Physical and Mechanical Characterization of Different Fiber-reinforced Composite Systems Used in Fixed Prosthesis

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The failure behaviour, stiffness and toughness of FRC bridges are dependent on the components of the composite system and their spatial relation. Of this study is to assess the flexural strength and the flexural modulus of two fiber reinforcement systems with different cross-sectional design.

Keywords: stiffness, toughness of FRC bridges, flexural strength , flexural modulus

The treatment of the single tooth edentulous areas still represents a true challenge from several points of view: biological, prophylactic, biomechanical, ergonomic and socio-economical.

Different indirect restorations used to replace a single missing tooth are available in dentistry: implant supported crowns (ISC), traditional full-coverage fixed dental prostheses (FDP), inlay or onlay-retained FDPs (or with other types of retainers), and resin-bonded fixed partial denture. The materials used in these restorations are cast metal, ceramics and, more recently, composites.

In oral biomechanical conditions, frequent technical failures occur, such as: loss of retentions, fracture or chipping of veneering, and fracture of framework materials. These complications are directly related with the imbalances between oral biomechanical stress and material properties [1, 2]. Consequently, a framework and veneering materials with correlated and lower modulus of elasticity than that of ceramics or metal alloys, but similar to dental structures, might be useful to reduce the chipping of veneering material and the debonding of the restoration. Therefore, new materials were subjected to tests in oral environment. Fiber-reinforced composites fixed dental prostheses (FRC-FDP) were developed as a necessity of minimal-invasive, reliable and low-cost prosthetic restorations.

Composite materials are defined as a combination of different heterogeneous materials having their own distinct and individual properties. This combination gains improved structural or functional properties not present in any individual component. This type of materials was developed by the aerospace industry, beginning with 1960, to answer the necessity of improving the characteristics of materials in accordance with specific requirements, in a specific environment [3]. Thus newer generation of aircraft contain in their structure up to 50% composite materials (e.g. Boeing – 787 Dreamliner). These materials offer, besides versatility, a much better strength-to-weