent geometric cross-sections; 2) alter the mechanical properties of the composites by varying the % Volume fraction of reinforcement fiber within each material; alter the mechanical properties of the composites by varying the number of twists per inch (TPI) incorporated in the reinforcing yarns; and 3) analyze the effects on the mechanical properties of the composites when the denier, number of S2-glass® filaments per yarn, was increased.

The **third hypothesis** of this work was that these photo-pultruded composites could be used effectively in clinical orthodontic situations involving bonded retention.

Specifically, the objectives to be accomplished in analyzing this third hypothesis were to: 1) bond these composite wires intra-orally to teeth in situations in which flexible bonded retention is traditionally indicated; and 2) monitor these retainers macroscopically during periodic recall appointments to ascertain structural integrity, maintenance of tooth position and patient acceptance.

The investigations in this work, as outlined above, are presented in Chapters 2-3 of this document. These chapters have each been designed as a stand-alone paper and submitted for publication. Since each chapter is submitted in journal format, the writing styles, terms and symbols may vary somewhat between them. All tables and figures appear after the reference sections of these chapters.

1.3 References

1. DAVIDSON, M., *Adv Mater & Proc* **146** (1994) 70.

2. GOLDBERG, A. J. and BURSTONE, C. J., "Orthodontic Appliance System" U.S. Patent No. 4,717,341 (1988).

3. GOLDBERG, A. J. and BURSTONE, C. J., "Passive Dental Appliances of Fiber-Reinforced Composites" U.S. Patent No. 4,894,012 (1990).

4. GOLDBERG, A. J. and BURSTONE, C. J., *Dent Mater* **8** (1992) 197.

5. KARMAKER, A. C., DIBENEDETTO, A. T., and GOLDBERG, A. J., *J Biomater Appl* **11** (1997) 318.

6. GOLDBERG, A. J., BURSTONE, C. J., HADJIINIKOLAU, I., and JANCAR, J., *J Biomed Mater Res* **28** (1994) 167.

7. JANCAR, J., DIBENEDETTO, A. T., HADZIINIKOLAU, Y., GOLDBERG, A. J., and DIANSELMO, A., *J Mater Sci: Mater Med* **5** (1994) 214.

8. JANCAR, J. and DIBENEDETTO, A. T., *J Mater Sci: Mater Med* **4** (1993) 555.

9. JANCAR, J., DIBENEDETTO, A. T., and GOLDBERG, A. J., *J Mater Sci: Mater Med* **4** (1993) 562.

10. KUSY, R.P. and KENNEDY, K. C., "Novel Pultruded Fiber- Reinforced Plastic and Related Apparatus and Method" U.S. Patent No. 5,869,178 (1999).

11. NARAYANAN, V. and SCRANTON, A. B., *Trends in Polymer Sci* **5** (1997) 415.

12. BIGG, D. M., HISCOCK, D. F., PRESTON, J. R., and BRADBURY, E. J., *Polymer Composites* **14** (1993) 26.

13. KENNEDY, K. C. and KUSY, R.P., *J Vinyl Additive Technol* **1** (1995) 182.

14. KENNEDY, K. C., CHEN, T., and KUSY, R.P., in Advanced Composites X.; Prodeedings of the 10th Annual ASM/ESD Advanced Composites Conference & Exposition, Dearborn, MI, Nov 7- 10, 1994 (ASM International, Materials Park, OH, 1994) p. 191.

15. KENNEDY, K. C., CHEN, T., and KUSY, R.P., *J Mater Sci: Mater Med* **9** (1998) 243.

16. KENNEDY, K. C., CHEN, T., and KUSY, R.P., *J Mater Sci: Mater Med* **9** (1998) 651.

17. KENNEDY, K. C. and KUSY, R.P., *J Biomed Mater Res* **41** (1998) 549.

18. REITAN, K., *The Angle Orthodontist* **2** (1959) 105.

19. PROFFIT, W. R., "Contemporary Orthodontics. 3 ed.", St. Louis: Mosby; 1999.

20. AXELSSON, S. and ZACHRISSON, B.U., *J Clin Orthod* **26** (1992) 480.

21. BEARN, D. R., *Am J Orthod* **108** (1995) 207.

2. VARIATION IN FLEXURAL PROPERTIES OF ROUND AND RECTANGULAR COMPOSITE ARCHWIRES[a]

2.1 Abstract

Prototype continuous, unidirectional, fiber-reinforced, composite archwires were manufactured into round and rectangular profiles utilizing a photo-pultrusion process. Both 0.022 inch (0.56mm) diameter and 0.021x0.028 inch (0.53x0.71mm) rectangular composites were formed utilizing commercially available S2-glass® reinforcement within a polymeric matrix. Reinforcement was varied according to the number, denier, and twists per inch (TPI) of four S2-glass® yarns to volume levels of 32 - 74% for round and 41 - 61% for rectangular profiles. Cross-sectional geometry was evaluated via light microscopy to determine loading characteristics; whereas, two flexural properties (the elastic moduli and flexural strengths) were determined by 3-point bending tests. Morphological evaluation of samples revealed that, as the TPI increased from 1 to 8, the yarns were more separated from one another and distributed more peripherally within a profile. For round and rectangular profiles utilizing 1TPI fibers, moduli increased with fiber content approaching theoretical values. For round profiles utilizing1TPI and 4TPI fibers, flexural strengths increased until the loading geometry was optimized. In contrast, the flexural strengths of composites that were pultruded with 8TPI fibers

[a] The contents of Chapter 2 were submitted for publication in the *Journal of Materials Science Materials in Medicine* under the title "Variation in Flexural Properties of Photo-pultruded Composite Archwires: Analyses of Round and Rectangular Profiles". The paper is reproduced here with the express permission of the co-author, R. P. Kusy.

were not improved at any loading level. Doubling the denier of the yarn, without altering the loading, increased both the moduli and flexural strengths in rectangular samples; whereas, the increases observed in round samples were not statistically significant. At optimal loading the maximum mean moduli and strengths equaled 53.6±2.0 and 1.36±0.17 GPa for round wire and equaled 45.7±0.8 and 1.40±0.05 GPa for rectangular wires, respectively. These moduli were midway between that of martensitic NiTi (33.4 GPa) and beta-titanium (72.4 GPa), and produced about one-quarter the force of a stainless steel wire per unit of activation. Values of strengths placed this composite material in the range of published values for beta-titanium wires (1.3-1.5 GPa).

2.2 Introduction

Since the first patent issued for pultrusion in 1951, substantial advancements have been made in this industry [1]. Although the first market for this process was in the field of sporting goods (solid fiberglass fishing rods), once techniques improved new markets soon opened-up in the hardware, automotive, electronic, aerospace, and the medical fields [2]. In the past decade, several investigations have been conducted documenting the feasibility of thermally pultruded continuous fiber reinforced composites in dentistry [3-7]. Recently, a novel approach for pultruding small diameter composites was designed utilizing photo-polymerization rather than heat-activated polymerization [8,9] which has many advantages over conventional thermal pultrusion. These advantages include a solvent-free process, high-energy efficiency, and control of the initiation reaction [10].

The photo-pultrusion process has spawned interest into the development of small diameter, fiber-reinforced plastics for the orthodontic field. To determine clinical feasibility, in vitro investigations have characterized the steady-state sorption [11] and hydrolytic stability [12]. Highly reinforced composite profiles have been fabricated, having diameters of approximately 0.5mm, that have demonstrated excellent flexural properties [13]. And although rectangular materials have been fabricated utilizing a two-stage technique (beta staging) [14], to date only round profiles have been fabricated utilizing this continuous process.

With the vast number of orthodontic wires on the market already demonstrating an array of flexural properties, esthetics would appear to be the main advantage of these composites for tooth movement and tooth retention. However, more important structural advantages exist. Because the geometry of the reinforcement fibers can be altered internally, the overall dimensional profile can be maintained while the flexural modulus is varied to suit the individual treatment objectives. This remains a distinct advantage in the practice of variable modulus orthodontics where, for the same size and shape of wire, the alloy type is altered to achieve the flexural properties necessary to efficiently move teeth [15]. Since the composite's size, shape, and chemistry are constant, more consistent wire-bracket couple interactions are possible. By maintaining more consistent wire-slot angular relationships, more reproducible levels of friction are achieved [16].

This investigation evaluates composites of round and rectangular, unidirectional, fiber-reinforced plastic (UFRP) profiles that were fabricated continuously using this novel photo-pultrusion process [8]. The bending tests demonstrate the influence of fiber reinforcement parameters on elastic moduli and flexural strengths. These findings show that, at selected loading levels, moduli can be varied by incorporating twist within the reinforcing fibers without a reduction in flexural strength; likewise, increasing the denier of the reinforcement yarn can enhance flexural properties.

2.3 Materials and Methods

2.3.1 Die Fabrication

Round and rectangular forming dies were fabricated from a type 400 stainless steel, housed within an aluminum core, and inserted into the pultrusion apparatus (Figure 1). The internal aspects of these dies were polished with a sequence of aqueous dispersions of Al_2O_3 (1.0 – 0.3μm).

2.3.2 Material Processing

Materials consisted of S2-glass® (magnesium aluminosilicate) fiber reinforcement (Owens-Corning Corp., Toledo, OH, USA) in a polymer matrix consisting of 61%wt bisphenol-A diglycidyl-methacrylate (Bis-GMA, Nupol 046-4005, Cook Composites and Polymers Co., North Kansas City, MO, USA) and 39%wt triethylene-glycol-dimethacrylate (TEGDMA, Polysciences Inc., Warrington, PA, USA). Benzoin-ethyl-ether (Aldrich Chemical Co., Inc. Milwaukee, Wis, USA), 0.4%wt, was added for photo-initiation. The S2-glass® fibers were acquired in yarn form, which had been pre-sized with a proprietary organo-silane binder. Four glass yarns were chosen (Table I), which differed in denier* and twist per inch (TPI).

*Denier, a measure of fiber size, is defined as the weight in grams of a 9000-meter length of fiber [17]. The manufacturer reports a converted yarn size by way of a coding system with the first number representing 1/100th the total approximate bare glass yardage in a pound of strand. The yardage per pound is then divided into a constant ($4.5x10^6$) to calculate a denier equivalent.

These yarns are supplied with a denier equivalent of 300 (CG150) or 600 (CG75), with the 300 having 50% less bare glass yardage per pound. Since the filament diameter is held constant, this difference in denier results because of an increase in the number of filaments per yarn. All yarns had a counter-clockwise pre-twist in the "Z" direction. These and other important material product designations are annotated in the footnote of Table I.

Round and rectangular composite profiles were generated utilizing a previously documented photo-pultrusion process [8,9] that incorporated a 300-450nm UV-curing lamp with an output provided by a 100 watt mercury-vapor bulb (Lightwave Energy Systems Co. Inc., LESCO, Redondo Beach, CA.). These materials were generated by a continuous process that varied the percent loading of reinforcement every 300cm. The percent loading by volume of fiber ($\%V_f$) was varied in a nominal 0.022 inch (0.56mm), round profile by staging the number of yarns incorporated into the pultrusion apparatus from 3 yarns ($32\%V_f$) to 14 yarns ($74\%V_f$). With the exception of S2 CG75 yarns, fabrication of composite materials with less than 8 yarns resulted in the flow of resin past the yarns into the curing chamber, causing clumps of cured resin on the profile. Due to the larger size of the CG75 yarn, round profiles could be fabricated with only 3 yarns (equivalent to six CG150 yarns or $32\%V_f$). The loading in a nominal 0.021x0.028 inch (0.53x0.71mm), rectangular profile was varied in stages from 12 yarns ($41\%V_f$) to 18 yarns ($61\%V_f$). When a CG75 fiber was used, the number of yarns was halved.

2.3.3 Morphological Examination

Samples were embedded in poly(methyl methacrylate), hand ground with SiC papers through 1200 grit, and polished in a Buehler® Vibromet polisher (Buehler LTD., Evanston, IL, USA) with a 1.0μm Al_2O_3 aqueous dispersion. Gross morphological examination was conducted with a Zeiss universal reflected-light microscope (Carl Zeiss, Oberkochen, Germany).

2.3.4 Light Source Distance Determination

Initial experimentation was conducted to produce and evaluate a material that was truly "rectangular". Because surface tension tends to cause the unpolymerized material to assume a round or oval profile, regardless of the die shape utilized, the optimal distance from the terminus of the die (Figure 1) to the point of initial polymerizing light exposure was required. Profiles were polymerized at 4 points beginning 3mm from the curing chamber and collected at each 1mm increment of distance until the die terminus was in the chamber (0mm from the light source).

Microscopic analysis revealed that the positioning of the die had profound effects on a profile's morphology. Positioning the die terminus at the maximum distance tested (3mm from the curing chamber) resulted in surface-tension induced deformation; whereas, positioning at 0-1mm from the chamber resulted in polymerization inside the forming die, causing partial blockage and poor geometry. The optimal geometry was achieved when the die terminus was positioned 2mm from the entrance to the curing chamber. Since the rate of pultrusion was 1.27mm/sec, this position placed the material within the curing chamber 1.6 seconds after exiting the die terminus.

2.3.5 Flexural Properties

Utilizing 3-point bending in an Instron® Universal Testing Machine (Model TTCM, Instron Corp. Canton, MA, USA), five, 20mm long samples of each $\%V_f$ were tested at room temperature (23°C). Diametral measurements of each sample were obtained utilizing a Sony μ-mate® Digital Micrometer (Sony Magnescale America, Inc., Orange, CA, USA) by averaging the measurements made at five radial locations in the center of each sample.

Bending loads were applied to failure at a deflection rate of 0.1cm/min. Values for elastic modulus (E) and flexural strength (FS) were calculated for each sample by utilizing equations 1 and 2:

$$E = PL^3 / 48I\delta \tag{1}$$

$$FS = Mc / I \tag{2}$$

where P = applied load, L = span length = 8.89 mm, I = area moment of inertia ($\pi D^4/64$ for round and $bh^3/12$ for rectangular profiles where D = diameter of sample, b = base of rectangle, and h = height of rectangle), δ = beam deflection, M = maximum bending moment, and c = sectional dimension for round (D/2) and for rectangular (h/2) sections [18].

A fully-factorial multiple analysis of variance (MANOVA) was performed to determine significant differences in E and FS as a function of denier, the TPI, and $\%V_f$ (SYSTAT Version 5, SYSTAT, Inc., Evanston, IL, USA). Statistical significance was ascribed to the results when a probability value of $p < 0.05$ was observed. P-values < 0.001 were noted as highly significant. Significant interactions were investigated further with the Tukey HSD post-hoc comparison of individual means.

2.3.6 Percent Loading Determination

The $\%V_f$ of S2-glass® in each profile is dependent upon the overall dimensions and shape of the profile and the individual size, number, and TPI of each filament within the yarn. As the number of twists per inch of each yarn increases, the helix angle of each filament decreases. This has the effect of increasing the $\%V_f$ loading of S2 glass® in each profile due to the increased area of the ellipse formed by each filament in cross section. Based upon the previously reported equation [19], the helix angle (α) for each filament can be calculated within the present context as

$$\alpha = \tan^{-1}[(TPI)(\pi)(d_y - d_f)]^{-1}, \quad (3)$$

where $d_y =$ overall diameter of a yarn [0.011 inch (0.28mm) for CG75 and 0.008 inch (0.20mm) for CG150], and $d_f =$ component filament diameter (0.000354 inch ≈ 9μm).

Once the helix angle is determined, the area (A) of the elliptical fibers can be calculated according to the equation,

$$A = N \pi d_f d / 4, \quad (4)$$

where $N =$ number of filaments, $d_f =$ length of the minor axis = component filament diameter, and $d =$ length of the major axis $= d_f / \sin \alpha$.

Therefore,

$$A = N \pi d_f^2 / 4 \sin \alpha, \quad (5)$$

which for CG150 and CG75 yarns may be written as

$$A = 204 \pi d_f^2 / 4 \sin \alpha \quad (6)$$

and

$$A = 408 \pi d_f^2 / 4 \sin \alpha, \quad (7)$$

respectively.

Finally, the $\%V_f$ may be obtained from A and the overall area of the round and rectangular composites may be written as

$$\%V_f = 100\ A\ /\ (0.785\ D^2) \tag{8}$$

and

$$\%V_f = 100\ A\ /\ (bh), \tag{9}$$

respectively.

2.4 Results

2.4.1 Morphological Examination

The evaluation of round and rectangular profiles revealed that the loading characteristics and profile morphology changed when $\%V_f$ and/or TPI were altered (Figures 2-5). When loading and morphology in round profiles were evaluated at 3 different levels of $\%V_f$ and TPI, as the twist was increased from 1 to 8TPI, increases in yarn isolation and intra-yarn voids are observed at each $\%V_f$ (Figure 2). When the denier was doubled, the morphology of round profiles was altered (Figure 3). When rectangular profiles were compared at 6 different levels of $\%V_f$, a marked improvement in the geometry was observed as the $\%V_f$ increased (Figure 4). When rectangular profiles with a constant $\%V_f$ were compared at 3 different levels of TPI (Figure 5), the same loading and morphological characteristics as those seen in round profiles were observed (Figure 2).

2.4.2 Flexural Properties

The $\%V_f$ determinations of round and rectangular profiles of differing TPI revealed that, as the twist increased from 1TPI to 8TPI, the $\%V_f$ of these small profiles never increased by more than 2% (Tables II and III). Therefore, nominal $\%V_f$'s were used for all calculations, independent of TPI. The evaluation of round and rectangular profiles in 3-point bending revealed that altering $\%V_f$, denier, and TPI influenced E's and FS's (Figures 6 and 7). The mean values for the round and rectangular profiles were calculated and standard deviations (s.d.) determined (Tables II and III). Analysis of this data revealed that the variability of s.d.'s among round profiles was generally below 15% of mean values for E's and FS's. The variability of s.d.'s for rectangular profiles was less than 5% of mean values for E's and generally less than 10% for FS's. When mean E's for round and rectangular profiles were plotted (Figure 6 and 7), a positive correlation with theoretical values predicted by the rule of mixtures for fiber reinforced composites [20], was generally observed (Figures 6 and 7, dotted line). Statistical analyses (Figures 6 and 7, right side) revealed that significant changes occurred when $\%V_f$, denier, and TPI were altered (Figures 6 and 7, right side).

2.5 Discussion

2.5.1 Morphology (Round)

The type of reinforcement fiber greatly influenced the morphology as well as the loading characteristics of these round, unidirectional, fiber-reinforced composites. As the TPI of the yarn was increased from 1 to 8, the yarn tended to retain its intra-yarn cohesion following the spreading procedure, which led to more isolated and peripherally placed yarns in the finished profile (Figure 2, row 1). This characteristic also had the negative effect of inhibiting ideal fiber separation during the spreading procedure, leading to incomplete resin coating and intra-yarn voids (Figure 2, arrows). As the $\%V_f$'s of 4 and 8TPI yarns were increased, the external surfaces of the samples became increasingly more convoluted, assuming the characteristic cross-sectional outline of a multistranded orthodontic archwire (Figure 2, columns 2 and 3).

With the profile dimensions utilized, 9 yarns ($48\%V_f$) could be placed to fill the periphery completely. Within the CG150/1TPI group (Figure 2, column1), the yarns loaded centrally until sufficient numbers of yarns were present to allow external surface tension to draw them toward the periphery. The CG150/1TPI group attained a peripheral loading of 9 yarns only after 12 yarns were incorporated ($63\%V_f$). Three yarns were needed in the central core to allow complete peripheral loading. Within the CG150/4TPI group (Figure 2, column 2), the yarns also loaded centrally until a sufficient number was present to allow complete peripheral loading of 9 yarns after 10 yarns were incorporated ($53\%V_f$). One yarn was placed centrally. An unusual observation was noted within the CG150/4TPI group in that, at a loading level of 12 yarns ($63\%V_f$), a tenth yarn was forced into the periphery. This occasional finding appeared to be a direct result of the greater intra-yarn cohesion leading to a tighter packing of yarns within the profile. Within the CG150/8TPI group (Figure 2, column 3), the yarns loaded peripherally even before the ideal number was present for complete peripheral loading. Peripheral loading occurred with 8 yarns ($42\%V_f$), prior to the presence of the geometrically optimal level of 9 yarns ($48\%V_f$).

When the denier of the reinforcement was varied in round profiles, differing morphological characteristics were observed. As with previous 1TPI yarns, loading began centrally and progressed peripherally until the profile was completely filled. At lower loading levels the circular geometry was better in both groups (Figure 3, row 1); at high loading levels the geometry of the CG75/1TPI group was negatively affected by an increase in yarn size (Figure 3, row 2). Based upon these observations, increasing the denier of the yarn had some beneficial effects when the loading was low; however, the large denier yarns apparently influenced more the morphology of these composites at high $\%V_f$.

2.5.2 Morphology (Rectangular)

Evaluation of rectangular samples revealed that, when CG150/1TPI yarns were used for reinforcement, the yarns initially loaded more peripherally leaving a matrix rich zone in the center of the profile. As additional yarns were added the matrix-rich zone decreased in area, although yarns were still being forced further to the periphery (Figure 4). "Filling-out" of the die and the resultant optimal rectangular profile were not observed until 17 yarns were incorporated ($58\%V_f$).

As seen in the loading characteristics of round profiles, the incorporation of increased twists per inch enhanced yarn isolation, increased peripheral loading at lower loading levels, and increased intra-yarn voids. Optimal rectangular morphology was observed at 14 yarns ($48\%V_f$) when CG150/4TPI and CG150/8TPI yarns were used for reinforcement (Figure 5). Moreover, as in round profiles, a convoluted external surface was evident. Based upon these observations, reinforcement of rectangular composite profiles with yarns incorporating more twists per inch apparently facilitates the attainment of the ideal rectangular morphology at lower $\%V_f$. This is most likely a result of the greater tendency of the twisted fibers to load peripherally, filling-out the die.

Although not shown, a comparative evaluation of the effects of increased denier (CG75 versus CG150) at 1TPI revealed no appreciable differences in the morphology of rectangular profiles.

2.5.3 Flexural Properties

In the study of anisotropic composite materials, we expect that at least the E would follow the "rule of mixtures" [20]. To evaluate this assumption, the theoretical values were calculated and compared with the experimental values observed in this study (Figures 6 and 7, dotted lines versus data). When 1TPI fibers were utilized, the E of the round and rectangular profiles generally increased as a function of fiber content in agreement with the rule of mixtures, albeit offset somewhat by the inefficiency caused by the less than perfect adhesion. When 4 and 8TPI fibers were utilized, E reached a maximum value after which additional loading was ineffective.

The FS's reached an optimal level, after which additional loading was not beneficial. This optimal level seemed dependent upon the denier of the yarn utilized for reinforcement, with the highest FS's being reached when the CG75 yarn was used. This optimal level was also dependent upon the TPI of the reinforcement yarn, with optimal FS's being reached at successively lower $\%V_f$'s as the TPI's increased. These optimal FS's occurred coincidently with optimal peripheral loadings (Figure 2).

For the CG150/1TPI **round profiles** of the group, the E's continued to rise as a function of fiber content to a maximum value of $74\%V_f$ (14 yarns) (Figure 6, upper left). The FS reached the highest level at $63\%V_f$ (12 yarns) (Figure 6, lower left), which corresponded to the level at which optimal peripheral loading occurred (Figure

2, column 1). Additional loading did not increase the strength, once the periphery of the profile was filled (Figure 6, lower right). The E and FS were not significantly altered for the same $\%V_f$, when the denier of the reinforcement fiber was doubled (Figure 6, right).

In the CG150/4TPI group, the E continued to rise as a function of fiber content to the level of $63\%V_f$ (12 yarns) (Figure 6, upper left), after which no significant difference was noted (Figure 6, upper right). The FS reached its highest level at $53\%V_f$ (10 yarns) (Figure 6, lower left), which corresponded to the first loading level after which optimal peripheral loading occurred (Figure 2, column 2). Although the maximum strength occurred at this $\%V_f$, no statistically significant difference was observed at any $\%V_f$ (Figure 6, lower right).

In the CG150/8TPI group, the E increased to a maximum value at $53\%V_f$ (10 yarns) (Figure 6, upper left), which was a significant change from the E at $42\%V_f$ (8 yarns). A further increase in $\%V_f$ to $63\%V_f$ (12 yarns) resulted in no significant change (Figure 6, upper right). The FS reached its highest level by $42\%V_f$ (8 yarns) (Figure 6, lower left), which corresponded to the first level observed to have all reinforcement yarns peripherally placed (Figure 2, column 3). The maximum FS occurred at $42\%V_f$ but was not significantly different from the values observed at other levels (Figure 6, lower right).

Evaluation of **rectangular profiles** revealed that, when 1TPI fibers were utilized, both E and FS increased as a function of fiber content at all loading levels (Figure 7, left). Comparisons between the two 1TPI groups revealed that, when the denier was doubled (CG75 versus CG150), an increase in E occurred, whose difference was highly significant at all loading levels except 48%V_f (Figure 7, upper right). Comparison of FS's revealed an increase at all loading levels (Figure 7, lower right).

Evaluation of 48%V_f samples as a function of TPI revealed that an increase in TPI resulted in no significant change in E (Figure 7, upper right). However, an increase in TPI resulted in a decrease in the FS of the CG150/8 TPI group that was highly significant (Figure 7, lower right). This decrease in FS appears to be a direct result of the decreased efficiency of fiber-matrix interfacial bonds as evidenced by the increased number of intra-yarn voids (Figures 2 and 5).

2.5.4 In Perspective

When loading was optimized according to %V_f, denier, and TPI, the maximum mean E's and FS's equaled 53.6±2.0 and 1.36±0.17 GPa for round profiles and equaled 45.7±0.8 and 1.40±0.05 GPa for rectangular profiles, respectively (Table II and III). Comparison of these E and FS values with other traditional and experimental materials (Table IV) [2,3,9,13,14,21-24] revealed that these materials could be engineered to exhibit a range of E's while demonstrating superior FS's than comparable reinforced plastics. When compared to currently available orthodontic archwires, moreover, these E's were midway between martensitic NiTi (44.4 GPa for round and 33.4 GPa for rectangular) and beta-titanium (72.4 GPa), that is, about one-quarter that of stainless steel (181-206 GPa) [21,23]. Comparison of FS values placed this composite material in the range of published values for beta-titanium wires (1.3-1.5 GPa) [21].

The round profiles having the highest mean E value (53.6±2.0 GPa) were fabricated with CG150/1TPI fibers at 74%V_f. When the TPI was increased using CG150/4TPI fibers, E equaled 52.5±3.1 GPa at only 64%V_f with identical FS's of 1.23±0.08 GPa (Table II). Consequently, the incorporation of 4TPI in the reinforcement fibers may be beneficial in round composites when higher E's are desired for a given %V_f (Figure 6) or when a higher degree of peripheral loading of yarns is desired (Figure 2).

The highest FS's in round and rectangular profiles were observed when composites were fabricated with CG75/1TPI fibers (Figures 6 and 7). When compared to CG150/1TPI fibers, the CG75/1TPI fibers produced a statistically significant difference in rectangular profiles, although the change noted for round profiles was not significant. Apparently increasing the denier of the reinforcing yarns improved the FS values, which are dependent upon many factors: (1), the individual strengths of the fibers; (2), the %V_f's; (3), the orientation of the fibers; (4), damage to the fibers during manufacture; and (5), the efficiencies of the fiber-matrix interfacial bonds. In this study most of these factors were maintained, while the denier was altered. Since the number of intra-yarn voids were comparable in the CG75/1TPI and CG150/1TPI groups (Figure 3), the efficiency of the fiber-matrix interfacial bond is not a major contributor to the increase in FS. On the other hand, increasing the number of glass fibers per yarn increases the likelihood of fiber uniformity by decreasing the number of independently oriented yarns within the profile. This enhancement of fiber alignment results in a more uniform transfer of load to the fiber resulting in an increased FS. Also, due to the increased size of the CG75 yarns, relatively speaking about 30% fewer fibers are exposed at the circumference of these yarns as compared to the equivalent $\%V_f$ of CG150 yarns. In absolute terms then, when compared at $63\%V_f$, about 200 fewer fibers are immediately susceptible to damage during handling in a 0.022in.(0.56mm) round wire prior to photo-pultrusion (Appendix 1).

2.6 Conclusions

The manufacture of continuous, small profile, rectangular composite profiles is possible utilizing this novel photo-pultrusion process.

The incorporation of increased twists per inch (TPI) within the reinforcement yarns enhances yarn isolation (increases the matrix-rich zones between yarns), increases peripheral loading, and provides more ideal morphology at lower loading levels ($\%V_f$'s), but inhibits ideal polymer coverage during manufacture and leads to voids.

The incorporation of 4TPI in the reinforcement fibers may be beneficial, when a higher modulus (E) is desired for a given $\%V_f$, but this benefit appears dependent on the $\%V_f$ selected.

The incorporation of 8TPI yarns does not enhance flexural strength (FS) at any $\%V_f$.

The E's increase as a function of loading in accordance with the rule of mixtures when 1TPI fibers are utilized. When 4TPI and 8TPI fibers are utilized for reinforcement, E reaches an optimal level, after which additional loading is ineffective. These optimal E's are reached at lower $\%V_f$ levels as the TPI is increased.

For FS's, an optimal $\%V_f$ is reached in all materials after which additional loading is ineffective. In round profiles utilizing 1TPI and 4TPI fibers, the optimal FS coincided with optimal peripheral loading.

When the denier is increased (by increasing the number of filaments per yarn), the FS's of round and rectangular profiles increase.

2.7 Acknowledgements

The authors would like to thank Mr. John Q. Whitley for artwork, the UNC-CH Department of Orthodontics for financial support, and Owens Corning Corp. and Atkins-Pearce Corp. for contributing the S2-glass® yarn materials.

2.8 References

1. M. Davidson, *Adv Mater & Proc* **146** (1994) 70.

2. T. J. Reinhart and L.L Clements, in "Engineered Materials Handbook, Vol. 1; Composites", ASM International (1987) p. 28.

3. A. J. Goldberg and C. J. Burstone, *Dent Mater* **8** (1992) 197.

4. A. C. Karmaker and A. T. DiBenedetto, and A.J. Goldberg, *J Biomater Appl* **11** (1997) 318.

5. J. Jancar, A. T. DiBenedetto, and A. J. Goldberg, *J Mater Sci: Mater Med* **4** (1993) 562.

6. J. Jancar, A. T. DiBenedetto, Y. Hadziinikolau, A. J. Goldberg, and A. Dianselmo, *J Mater Sci: Mater Med* **5** (1994) 214.

7. J. Jancar and A. T. DiBenedetto, *J Mater Sci: Mater Med* **4** (1993) 555.

8. R. P. Kusy and K. C. Kennedy, "Novel Pultruded Fiber- Reinforced Plastic and Related Apparatus and Method" U.S. Patent No. 5,869,178 (1999).

9. K. C. Kennedy and R. P. Kusy, *J Vinyl Additive Technol* **1** (1995) 182.

10. V. Narayanan and A. B. Scranton, *Trends in Polymer Sci* **5** (1997) 415.

11. K. C. Kennedy, T. Chen, and R. P. Kusy, *J Mater Sci: Mater Med* **9** (1998) 243.

12. K. C. Kennedy, T. Chen, and R. P. Kusy, *J Mater Sci: Mater Med* **9** (1998) 651.

13. K. C. Kennedy, T. Chen and R.P. Kusy, in Advanced Composites X.; Prodeedings of the 10th Annual ASM/ESD Advanced Composites Conference & Exposition, Dearborn, MI, Nov 7- 10, 1994 (ASM International, Materials Park, OH, 1994) p. 191.

14. K. C. Kennedy and R. P. Kusy, *J Biomed Mater Res* **41** (1998) 549.

15. C. J. Burstone, *Am J Orthod* **80** (1981) 1.

16. R. P. Kusy, *The Angle Orthodontist* **67** (1997) 197.

17. R. A. Flinn and P. K. Trojan, "Engineering Materials and Their Applications, Third Edition", (Houghton Mifflin Company, Boston, 1986) p. 447.

18. O. W. Eshbach and M. Souders, "Handbook of Engineering Fundamentals 3rd ed." (John Wiley and Sons, New York, NY, 1975) 513 and 518.

19. R. P. Kusy and L. E. Stevens, *The Angle Orthodontist* **57** (1987) 18.

20. J. F. Shackelford, "Introduction to Materials Science for Engineers 2nd ed." (Macmillan Publishing Co., New York, NY, 1988) p. 473.

21. R. P. Kusy and A. M. Stush, *Dent Mater* **3** (1987) 207.

22. A.J. Goldberg, C.J. Burstone, I. Hadjinikolaou, and J. Jancar, *J Biomed Mater Res,* **28** (1994) 167.

23. R.P. Kusy, G.J. Dilley, and J.Q. Whitley, *Clinical Mater* **3** (1988) 41.

24. Elgiloy® and Tru-Chrome® Stainless Steel Orthodontic Treatment Wires, promotional literature of Rocky Mountain Orthodontics, (1977) p. 5.

Table 2-1. Specifications of S2 glass® yarns investigated.

Material Product Designation*	Denier Equivalent	Bare Glass (yds./lb.)	Filament Diameter, d_f (μm)	Twists Per Inch (TPI)
S2 CG75 1/0 1.0Z 493	600	7,500	9	1
S2 CG150 1/0 1.0Z 493	300	14,900	9	1
S2 CG150 1/0 4.0Z 493	300	14,900	9	4
S2 CG150 1/0 8.0Z 493	300	14,900	9	8

*U.S. Customary System is used for fiberglass yarn nomenclature, where:
S2 denotes the type of glass yarn,
C denotes continuous fiber type,
G denotes filament diameter code of 9 microns,
75 denotes 1/100th the bare glass yardage per pound of strand, equal to 7,500yds/lb or 600 denier equivalent or
150 denotes 1/100th the bare glass yardage per pound of strand, equal to 15,000yds/lb or 300 denier equivalent,
1/0 denotes 1 yarn without additional plies,
1.0Z denotes 1 twist per inch twisted in the "Z" direction (counter-clockwise), and
493 denotes the recommended sizing for use in Bisphenol-A type polymers.

Table 2-2. Summary of flexural properties for round composite profiles.

Yarn Type	Loading (%V_f)	(# yarns)	Elastic Modulus, E (GPa)*	Flexural Strength, FS (GPa)*
CG75/1TPI	32	3	21.3±2.1 (9)	1.02±0.12 (12)
	42	4	29.4±5.3 (18)	1.12±0.11 (10)
	53	5	43.2±5.5 (13)	1.36±0.17 (13)
	63	6	46.0±1.8 (4)	1.35±0.10 (7)
CG150/1TPI	42	8	33.7±5.7 (17)	1.11±0.11 (10)
	48	9	34.7±3.9 (11)	1.18±0.11 (9)
	53	10	37.8±1.3 (3)	1.18±0.13 (11)
	63	12	44.5±3.1 (7)	1.34±0.14 (10)
	74	14	53.6±2.0 (4)	1.23±0.09 (7)
CG150/4TPI	43	8	29.5±3.0 (10)	1.08±0.08 (7)
	48	9	39.5±2.2 (6)	1.09±0.13 (12)
	53	10	44.9±3.8 (8)	1.26±0.15 (12)
	64	12	52.5±3.1 (6)	1.23±0.08 (7)
	74	14	52.4±3.3 (6)	1.25±0.12 (10)
CG150/8TPI	43	8	29.7±2.6 (9)	1.07±0.06 (6)
	54	10	40.8±2.8 (7)	0.98±0.04 (4)
	65	12	39.5±1.4 (4)	1.01±0.03 (3)

*Mean ± one standard deviation (s.d.) for five specimens tested. The number in parentheses represents the precision as a percent = 100(s.d./mean).

Table 2-3. Summary of flexural properties for rectangular composite profiles.

Yarn Type	Loading (%V_f)	Loading (# yarns)	Elastic Modulus, E (GPa)*	Flexural Strength, FS (GPa)*
CG75/1TPI	41	6	28.9±0.4 (1)	0.91±0.08 (9)
	48	7	34.0±1.1 (3)	1.05±0.05 (5)
	54	8	39.3±1.2 (3)	1.25±0.07 (6)
	61	9	45.7±0.8 (2)	1.40±0.05 (4)
CG150/1TPI	41	12	19.6±0.3 (2)	0.78±0.06 (8)
	48	14	32.7±0.6 (2)	0.98±0.11 (11)
	54	16	36.7±0.3 (1)	1.07±0.11 (10)
	61	18	38.6±1.8 (5)	1.17±0.06 (5)
CG150/4TPI	48	14	30.2±1.4 (5)	1.04±0.07 (7)
CG150/8TPI	48	14	32.4±0.3 (1)	0.84±0.06 (7)

*Mean ± one standard deviation (s.d.) for five specimens tested. The number in parentheses represents the precision as a percent = 100(s.d./mean).

Table 2-4. Comparison of flexural properties for conventional orthodontic materials and pultruded composites.

Material	Reference E	Reference FS	Elastic Modulus, E (GPa)*	Flexural Strength, FS (GPa)*
Conventional Orthodontic Materials				
Stainless Steel	[23]	[23]	181 - 206	2.10 - 2.85
Cobalt-chromium	[24]	[24]	196	2.34
Martensitic nickel titanium	[21]	[21]	33.4 - 44.4	1.55 - 1.93
Beta-titanium	[21]	[21]	72.4	1.31 - 1.50
Thermally-pultruded Composites				
E glass Reinforced				
70%V_f –unidirectional	[2]	[2]	41.4	0.69
S2 glass® Reinforced				
[a]42%V_f –unidirectional	[22]	[22]	17.9	0.43
[b]43%V_f –unidirectional	[3]	[3]	19.7	0.55
[c]45%V_f –unidirectional	[3]	[3]	21.1	0.58
Photo-pultruded Composites				
Quartz Reinforced				
[d]38%V_f–unidirectional	[9]	[9]	25	1.4
[d]70%V_f–unidirectional	[9]	[9]	45	2.1
[d]75%V_f–unidirectional	[13]	[13]	45.2	0.94
E glass Reinforced				
[d]70%V_f–unidirectional	[13]	[13]	38.8	1.14
S2 glass® Reinforced				
[d]42%V_f –unidirectional	Table II		29.4	1.12
[d]46%V_f–unidirectional	[13]	[13]	35.9	1.20
[e]57%V_f–unidirectional	[14]	[14]	45.1 - 47.2	1.15 - 1.72
[d]61%V_f–unidirectional	Table III		45.7	1.40
[d]70%V_f–unidirectional	[13]	[13]	47.7	1.29
[d]74%V_f–unidirectional	Table II		53.6	1.23
[d]79%V_f–unidirectional	[13]	[13]	56.4	0.77

[a] Polycarbonate polymeric matrix.

[b] Poly(ethylene terephthalate glycol) polymeric matrix.

[c] Poly(1,4-cyclohexylene dimethylene terephthalate glycol) polymeric matrix.

[d] 61$\%_{wt}$ BIS-GMA and 39$\%_{wt}$ TEGDMA (formulation used in current study).

[e] 60$\%_{wt}$ BIS-GMA and 40$\%_{wt}$ methylmethacrylate.

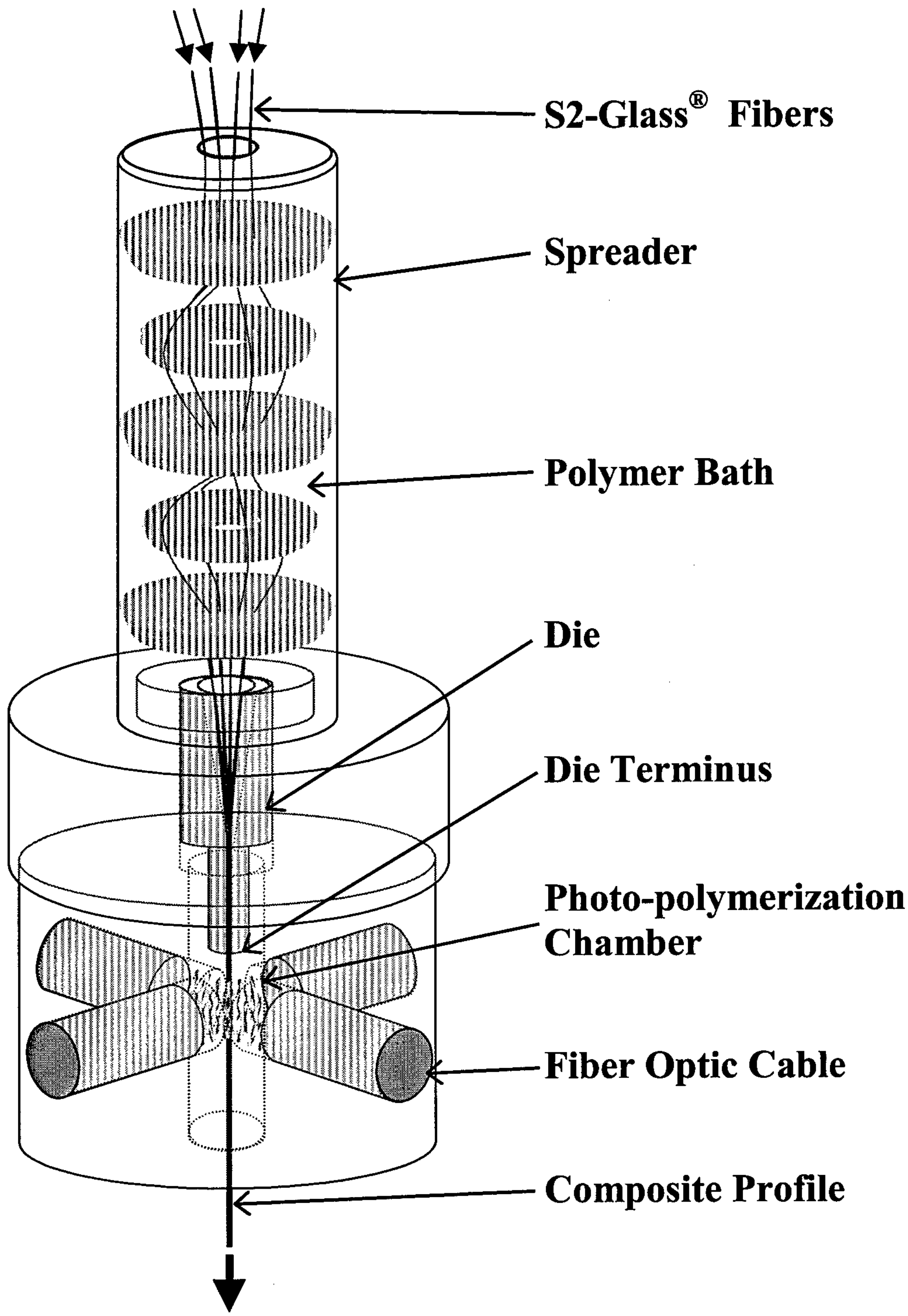

Fig. 2-1. Schematic diagram of the photo-pultrusion apparatus showing fibers initially entering the spreader and the composite profile finally exiting the photo-polymerization chamber [8].

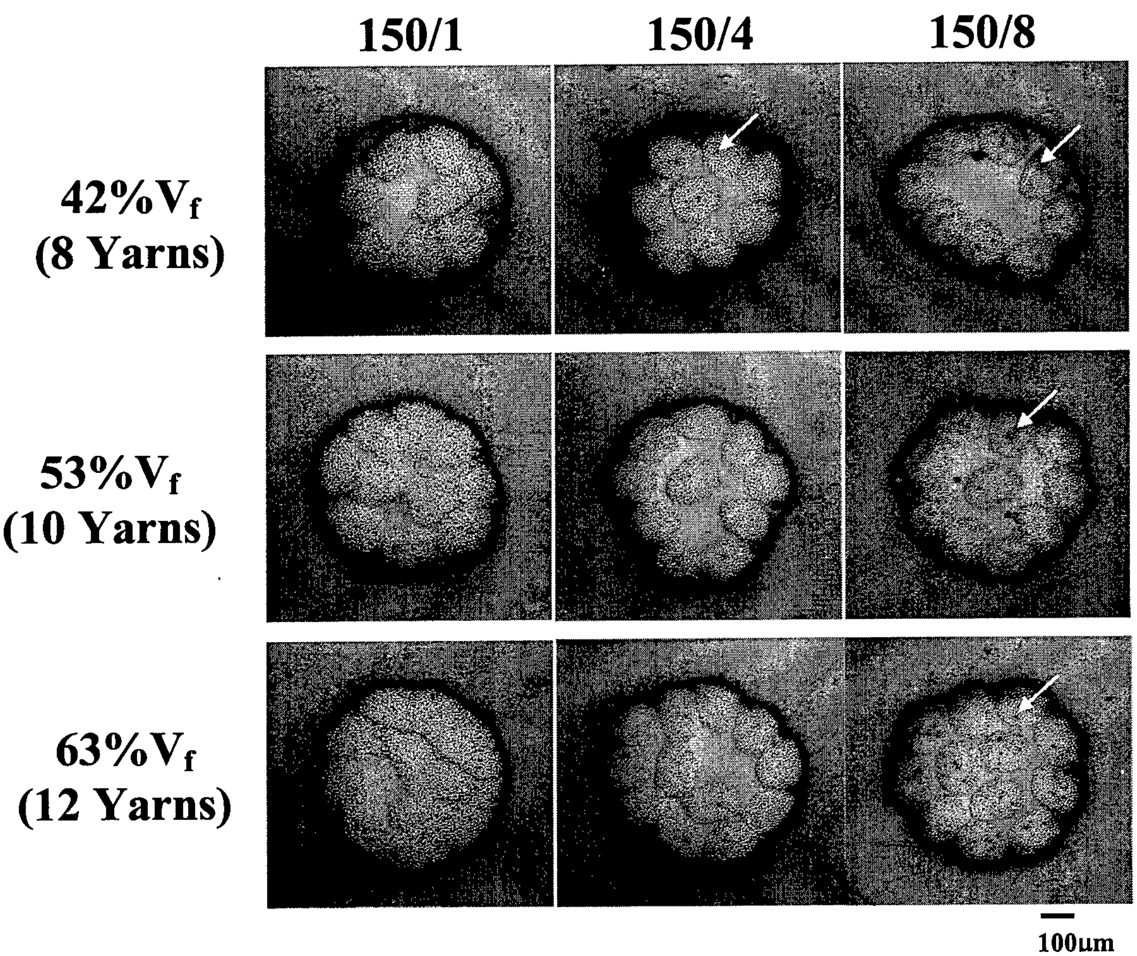

Fig. 2-2. Photomicrographs of round, S2-glass® reinforced profiles at three loading levels: 42, 53 and 63%V_f or 8, 10, and 12 yarns. The numbers at the top of the columns indicate CG150 yarns of 1, 4, and 8TPI, respectively. Arrows identify intra-yarn voids.

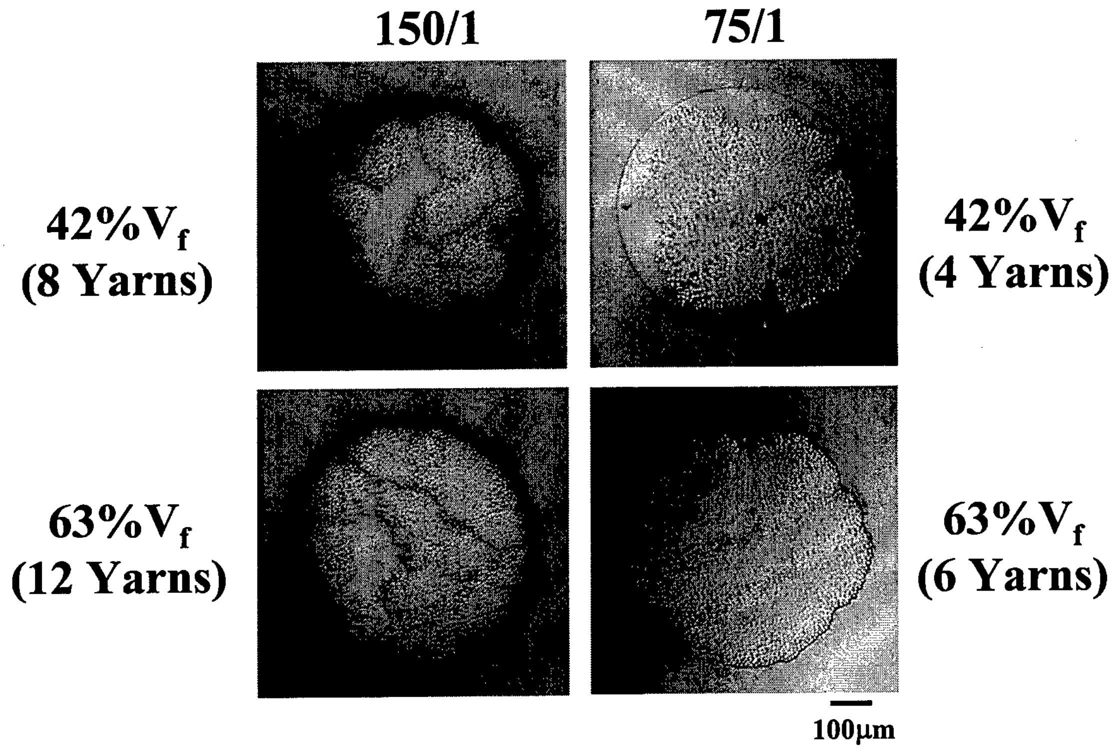

Fig. 2-3. Photomicrographs of round, S2-glass® reinforced profiles of two deniers at two loading levels. The numbers at the top of the columns denote deniers of 150 and 75 for 1TPI yarns. The numbers to the left and right of the rows denote the loading levels in terms of $\%V_f$'s and the numbers of reinforcement yarns (each row shows equivalent $\%V_f$'s even though the number of yarns differ).

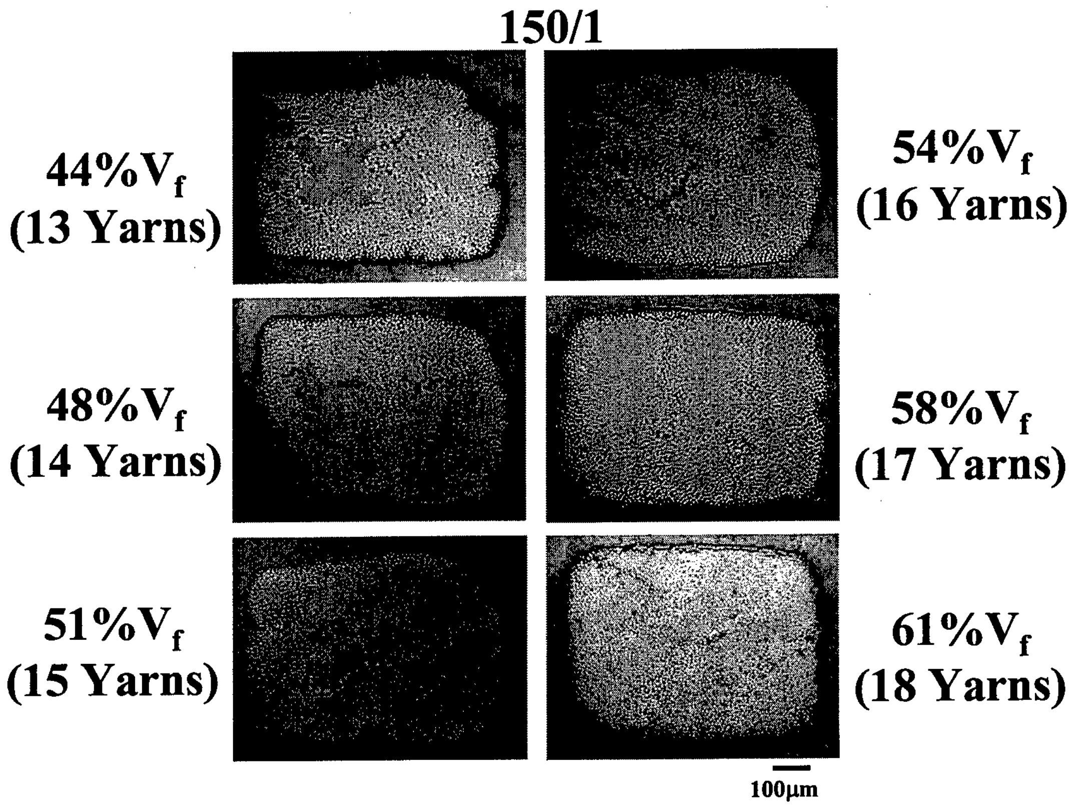

Figure 2-4. Photomicrographs of rectangular, S2 CG150/1TPI-glass® reinforced profiles at six levels of reinforcement: 44, 48, 51, 54, 58, and 61%V_f or 13, 14, 15, 16, 17, and 18 yarns.

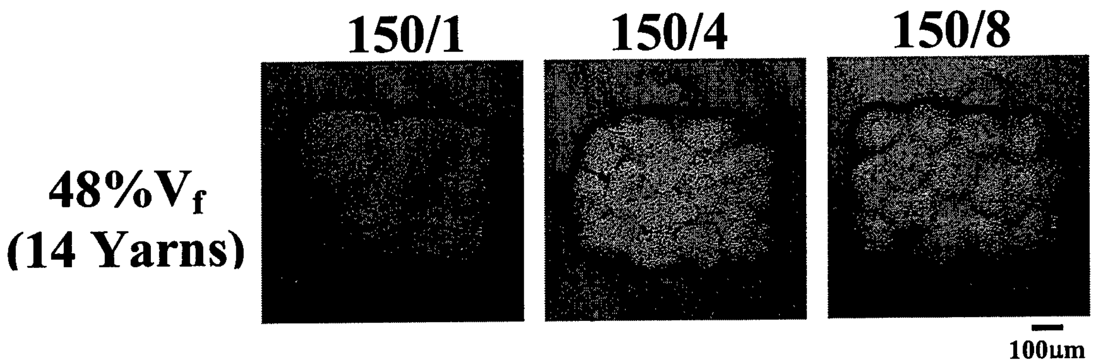

Figure 2-5. Photomicrographs of various rectangular, S2-glass® reinforced profiles at 48%V_f. The numbers at the top indicate CG150 yarns of 1, 4, and 8TPI, respectively.

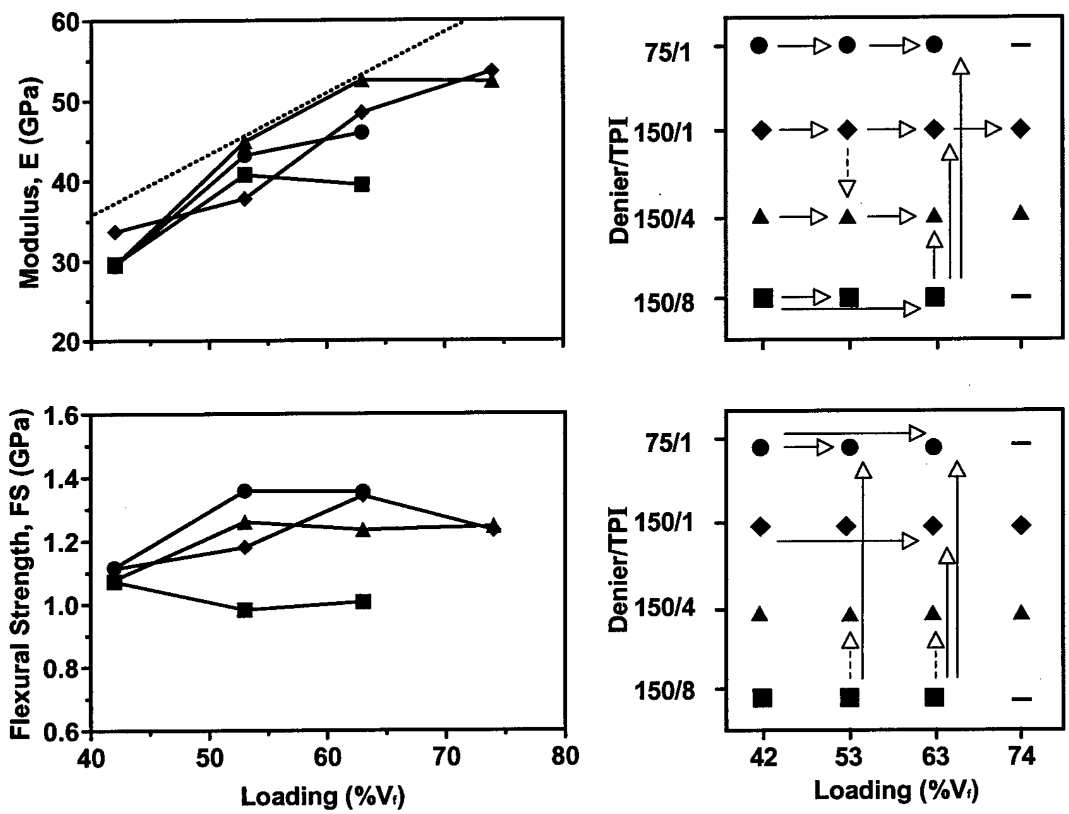

Fig. 2-6. Plots of mean values and statistical comparisons of flexural properties for round profiles of CG75/1TPI (●) and CG150 yarns at 1TPI (◆), 4TPI (▲), and 8TPI (■) at various levels of reinforcement. The dotted line represents theoretical values according to the rule of mixtures [20]. The open arrows (—▷) denote highly significant comparisons at $p < 0.001$; whereas, the dotted arrows (---▷) denote significant comparisons at $p < 0.05$. The arrow points to the higher mean value.

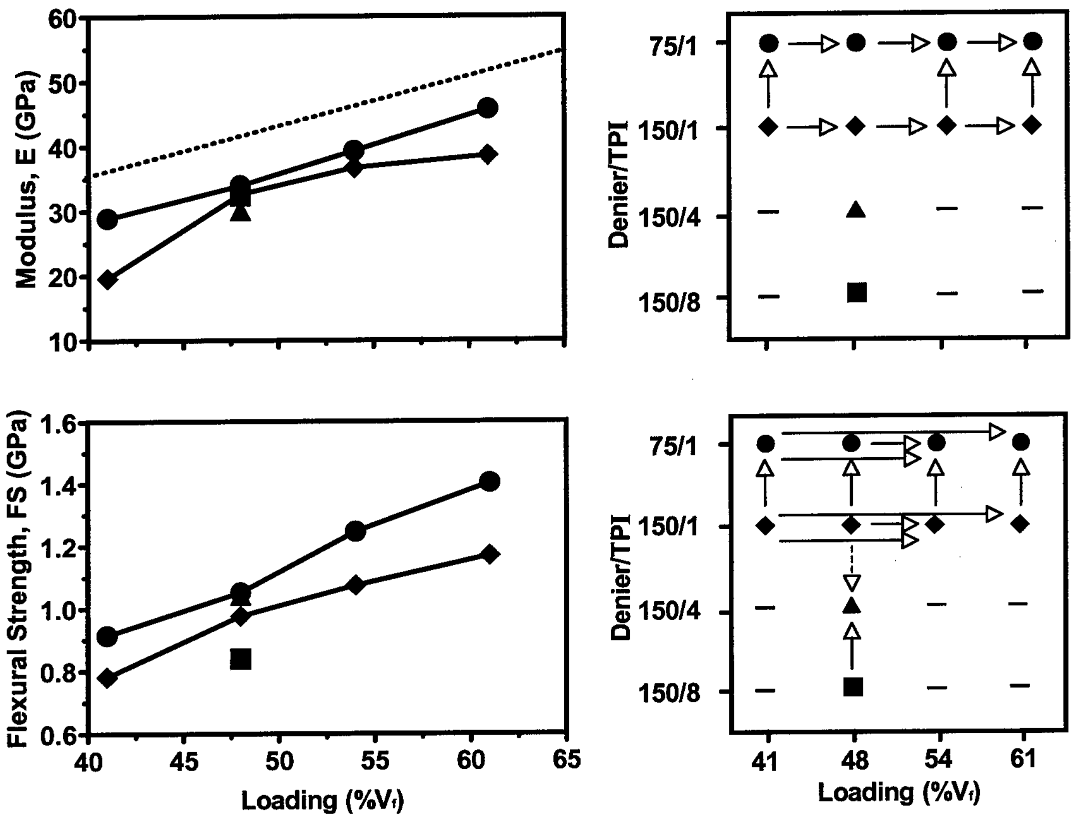

Fig. 2-7. Plots of mean values and statistical comparisons of flexural properties for rectangular profiles of CG75 and CG150 yarns of 1TPI (● and◆, respectively) at various levels of reinforcement and of CG150 yarns of 4TPI (▲) and 8TPI (■) at 48%V_f. The dotted line [20], open arrows (—▷) and dotted arrows (--▷) have the same connotations as in Figure 6.

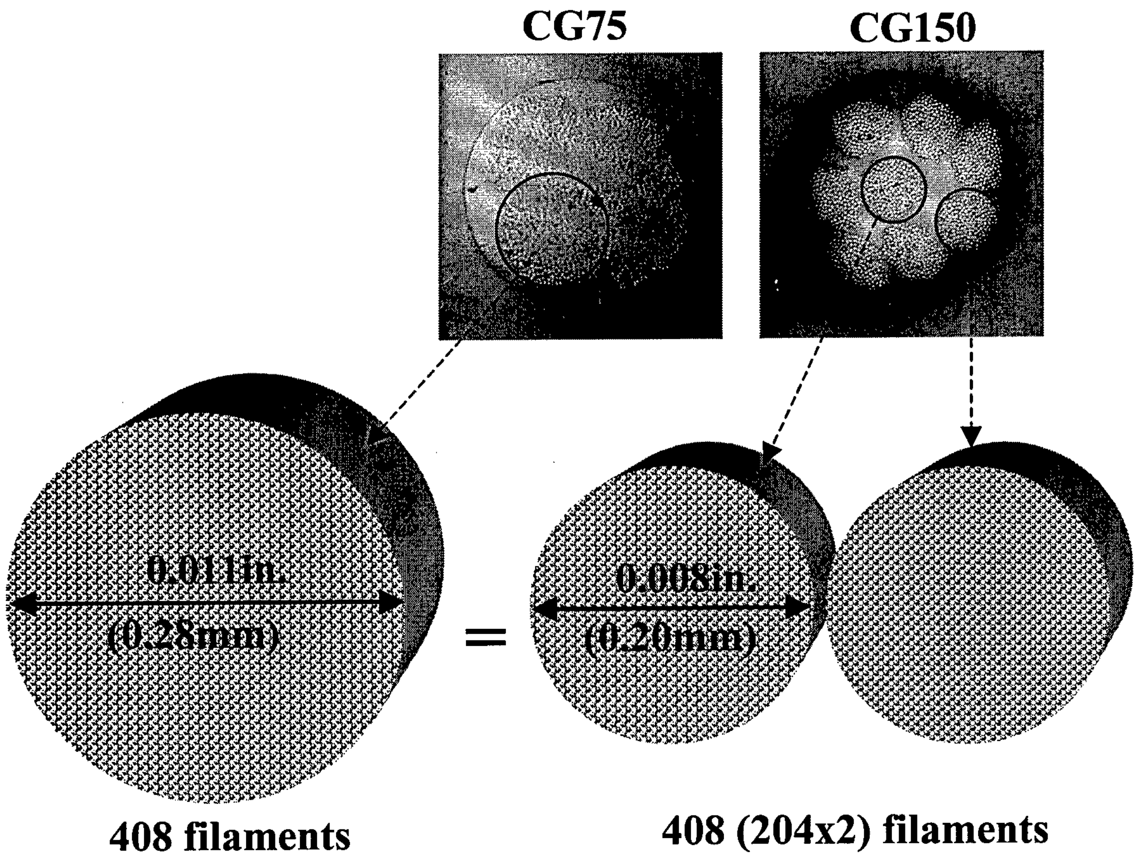

Fig. 2-A1. Photomicrographs and schematic representation of the numbers of constituent filaments and diametric differences between the CG75 and CG150 yarns.

3. CLINICAL USE OF PHOTO-PULTRUDED COMPOSITE WIRES FOR FLEXIBLE-BONDED RETAINERS[a]

3.1 Abstract

Novel esthetic S2-glass® fiber reinforced composite wires were fabricated in round (0.022 inch) and rectangular (0.021 x 0.028 inch) profiles with flexural moduli comparable to martensitic nickel titanium and flexural strengths comparable to beta titanium wires. These wires were bonded clinically to the facial surfaces of teeth in three situations in which flexible-bonded retainers are conventionally used: the retention of a closed median diastema, the retention of space closure following premolar extraction, and the retention of a canine that had been severely malpositioned. These bonded esthetic wires were monitored clinically up to 12 months to ascertain patience acceptance and structural integrity of the retainer. No clinically observable defects were noted during the study, and patients described no adverse intraoral effects from the retainer's presence. In this report the current theories governing the indications, design, and physiological requirements for bonded retention are discussed, along with the wire properties necessary to achieve optimal stability of tooth position. In addition to demonstrating excellent esthetic

[a] The contents of Chapter 3 were submitted for publication in the *Journal of Clinical Orthodontics and Research* under the title "Novel Esthetic Bonded Retainers: A Blend of Art and Science". The paper is reproduced here with the express permission of the co-author, R. P. Kusy.

characteristics, these photo-pultruded composite wires satisfy the flexural requirements necessary to achieve physiologic stability when used for flexible-bonded retention.

3.2 Introduction

Maintaining an esthetic and stable treatment result has been an ever-present challenge to the practicing orthodontist since the profession's infancy. As Calvin Case stated in 1920, "But after all, what does this temporary pleasure and satisfaction to ourselves and our patients amount to, if we find in a few years that the very cases which create in us the greatest pride, are going back to their former malpositions and disharmonies, in spite of everything we have been able to do with retaining appliances" (1). Although removable vulcanite retainers were used as early as 1881 (2), Dr. Case used a variety of fixed retainers, consisting of cemented bands, spurs, and gold staples to prevent relapse of a diastema (1). Dr. Edward Angle also designed many appliances consisting of cemented bands and spurs for use as fixed retainers. In fact, his pin and tube appliance was developed for use as an active retainer (3).

The introduction of the acid etch technique by Buonocore (4) and its utilization by Newman (5) in the design of bonded orthodontic attachments paved the way for new designs and applications for fixed retainers. Although traditional designs incorporated a single round or rectangular stainless steel orthodontic wire (6-10), Zachrisson's design that utilized a multistrand wire improved the retention of the wire in the composite (11). Initially, applications for bonded fixed retainers were limited to the maintenance of lower anterior alignment but later included retention of tooth position following premolar extraction, palatal impaction (canines) and severe rotation (12).

During the past decade, recommendations for the use of fiber reinforced plastics in orthodontics have steadily increased (13-18), resulting in continued research to characterize the materials' properties (19-23). These composite materials have been fabricated utilizing a wide variety of reinforcement fibers ranging from S2-glass® to Kevlar® and have shown great promise for use in fixed retainers.

In 1951, W.B. Goldsworthy patented a continuous process for fabricating reinforced plastics called "pultrusion" (24). The process of pultrusion was ideal for generating reinforced materials of constant geometry and originally consisted of "creels" of polyester fibers that were coated with a thermosetting resin prior to being "pulled-through" a heated die of a specific geometric profile. Although fiberglass fishing rods were the first application for thermal pultrusion, manufacturers soon found applications in the automotive, hardware, and aerospace industries (25). In the past ten years, thermal pultrusion has found applications in the medical and dental professions (15,16,17,19,26), with dental applications including frameworks for provisional bridges, splints, retainers, space maintainers, and orthodontic wires (17).

A new pultrusion process has been patented recently (27) utilizing photo-polymerization. This process has many advantages, when compared to conventional thermal polymerization (28), and has been utilized to manufacture small profile (0.5mm) composite orthodontic archwires. These composite materials consist of S2-glass®* reinforcement within a Bis-GMA-based copolymer and have flexural

*S2-glass®, manufactured by Owens-Corning, Inc., is known for its higher strength and stiffness on a per weight basis when compared to conventional E-glass. These S2-glass® fibers were also used in military armored personnel carriers and tanks, because of their ability to absorb extreme impacts.

properties that range between nickel titanium and beta titanium orthodontic wires (20,21,23). Recently, this photo-pultrusion process was utilized to fabricate 0.021 x 0.028 inch rectangular archwires with nearly the same range of flexural properties as the round materials (23).

The flexibilities of these pultruded composite materials can be altered by changing the amounts of glass reinforcements within the materials without altering the outer geometries or adversely affecting the materials' strengths. The feasibility of post-forming these photo-pultruded materials into other desired shapes prior to complete polymerization has also been demonstrated, by changing the polymer formulations (22). The esthetic and flexural properties of these materials make them very appealing for use as bonded retainers in cases where a flexible, strong, and inconspicuous material is required.

Inevitably, the materials with which practitioners attempt to maintain tooth position will continue to change; whereas, the physiological mechanisms that govern tooth position will remain constant. Therefore, as we enter the 21st century and new materials become available, we must carefully consider the physiological as well as the mechanical requirements when fixed retention is necessary. This report documents the clinical use of photo-pultruded composite wire for use as flexible-bonded retainers. It also reviews the indications, design, and current theory governing the physiological requirements for flexible-bonded retainers and describes how this recently developed composite material can satisfy these requirements.

3.3 Materials and Methods

Prototype round and rectangular, fiber-reinforced, composite wires were manufactured into 0.022 inch diameter and 0.021 x 0.028 inch profiles utilizing the previously referenced photo-pultrusion process (27). The reinforcement fibers within these composites consisted of S2-glass® (magnesium aluminosilicate) (Owens-Corning Corp., Toledo, OH, USA) and ranged from 61 to 63 percent, by volume ($\%V_f$) for rectangular and round cross-sections, respectively. The matrix consisted of a copolymer of 61%wt bisphenol-A diglycidyl-methacrylate (Bis-GMA, Nupol 046-4005, Cook Composites and Polymers Co., North Kansas City, MO, USA) and 39%wt triethylene-glycol-dimethacrylate (TEGDMA, Polysciences Inc., Warrington, PA, USA). Benzoin-ethyl-ether (Aldrich Chemical Co., Inc. Milwaukee, Wis, USA), 0.4%wt, was added for photo-initiation.

These materials were bonded facially to teeth with Transbond® (3M Company, St. Paul, MN, USA) utilizing the acid-etch technique in three orthodontic situations in which a flexible-bonded retainer is traditionally indicated (Table 1). These indications included: retention of a closed diastema, retention of space closure following premolar extraction, and retention of a canine that had previously been severely malpositioned. The protocol included 2, 2, 4, 8, and 8 week recall appointments, for a 6-month total duration of study, following initial study models and photographs. This protocol was accepted by the institution's Human Subjects Committee and represented the first clinical use of this composite. Consequently, clinical feasibility was evaluated by ascertaining patient acceptance and structural integrity of the retainer.

3.4 Results

The retainers demonstrated excellent esthetic characteristics, structural integrity, and patient acceptance for the duration studied. Although the observation period was limited to 6 months, the majority of the retainers had been in place for 9 months at the time of this writing, and one had been in place for over 1 year. Each patient was pleased with the feel, ease of cleansing, and esthetics of her retainer and described no adverse intraoral effects from the its presence.

Case Reports

3.4.1 Case 1- Retention of a Closed Median Diastema

A 22-year-old woman presented for orthodontic evaluation stating her chief complaint as, "I want the gap between my front teeth closed." Her past medical history was non-contributory to dental care, and she had no previous history of orthodontic treatment. Exam revealed that she had an orthognathic profile, class I malocclusion and no missing teeth. She exhibited good alignment of her mandibular teeth and 1.5mm midline spacing in the maxillary arch with mild super-eruption of the central incisors resulting in a increased overbite (Figure 1, a and b). A Bolton analysis revealed mandibular anterior excess due to reduced mesial-distal width of her maxillary lateral incisors. All periodontal probing depths were less than 3mm; however, intraoral soft tissue exam revealed blanching of the incisive papilla from a pronounced maxillary labial frenum. After discussing treatment options, the patient consented to a treatment sequence including: diastema closure utilizing a removable appliance with finger springs, esthetic bonding of her maxillary lateral incisors to correct the Bolton discrepancy, and surgical frenectomy to improve prognosis of maintaining space closure. Upon completion of the established treatment plan, the patient was given the retention options of a removable retainer (conventional Hawley or clear plastic vacuum-formed retainer) or a fixed wire. The patient preferred to have a bonded retainer; however, the depth of her bite precluded the use of a conventional lingually bonded wire. Consequently, an esthetic, photo-pultruded round composite archwire, as previously described, was utilized (Figure 1, c and d). The patient was very pleased with the esthetics and comfort of this retainer and reported no adverse effects during the one-year period of observation (Figure1, c-h).

3.4.2 Case 2- Retention of Space Closure Following Premolar Extraction

A 34-year-old woman presented two years following comprehensive orthodontic treatment stating her chief complaint as, "The spaces where my teeth were extracted are opening." Her past medical history was non-contributory to dental treatment, and orthodontic evaluation revealed an orthognathic profile, class I malocclusion with missing maxillary and mandibular first premolars. She exhibited good alignment of her maxillary teeth; however, due to less than ideal wear of her removable retainers, 1.5mm bilateral spaces had opened distal to her mandibular canines (Figure 2, a and b). After discussing treatment options, the patient consented to a treatment plan sequence including space closure utilizing fixed orthodontic appliances followed by bonded retention. At the completion of fixed appliance treatment, rectangular esthetic composite wires as previously described were bonded bilaterally to maintain space closure (Figure 2, c and d). The patient reported no adverse effects for the 9-month period of observation, and space closure was maintained.

3.4.3 Case 3- Retention of a Canine that had been Severely Malpositioned

An 18-year-old woman presented for a one-year recall appointment following completion of comprehensive orthodontic treatment with the complaint that, "My tooth is moving back up." Her past medical history was non-contributory to dental treatment, and orthodontic evaluation revealed an orthognathic profile and a class I malocclusion. Although she had been consistently wearing a removable retainer (Hawley design), her maxillary left canine had moved away from the plastic retainer in an apical direction (Figure 3, a and b). A review of her previous orthodontic record revealed that both canines had been severely malpositioned facially upon initial presentation. After discussing treatment options, the patient consented to limited orthodontic treatment including bonded attachments on her maxillary left canine and lower left first premolar along with interarch elastics to reposition the canine. Her current removable maxillary and mandibular retainers were used for stabilization of the remaining teeth. Upon completion of the limited orthodontic treatment, a rectangular esthetic composite wire, as previously described, was bonded between the maxillary canine and first premolar to maintain the tooth position (Figure 3, c and d). As seen in the previous cases, the patient reported no adverse effects during the 6-month period of observation and tooth position was maintained.

3.5 Discussion

3.5.1 Indications for Flexible Bonded Retainers

Current description (31) places bonded retainers into two distinct categories: those requiring a high degree of rigidity (stiffness), and those requiring flexibility. Rigid-bonded retainers are usually indicated for maintenance of the anteroposterior or lateral position of the lower labial segment (31) or for maintaining pontic/implant spaces (29). Flexible-bonded retainers are indicated in situations where individual tooth movements are prone to relapse (31). According to the literature (12,29,30), a flexible bonded retainer is traditionally indicated in ten types of cases (Table 1). The current theories concerning the physiological and structural requirements of these flexible-bonded retainers will be discussed in the remainder of this paper.

3.5.2 Aspects of Most Commonly Used Flexible Bonded Retainers

Traditionally, the most common wire used for the fabrication of a flexible-bonded retainer is a round stainless steel multistrand wire varying in diameter from 0.015 to 0.0215 inch (12,31). This multistrand wire is most commonly bonded with a conventional restorative composite based on Bis-GMA (31). Although many luting composites have been studied, those using Concise® (auto-cure) (3M Company, St. Paul, MN, USA) have reported fewer bond failures (32,33). Transbond® (light-cure), which has the same filler as Concise®, has been shown to have similar results (33). Based on studies of *in vitro* abrasion resistance, researchers found that Concise® and Transbond® had superior abrasion resistances compared to other composites and that their abrasion resistances were comparable with restorative composites (33). The optimal thickness of luting composite that should overlay the wire to provide maximal strength and minimal bulk is about 1.0mm (33). And although bond failure rates differ from study-to-study, the most common type of failure in bonded retainers is a detachment at the wire-composite interface, which is usually associated with a loss of luting composite from abrasion (32).

3.5.3 Designing a Flexible-Bonded Retainer Utilizing Composites

When designing a composite flexible-bonded retainer, the further that the reinforcement fibers are placed from the teeth that are retained the less of the load will be carried by these fibers and the more of the load will be carried by the luting composite. Therefore, to take full advantage of the strength of the fibers within the composite, the bulk of the fiber reinforcement should be placed as close to the teeth as possible. This would favor the use of a rectangular wire bonded "flatwise" to the teeth as opposed to a round material, which has only a point contact with the teeth.

Bearn (31) believed that the characteristics of both the wire and the luting composite were important in order to construct a bonded fixed retainer. This recommendation was made for conventional alloy wires bonded to teeth with a luting composite, but is still applicable when discussing the present S2-glass® reinforced composite material. Regardless of the type, the properties of the material should be adequate to withstand the assault by various intra-oral forces, the magnitudes of which should be determined, if possible, prior to design.

In general, these forces can be divided into two main categories: those grouped into the category of relapse forces and those derived from a functioning occlusion. A recent study (34) has documented that the eruption forces originating from the PDL follow the circadian rhythm under hormonal control and would thus be characterized as light intermittent forces; therefore, it is likely that relapse forces resulting from PDL metabolism would behave similarly. However, relapse forces that originate from the gingival fiber network or peri-oral soft tissues would likely be light continuous forces. In contrast, the occlusal forces would be heavy intermittent forces-- the level and direction of which would be determined by the region of the mouth in which they are encountered.

When maintaining closure of a midline diastema or premolar extraction space, a labially-bonded esthetic wire must withstand continuous relapse forces that are predominantly tensile; whereas, when maintaining the position of a canine, which was palatally impacted, the wire must withstand mainly flexural relapse forces. The heavy intermittent occlusal forces that the wire must withstand would contain a variety of torsional and flexural components, depending upon the quality of the occlusion achieved after treatment and the presence of canine guidance or group function.

In the strictest sense, a flexible-bonded retainer that is placed to prevent relapse is not a "passive appliance", for the retainer must provide a force equal and opposite to the relapse force. To prevent the expression of the relapse force and to withstand occlusal forces, such a retainer should be thought of as a "reactive appliance". The retainer's ability to "react" to the force, which is applied against it, is a function of the properties of the material. In the case of a composite material, although the constituent parts of that composite have inherent mechanical properties, the interaction of those parts results in apparent mechanical properties of the overall composite. As discussed by Rudo (35), these apparent properties are "conditional"--

that is, they are dependent upon the presence of cracks or defects during the processing, production, or handling of the material. These "conditional properties" are particularly variable in rigid-composite materials that are fabricated by traditional hand lay-up methods in an uncontrolled intra-oral enviroment.

When evaluating flexible-composite materials with a consistent geometry and processing method, the measurement of flexural strength provides a comparison to other materials and an indication of the ability to withstand distributed forces. Therefore, the optimal flexible-bonded retainer would generally be the composite having the highest flexural strength, assuming the desired flexibility was attained.

The esthetic composite materials that have been fabricated utilizing the photo-pultrusion process demonstrate excellent tensile and flexural properties (20,21,23). In particular, flexural strengths (FS) are comparable to proportional limits (σ_{PL}'s) of conventional materials (Figure 4), allowing composites to withstand occlusal forces. The high flexural strengths occur because S2-glass® reinforcement fibers are strong and the interfacial bonds between the pultruded fibers and copolymer are so effective. These composites are elastic up to the point of failure (σ_f), evidenced by a sudden drop in the force-deflection curve (20,21,23). A flexural strength – relative range plot that compares a 0.0215 inch stainless steel multi-twist wire and a 0.022 inch composite material shows a coincident occurrence of the σ_{PL} and σ_f (Figure 4). Further analysis (Appendix 2), demonstrates that such failure results in equality of two important flexural characteristics—working range and flexibility, both of which are proportional to resilience. These three characteristics can be modified by altering the amount of reinforcement fiber incorporated within the wire without changing the geometric shape or size of the profile (Figure 5). Thus, the versatility of the material for use in a variety of clinical situations is enhanced.

At this time, the composite material of choice would be a 0.021 x 0.028 inch rectangular composite archwire having a $\%V_f$ of 61% S2-glass®. This wire has a low modulus (45.7 GPa) and the highest flexural strength (1.4 GPa) (23). This modulus is comparable to martensitic nickel titanium (33.4-44.4 GPa) (38) producing only about one-quarter the force of a stainless steel wire per unit of activation, making individual tooth response possible. The flexural strength of this composite material is comparable to the spectrum of published values for beta-titanium wires (1.3-1.5 GPa) (38) and are consequently capable of withstanding occlusal forces.

3.5.4 Physiologic Rationale for Retention and the Need for Flexibility

In a recent review concerning retention and post-treatment stability, Blake and Bibby (39) concluded that orthodontists should be more proactive when considering the factors associated with relapse. To attain this goal and use retentive devices most effectively requires a thorough understanding of the physiologic requirements for maximum stability.

According to Proffit (29), a number of factors influence long-term results because orthodontic treatment outcomes are potentially unstable. Consequently, retention should be used because: (1) reorganization of the gingival and periodontal tissues is required after appliances are removed; (2) teeth may be in an unstable position following treatment, so that tongue and cheek pressures foster relapse; and (3) growth may alter the outcome of treatment. Even in the absence of instability and growth, retention still is necessary until reorganization of tissues is completed.

Reorganization of the gingival and periodontal tissues plays a major role in attaining stability of individual teeth that were severely rotated or malaligned. As Reitan (40) demonstrated from histological sections, reorganization of the PDL occurs over a 3-4 month period, but some of the gingival fiber bundles remain displaced and stretched even after a retention period of over 7 months. Therefore, a moderate period of retention is necessary following all routine orthodontic treatments; whereas the use of long-term, fixed retention is appropriate in those cases most prone to relapse.

Determining the necessary duration of retention is difficult, at best, and is complicated by the question of when the retentive phase actually begins. For example, when a tooth is affixed by a stiff orthodontic wire or otherwise splinted to its contiguous teeth, the periodontium will not assume a normal anatomy. Thus retention can not begin so long as the teeth are rigidly supported with passive wires. Indeed, not until each tooth can once again be displaced independently of its contiguous teeth can reorganization of periodontium occur over Reitan's period. Thus only if a removable appliance is prescribed and worn at all times except mealtimes, or if a compliant fixed-retainer is utilized, can the tooth resume its normal stimulation, and reorganization of the periodontium commence (29). This requirement, for the periodontium to sense the forces of normal occlusion and initiate reorganization, is analogous to that seen in bone according to Wolff's law. This law states that remodeling of bone takes place in response to mechanical stimulation so that the new structure becomes better adapted to the load (41). If an orthopedic plate that is used to splint bone is too rigid, the plate can carry so much of the load that the bone is understressed leading to atrophy. The periodontal ligament appears to demonstrate this same "stress-shielding effect" (41) when a rigid, fixed-retainer is used. In those cases where long-term retention is deemed appropriate, a fixed-retainer would satisfy the physiologic requirements necessary to establish optimal stability as long as the retainer could be engineered to allow individual tooth movements during mastication.

3.5.5 Advantages of Pultruded Esthetic Flexible Bonded-Retainers

Pultruded composite materials have at least ten distinct advantages over conventional materials, when used for flexible-bonded retainers (Table 2). In addition to the esthetic advantages of composite wires for use in flexible bonded-retainers (15), there are also structural and clinical advantages (15,16,20,21,23,42,43). These advantages are not only due to the inherent properties of the individual components, but also the compatibility of these components with each other and with current bonding techniques. Since composites inherently contain two or more classes of materials, the material properties necessary for specific applications can be more-readily engineered than when limited to only one class of material. Therefore, versatility in design is one of the major advantages of composites that will be appreciated as these materials are further developed.

3.6 Conclusion

3.6.1 Retention Requires a Paradigm Shift

In a recent publication (18), Kusy elaborates on the traditional mechanical-regenerative paradigm of orthodontic treatment and predicts that this paradigm will someday yield to a more sophisticated regenerative-mechanical paradigm in which appliances will provide guidance in a passive fashion. Although this statement describes a future process of orthodontic tooth movement, that process is already encountered when striving to maintain tooth position. Once orthodontic treatment ceases and appliances are removed, a regenerative process begins that leads to a mechanical force capable of moving the teeth. Whether these forces are caused by instability in the PDL, the gingival fiber network, or the peri-oral tissues, these forces must be controlled until the periodontium adapts to the new tooth positions.

3.6.2 Retention Requires a Disciplined Approach

Although individual variation exists, the most prudent plan to avoid the relapse of individual teeth requires a disciplined approach that controls the relapse forces while allowing functional tooth response for at least 7 months (29,40). Photo-pultruded flexible-bonded retainers are easy to use, esthetically pleasing, strong materials with the flexibility necessary to meet both the mechanical and physiological retention requirements as they are currently understood. Although these materials show good structural integrity and patient acceptance in the short-term (up to 1 year), the clinical durability of these retainers requires further study to ascertain their longevity as compared to conventional materials.

3.7 Acknowledgements

The authors would like to thank the UNC-CH Department of Orthodontics for financial support, Dr. William Brown, Dr. Jaqueline Malone and Dr. Kirt E. Simmons for clinical cases, and Owens Corning Corp. for contributing the S2-glass® yarn reinforcement materials used in these composites.

3.8 References

1. Case CS. Principles of retention in orthodontia. American Journal of Orthodontics & Dentofacial Orthopedics 1920; (Nov.): 3-34.

2. Weinberger BW. Orthodontics: a historical review of its origin and evolution. St. Louis: The CV Mosby Company; 1926.

3. Angle EA. Treatment of malocclusion of the teeth. 7 ed. Philadelphia: SS White Manufacturing Co.; 1907.

4. Buonocore MG. A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces. Journal of Dental Research 1955; 34: 849-53.

5. Newman GV. Epoxy adhesives for orthodontic attachments: progress report. American Journal of Orthodontics 1965; 51: 901-12.

6. Knierim RW. Invisible lower cuspid to cuspid retainer. Angle Orthodontist 1973; 43: 218-9.

7. Rubenstein BM. A direct bond maxillary retainer. Journal of Clinical Orthodontics 1976; 10: 43-4.

8. Carter RN. Simplified direct-bonded retainer. Journal of Clinical Orthodontics 1978; 12: 221-2.

9. Lubit EC. The bonded lingual retainer. Journal of Clinical Orthodontics 1999; 13: 311-3.

10. Lee RT. The lower incisor bonded retainer in clinical practice: a three year study. British Journal of Orthodontics. 1981; 8: 150-8.

11. Zachrisson BU. Clinical experience with direct-bonded orthodontic retainers. American Journal of Orthodontics 1977; 71: 440-8.

12. Axelsson S, Zachrisson BU. Clinical experience with direct-bonded labial retainers. Journal of Clinical Orthodontics 1992; 26: 480-90.

13. Diamond M. Resin fiberglass bonded retainer. Journal of Clinical Orthodontics 1987; 21: 182-3.

14. Orchin JD. Permanent lingual bonded retainer. Journal of Clinical Orthodontics 1990; 24: 229-31.

15. Goldberg AJ, Burstone CJ. inventors. Orthodontic Appliance System. 4,717,341. 1988.

16. Goldberg AJ, Burstone CJ. inventors. Passive Dental Appliances of Fiber-Reinforced Composites. 4,894,012. 1990.

17. Goldberg AJ, Burstone CJ. The use of continuous fiber reinforcement in dentistry. Dental Materials 1992; 8: 197-202.

18. Kusy RP. The future of orthodontic materials: The long term view. American Journal of Orthodontics & Dentofacial Orthopedics 1998; 113: 91-5.

19. Karmaker AC, Dibenedetto AT, Goldberg AJ. Continuous fiber reinforced composite materials as alternatives for metal alloys used for dental appliances. Journal of Biomaterials Applications 1997; 11: 318-28.

20. Kennedy KC, Chen T, Kusy RP. Mechanical properties of micron-sized pultruded composite profiles. 94 A.D.; Dearborn, Michigan, USA: ASM International; Proceeding of the 10th Annual ASM/ESD, 1994; 191-200.

21. Kennedy KC, Kusy RP. UV-Cured Pultrusion processing of glass-reinforced polymer composites. Journal of Vinyl and Additive Technology 1995; 1: 182-6.

22. Kennedy KC, Kusy RP. Investigation of dual-staged polymerization and secondary forming of photopultruded, fiber-reinforced, methacrylate-copolymer composites. Journal of Biomedical Materials Research 1998 ;41: 549-559.

23. Fallis DW, Kusy RP. Variation in flexural properties of photo-pultruded composite archwires: Analyses of round and rectangualr profiles. (In Press).

24. Price HL. Curing and flow of thermosetting resins for composite material pultrusion [Master's thesis]. Old Dominion University; 1979.

25. Reinhart TJ; Clements LL. Engineered materials handbook; composites. ASM International; 1987. p. 28.

26. Goldberg AJ, Burstone CJ, Hadjinikolaou I, Jancar J. Screening of matrices and fibers for reinforced thermoplastics intended for dental applications. Journal of Biomedical Materials Research 1994; 28: 167-73.

27. Kusy RP, Kennedy KC. inventors. Novel pultruded fiber-reinforced plastic and related apparatus and method. 5,869,178. 1999.

28. Narayanan V, Scranton AB. Photopolymerization of composites. Trends in Polymer Science 1997; 5: 415-9.

29. Proffit WR. Contemporary orthodontics. 3 ed. St. Louis: Mosby; 1999 (In Press).

30. Zachrisson BU. The bonded lingual retainer and multiple spacing of anterior teeth. Swedish Dental Journal - Supplement 1982;15: 247-55.

31. Bearn DR. Bonded orthodontic retainers: a review. American Journal of Orthodontics & Dentofacial Orthopedics 1995; 108: 207-13.

32. Dahl EH, Zachrisson BU. Long-term experience with direct-bonded lingual retainers. Journal of Clinical Orthodontics 1991; 25: 619-30.

33. Bearn DR, McCabe JF, Gordon PH, Aird JC. Bonded orthodontic retainers: the wire-composite interface. American Journal of Orthodontics & Dentofacial Orthopedics 1997; 111: 67-74.

34. Risinger RK, Proffit WR. Continuous overnight observation of human premolar eruption. Archives of Oral Biology 1996; 41: 779-89.

35. Rudo DN, Karbhari VM. Physical behaviors of fiber reinforcement as applied to tooth stabilization. Dental Clinics of North America 1999; 43: 7-35.

36. Eschbach OW; Souders O. Handbook of Engineering Fundamentals. 3 ed. New York: John Wiley & Sons; 1974. p. 496-7.

37. Kusy RP. On the use of nomograms to determine the elastic property ratios of orthodontic arch wires. American Journal of Orthodontics 1983; 83; 374-381.

38. Stush A, Kusy RP. Geometric and material parameters of a nickel-titanium and a beta-titanium orthodontic archwire alloy. Dental Materials 1987; 3: 207-17.

39. Blake M, Bibby K. Retention and stability: a review of the literature. American Journal of Orthodontics & Dentofacial Orthopedics 1998; 114: 299-306.

40. Reitan K. Tissue rearrangement during retention of orthodontically rotated teeth. Angle Orthodontist 1959; 2: 105-13.

41. Park JB; Lakes RS. Biomaterials: an introduction. 2 ed. New York: Plenum Press; 1992; p. 301-2.

42. Kusy RP. A Review of contemporary archwires: their properties and characteristics. Angle Orthodontist 1996; 67: 197-208.

43. Al-Waheidi EMH. Allergic reaction to nickel orthodontic wires: a case report. Quintessence International 1995; 26: 385-7.

Table 3-1. Indications for Flexible Bonded Retainers

Indications	References
1. Retention of lower incisors that were severely rotated, as in a lower canine-to-canine retainer with bonding of one or more intermediate teeth.	(29)
2. Maintenance of closed median diastemas.	(30)
3. Maintenance of spaced anterior teeth.	(30)
4. Retention of teeth in adult cases with potential postorthodontic tooth migration.	(30)
5. Retention of large anterior spaces in cases of accidental loss of maxillary incisors, which require closure.	(30)
6. Prevention of space reopening, after mandibular incisor extractions.	(30)
7. Maintenance of positions of maxillary incisors, which had been severely rotated.	(30)
8. Retention of premolars, which had been severely rotated (bonded labially).	(12)
9. Maintenance of closure of premolar extraction sites (bonded labially).	(12)
10. Prevention of lingual crown relapse of canines that had been palatally impacted.	(12)

Table 3-2. Advantages of Pultruded Composites as Compared to Conventional Alloys for use in Flexible Bonded Retainers.

Advantages	References
1. Esthetics are very good.	(15)
2. Moduli are in the range between NiTi and TMA orthodontic wires, allowing individual tooth movement relative to other teeth in the retained segment.	(23,42)
3. Strengths in flexure are comparable to TMA wire.	(20,21,23)
4. Flexibility of the material can be altered by changing the internal reinforcement without substantially affecting the strength.	(15,20,21,23)
5. Appliances can be fabricated with great strength and less bulk than conventional appliances.	(16)
6. Bonding is facilitated because the polymer used in the composite is Bis-GMA based and is compatible with restorative composites, thereby eliminating the problematic wire-composite interface.	This Study
7. Thickness of luting composite can be less than the1.0mm needed in conventional bonded-retainers, since there is no metal-composite interface to protect.	This Study
8. Potential damage of the material from strong occlusal forces is reduced because the material can be bonded on the facial surfaces of the maxillary teeth.	This Study
9. These materials do not interfere with nuclear magnetic resonance diagnostic testing procedures as seen with metal alloys.	(15)
10. These materials do not contain nickel, documented to be a potential allergen.	(43)

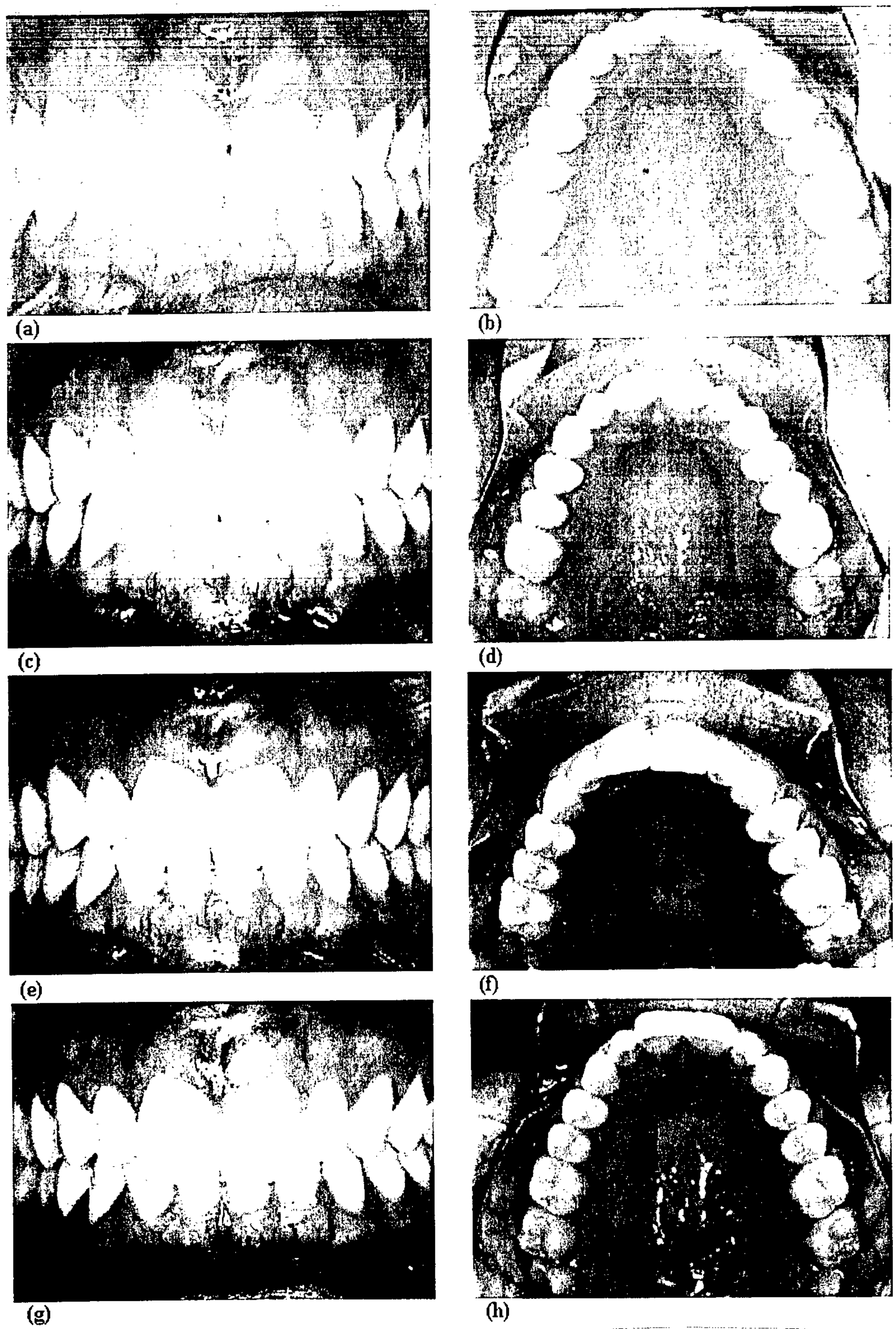

Figure 3-1 Clinical photographs of Case1 at initial presentation (a,b), 1 week (c,d), 1 month (e,f) and 1 year (g,h) following bonding of composite flexible retainer to maintain midline diastema closure.

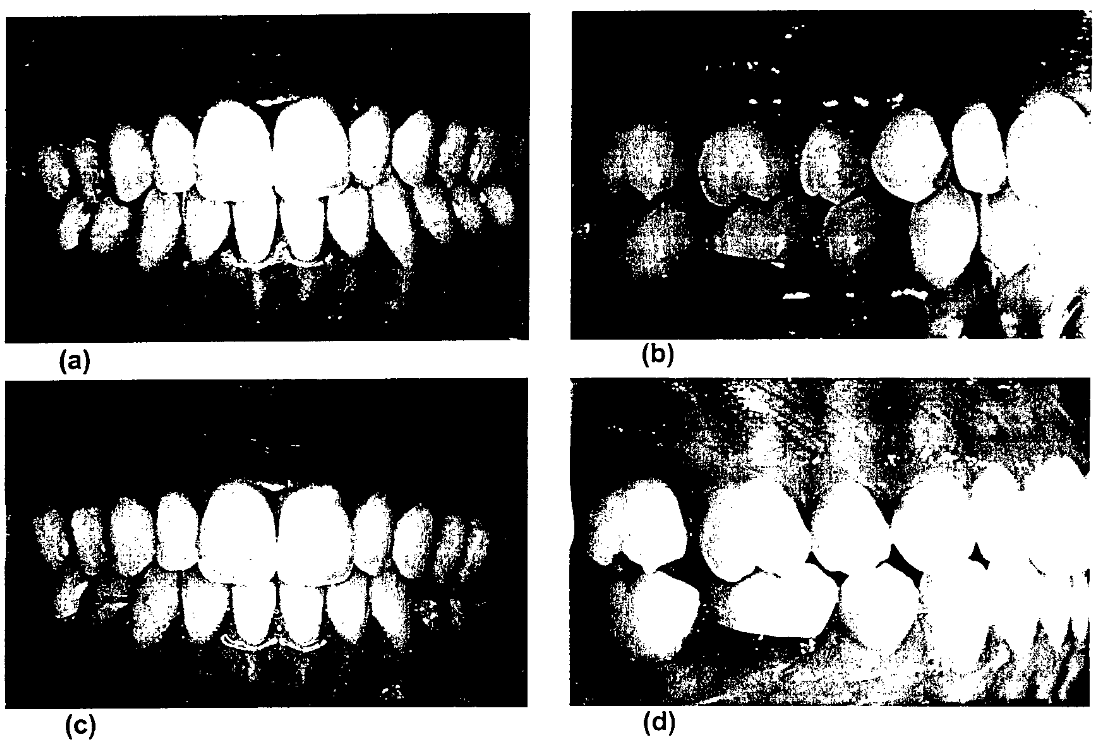
(a) (b) (c) (d)

Figure 3-2 Clinical photographs of Case 2 at initial presentation (a,b) and 1 week (c,d) following bonding of composite flexible retainer to maintain premolar extraction space closure. There were no discernable differences observed in the appearance of the retainer at 1 week and at 9 months.

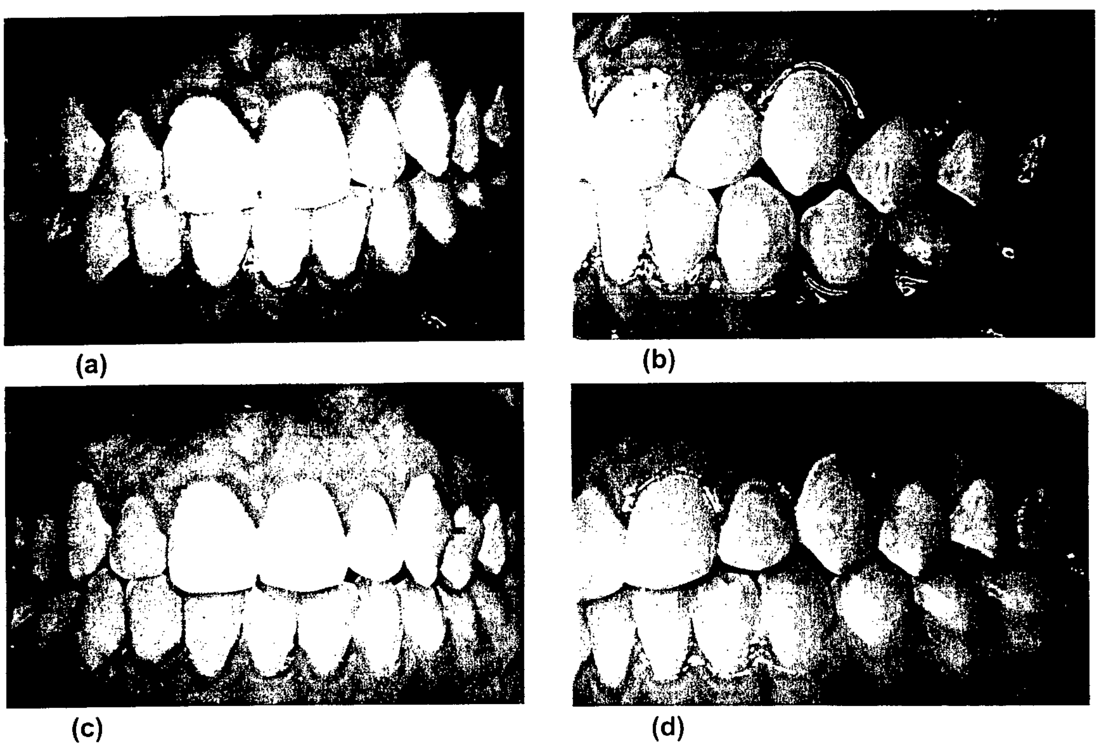

Figure 3-3 Clinical photographs of Case 3 at initial presentation (a,b) and 1 week (c,d) following bonding of composite flexible retainer to maintain alignment of a canine that had been severely malpositoned. There were no discernable differences observed in the appearance of the retainer at 1 week and at 6 months.

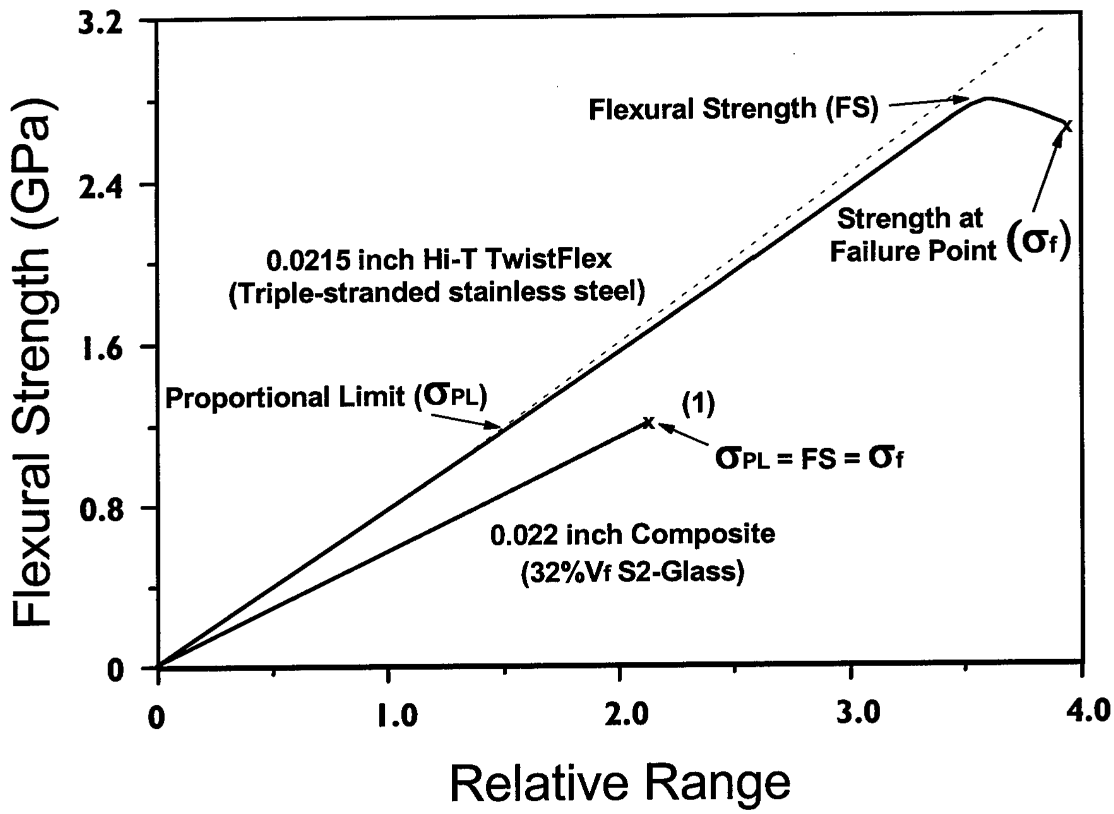

Figure 3-4 Flexural strength-relative range diagram of 0.0215inch stainless steel multi-stand wire, compared to a photo-pultruded 0.022 inch S2-glass® reinforced (32% V_f) composite wire demonstrating the elastic behavior seen in the composite up to the point of failure (σ_f), coinciding with the proportional limit (σ_{PL}). (See Appendix 2.)

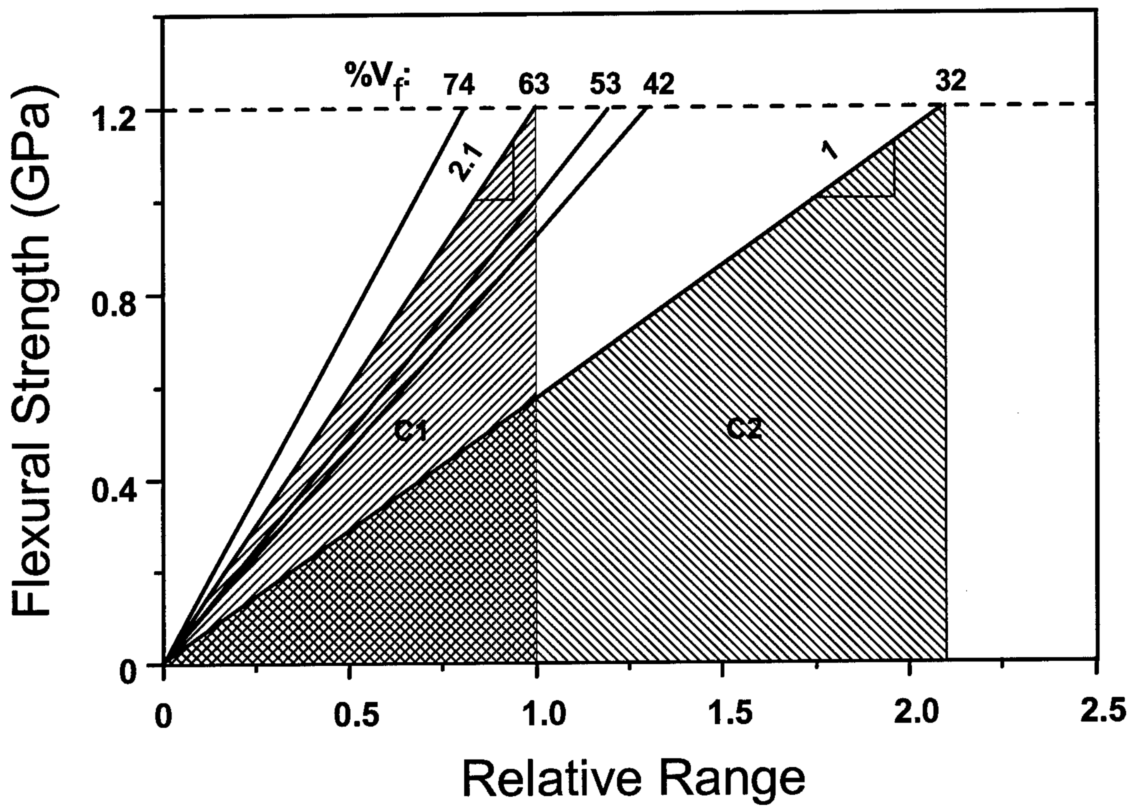

Fig. 3-5 Flexural strength-relative range diagram of photo-pultruded 0.022inch composite wires at 32, 42, 53, 63, and 74%V_f of S2-glass® reinforcement, demonstrating the relative change in stiffness (slope of each line), range or flexibility (X-axis), and resilience (areas C1 and C2) observed when %V_f is altered. The horizontal line at 1.2 GPa represents the mean flexural strength for all materials represented (23). (See Appendix 2.)

4. CONCLUSION

4.1 Summary of important findings

Photo-pultrusion can be utilized to generate round and rectangular fiber-reinforced composites that are comparable in size to conventional orthodontic archwires. The flexural properties of these materials can be altered by changing the % volume of fiber (%V_f), twists per inch (TPI), and denier of the internal reinforcement. Consequently, the moduli and resultant stiffnesses of these composites can be "tailored" to cover the flexural spectrum of orthodontic wires traditionally used in the early to intermediate stages of treatment.

By utilizing S2-glass® reinforcement, flexural strengths (FS's) of these composites can attain values as high as 1.4GPa, which is comparable to beta-titanium wires. However, the attainment of high FS's is dependent upon the optimal geometric placement of the reinforcement fibers within the material. The maximum FS's are observed when the bulk of reinforcement is placed toward the periphery, as observed in cross-section. Therefore, an optimal %V_f is reached in all materials after which additional loading is ineffective in increasing FS.

As the number of twists per inch (TPI) increases, the yarn isolation and peripheral loading of the yarns within each profile increases, which leads to more ideal morphology at lower loading levels (%V_f's). On the other hand, the increase in TPI inhibits ideal polymeric coverage during manufacture and leads to voids. The presence of these voids can have a detrimental effect on the flexural properties as TPI increases.

Photo-pultruded fiber-reinforced composite wires can be engineered with flexural properties that are acceptable for clinical use as flexible-bonded orthodontic retainers. The range, flexibility and resilience of the material can also be manipulated by altering the $\%V_f$ of reinforcement fibers. When used in clinical situations requiring bonded retention, these composites are easy to use, esthetically pleasing, and strong, having the flexibility necessary to meet both the mechanical and physiological requirements for a bonded-flexible retainer in the short-term (1 year).

4.2 Potential uses and recommendations

The advantages of these composites for use in future orthodontic appliances results not only from their superior esthetics but also from their versatility in design. Their versatility is enhanced not only because of the inherent properties of the individual components but also because of the compatibility of these components with each other and with current dental bonding techniques. Since composites inherently contain two or more classes of materials, the material properties necessary for specific applications can be more-readily engineered than when limited to only one class of material.

These photo-pultruded composite wires have demonstrated moduli and stiffnesses suited for many orthodontic applications as well as sufficient strength to survive in the intra-oral environment. With numerous applications that include orthodontic archwires, esthetic bonded retainers and space maintainers, this research will provide the impetus towards their further development.

5. APPENDICES

5.1 Appendix 1: Comparison of Exposed Filaments in CG75 versus CG150 Yarns

The difference between the diameters of the S2-glass® yarns [D_{75} = 0.011in. (0.27mm) for the CG75 yarn versus D_{150} = 0.008in. (0.20mm) for the CG150 yarn] is due to a difference in the number, N, of constituent glass filaments per yarn (408 for CG75 yarn versus 204 for CG150 yarn) (Figure A1), according to the equation,

$$N_{75} = 2 \times N_{150}. \qquad \text{(A1)}$$

When equal numbers of filaments are compared between the yarns, their diametric difference results in a decreased overall circumference, C, of the one CG75 yarn as compared to the two CG150 yarns according to the equations,

$$C_{75} = \pi D_{75} \qquad \text{(A2)}$$
$$= \pi \text{ (0.011in. or 0.28mm)} = 0.035\text{in. or } 0.88\text{mm}$$

and

$$C_{150} = 2\pi D_{150} \qquad \text{(A3)}$$
$$= 2\pi \text{ (0.008in. or 0.20mm)} = 0.05\text{in. or } 1.28\text{mm.}$$

Therefore, from equations A2 and A3,

$$C_{75} = 0.7\ C_{150.} \qquad \text{(A4)}$$

This decrease in the overall circumference of the CG75 yarn results in a 30% decrease in the number of exposed filaments that are susceptible to damage during handling and pultrusion processing.

The actual number of these 0.000354in. (9μm) diameter exposed filaments, N^*, in each yarn can be theoretically determined for the CG75 (N^*_{75}) yarn and the CG150 (N^*_{150}) yarns according to the equations,

$$N^*_{75} = C_{75} / (0.000354\text{in. or } 9\mu\text{m}) \quad \text{(A5)}$$

and

$$N^*_{150} = C_{150} / (0.000354\text{in. or } 9\mu\text{m}). \quad \text{(A6)}$$

Substituting the outcomes of equations A2 and A3 into equations A5 and A6, respectively, yields 98 exposed filaments for one CG75 yarn and 140 (70 per yarn) exposed filaments for two CG150 yarns.

In absolute terms, the 63%V_f, 0.022in. (0.56mm) diameter profiles incorporate either 6, CG75 yarns or 12, CG150 yarns with equal numbers of filaments (see Figure A1 in which 4 and 8 yarns are used to demonstrate yarn distribution). Assuming an ideal heterogeneous distribution of filaments (100% around the circumference), there would be 588 total exposed filaments in the 63%V_f, 0.022in. (0.56mm) diameter, CG75 profile (98 x 6) and 840 total exposed filaments in the CG150 profile (70 x 12), for a total of 252 fewer exposed filaments. Assuming a more realistic homogeneous distribution of filaments (63% around the circumference), there would be 370 exposed filaments in the CG75 profile (0.63 x 588) and 529 exposed filaments in the CG150 profile (0.63 x 840), for a total of 159 fewer exposed filaments. An average of these two values (since the truest number is, most likely, somewhere in between these two values) reveals that approximately 200 fewer fibers are exposed in the 63%V_f, 0.022in. (0.56mm) diameter composite when CG75 yarns are used in comparison to CG150 yarns.

5.2 Appendix 2: Analysis of Flexibility, Range and Resilience Equations for Photo-pultruded Composite Archwires.

Photo-pultruded esthetic composite materials exhibit elastic deformation, as a function of their *modulus of elasticity* in bending (E), to the point of failure, as demonstrated on a *stress-strain* (σ-ε) diagram. This is traditionally represented in an analogous way in the orthodontic literature as *stiffness* on a plot of *strength* versus *range* (Figure 4). These values vary according to the $\%V_f$ of reinforcement glass (Figure 5) (23) and are inter-related according to *Hooke's law* ($\sigma = E\varepsilon$) (36), represented in the orthodontic literature as *strength* = *stiffness* x *range* (37). Due to this failure characteristic, the *flexural strength* (FS) and the *strength at failure point* (σ_f) occur coincidentally at the last point at which σ and ε are proportional, defined as the *proportional limit* (σ_{PL}) (analogous in Figure 4 to point (1)).

Resilience is defined as the strain energy that may be recovered from a deformed body when the load causing the stress is removed (41) and is represented as the area under the stress-strain curve (analogous in Figure 5 to areas C1 and C2). When σ is equal to σ_{PL}, the *modulus of resilience* or simply *resilience* (U_R) is defined as,

$$U_R = \tfrac{1}{2}\, \sigma_{PL}\, \varepsilon. \qquad \text{(A1)}$$

By substituting (σ_{PL}/E) for ε according to Hooke's law:

$$U_R = \tfrac{1}{2}\, \sigma_{PL}(\sigma_{PL}/E) = \sigma_{PL}^{2}/2E. \qquad \text{(A2)}$$

In these composite materials *flexibility* may be defined as:

$$\mathit{Flexibility} = \sigma_{PL}/E. \qquad \text{(A3)}$$

Consequently, at the same σ_{PL}, a decrease in E will result in a proportional increase in *flexibility*.

Comparison of equations (A2) and (A3) reveals that *resilience* and *flexibility* are proportionally-related, too:

$$U_R = (\tfrac{1}{2}\,\sigma_{PL})\,\textit{Flexibility}. \qquad \text{(A4)}$$

Working range is defined as the distance that a wire will deflect elastically before permanent deformation occur (30), which in the present example is equal to ε_{PL} at the proportional limit (σ_{PL}). Therefore, the *working range* of each composite equals *flexibility*, when Hooke's law is substituted into equation (A3).

Utilizing equations (A1)-(A4) in the comparison of the present S2-glass® reinforced composites reveals that, as the $\%V_f$ of reinforcement and E is decreased whilst σ_{PL} is nearly constant (23) (Figure 5), the *range*, *flexibility*, and *resilience* will proportionally increase. Thus, when composites having $63\%V_f$ and $32\%V_f$ are compared, stiffness decreases by 2.1, but range or flexibility increases by 2.1. And because here $\sigma_{PL} = FS = \sigma_f =$ constant, the resilience increases from C1 to C2 or by a factor of $\tfrac{1}{2}\sigma_{PL}$ in accordance with equation (A4).

6. BIBLIOGRAPHY

Al-Waheidi EMH. Allergic reaction to nickel orthodontic wires: a case report. Quintessence International 1995; 26: 385-7.

Angle EA. Treatment of malocclusion of the teeth. 7 ed. Philadelphia: SS White Manufacturing Co.; 1907.

Axelsson S, Zachrisson BU. Clinical experience with direct-bonded labial retainers. Journal of Clinical Orthodontics 1992; 26: 480-90.

Bearn DR. Bonded orthodontic retainers: a review. American Journal of Orthodontics & Dentofacial Orthopedics 1995; 108: 207-13.

Bearn DR, McCabe JF, Gordon PH, Aird JC. Bonded orthodontic retainers: the wire-composite interface. American Journal of Orthodontics & Dentofacial Orthopedics 1997; 111: 67-74.

Bigg DM, Hiscock DF, Preston JR, Bradbury EJ. Polymer Composites 1993; 14: p. 26.

Blake M, Bibby K. Retention and stability: a review of the literature. American Journal of Orthodontics & Dentofacial Orthopedics 1998; 114: 299-306.

Burstone CJ. Variable-modulus orthodontics, American Journal of Orthodontics 1981; 80:1-16.

Buonocore MG. A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces. Journal of Dental Research 1955; 34: 849-53.

Carter RN. Simplified direct-bonded retainer. Journal of Clinical Orthodontics 1978; 12: 221-2.

Case CS. Principles of retention in orthodontia. American Journal of Orthodontics & Dentofacial Orthopedics 1920;(Nov.):3-34.

Dahl EH, Zachrisson BU. Long-term experience with direct-bonded lingual retainers. Journal of Clinical Orthodontics 1991; 25: 619-30.

Davidson M. Advanced Materials and Procedures 1994; 146: p.70.

Diamond M. Resin fiberglass bonded retainer. Journal of Clinical Orthodontics 1987; 21: 182-3.

Elgiloy® and Tru-Chrome® Stainless Steel Orthodontic Treatment Wires, promotional literature of Rocky Mountain Orthodontics, 1977. p. 5.

Eschbach OW, Souders O. Handbook of engineering fundamentals. 3 ed. New York: John Wiley & Sons; 1974. p. 513, 518, and 496-97.

Fallis DW, Kusy RP. Variation in flexural properties of photo-pultruded composite archwires: Analyses of round and rectangualr profiles. (In Press)

Flinn RA, Trojan PK. Engineering materials and their applications. 3rd ed, Boston; Houghton Mifflin Company; 1986. p. 447.

Goldberg AJ, Burstone CJ. inventors. Orthodontic Appliance System. 4,717,341. 1988.

Goldberg AJ, Burstone CJ. inventors. Passive Dental Appliances of Fiber-Reinforced Composites. 4,894,012. 1990.

Goldberg AJ, Burstone CJ. The use of continuous fiber reinforcement in dentistry. Dental Materials 1992; 8: 197-202.

Goldberg AJ, Burstone CJ, Hadjinikolaou I, Jancar J. Screening of matrices and fibers for reinforced thermoplastics intended for dental applications. Journal of Biomedical Materials Research 1994; 28: 167-73.

Goldberg AJ, Burstone CJ, Hadjinikolaou I, Jancar J. Screening of matrices and fibers for reinforced thermoplastics intended for dental applications. Journal of Biomedical Materials Research 1994; 28; 167-173.

Jancar J, Dibenedetto AT. Journal of Material Science: Materials in Medicine 1993; 4; 555-561.

Jancar J, Dibenedetto AT, Goldberg AJ. Journal of Material Science: Materials in Medicine 1993; 4; 562-568.

Jancar J, Dibenedetto AT, Hadziinikolau Y, Goldberg AJ, Dianselmo A. Measurement of the elastic modulus of fibre-reinforced composites used as orthodontic wires. Journal of Material Science: Materials in Medicine 1994; 5; 214-218.

Karmaker AC, Dibenedetto AT, Goldberg AJ. Continuous fiber reinforced composite materials as alternatives for metal alloys used for dental appliances. Journal of Biomaterials Applications 1997; 11: 318-28.

Kennedy KC, Chen T, Kusy RP. Behavior of photopolymerized silicate-glass-fiber-reinforced dimethacrylate composites subjected to hydrothermal aging- part I steady-state sorption characteristics. Journal of Material Science: Materials in Medicine 1998; 9; 243-?

Kennedy KC, Chen T, Kusy RP. Behavior of photopolymerized silicate-glass-fiber-reinforced dimethacrylate composites subjected to hydrothermal aging- part II hydrolytic stability of mechanical properties. Journal of Material Science: Materials in Medicine 1998; 9; 651-?

Kennedy KC, Chen T, Kusy RP. Mechanical properties of micron-sized pultruded composite profiles. 94 A.D.; Dearborn, Michigan, USA: ASM International; Proceeding of the 10th Annual ASM/ESD, 1994; 191-200.

Kennedy KC, Kusy RP. UV-Cured Pultrusion processing of glass-reinforced polymer composites. Journal of Vinyl and Additive Technology 1995; 1: 182-6.

Kennedy KC, Kusy RP. Investigation of dual-staged polymerization and secondary forming of photopultruded, fiber-reinforced, methacrylate-copolymer composites. Journal of Biomedical Materials Research 1998 ;41: 549-559.

Knierim RW. Invisible lower cuspid to cuspid retainer. Angle Orthodontist 1973; 43: 218-9.

Kusy RP. The future of orthodontic materials: The long term view. American Journal of Orthodontics & Dentofacial Orthopedics 1998; 113: 91-5.

Kusy RP. A Review of contemporary archwires: their properties and characteristics. Angle Orthodontist 1996; 67: 197-208.

Kusy RP, Dilley GJ, Whitley JQ. Mechanical properties of stainless steel orthodontic archwires. Clinical Materials 1988; 3; 41-59.

Kusy RP, Kennedy KC. inventors. Novel pultruded fiber-reinforced plastic and related apparatus and method. 5,869,178. 1999.

Kusy RP, Stevens LE. Triple-stranded stainless steel wires- Evaluation of mechanical properties and comparison with titanium alloy alternatives, Angle Orthodontist 1987; 57; 18-32.

Lee RT. The lower incisor bonded retainer in clinical practice: a three year study. British Journal of Orthodontics. 1981; 8: 150-8.

Lubit EC. The bonded lingual retainer. Journal of Clinical Orthodontics 1999; 13: 311-3.

Narayanan V, Scranton AB. Photopolymerization of composites. Trends in Polymer Science 1997; 5: 415-9.

Newman GV. Epoxy adhesives for orthodontic attachments: progress report. American Journal of Orthodontics 1965; 51: 901-12.

Orchin JD. Permanent lingual bonded retainer. Journal of Clinical Orthodontics 1990; 24: 229-31.

Park JB; Lakes RS. Biomaterials: an introduction. 2 ed. New York: Plenum Press; 1992; p. 301-2.

Price HL. Curing and flow of termosetting resins for composite material pultrusion [Master's thesis]. Old Dominion University; 1979.

Proffit WR. Contemporary orthodontics. 3 ed. St. Louis: Mosby; 1999 (In Press).

Reinhart TJ, Clements LL. Engineered materials handbook; composites. ASM International; 1987. p. 28.

Reitan K. Tissue rearrangement during retention of orthodontically rotated teeth. Angle Orthodontist 1959; 2: 105-13.

Risinger RK, Proffit WR. Continuous overnight observation of human premolar eruption. Archives of Oral Biology 1996; 41: 779-89.

Rubenstein BM. A direct bond maxillary retainer. Journal of Clinical Orthodontics 1976; 10: 43-4.

Rudo DN, Karbhari VM. Physical behaviors of fiber reinforcement as applied to tooth stabilization. Dental Clinics of North America 1999; 43: 7-35.

Shackelford JF. Introduction to materials science for engineers. 2nd ed, New York; Macmillan Publishing Company; 1988. p. 473.

Stush A, Kusy RP. Geometric and material parameters of a nickel-titanium and a beta-titanium orthodontic archwire alloy. Dental Materials 1987; 3: 207-17.

Weinberger BW. Orthodontics: a historical review of its origin and evolution. St. Louis: The CV Mosby Company; 1926.

Zachrisson BU. Clinical experience with direct-bonded orthodontic retainers. American Journal of Orthodontics 1977; 71: 440-8.

Zachrisson BU. The bonded lingual retainer and multiple spacing of anterior teeth. Swedish Dental Journal - Supplement 1982;15: 247-55.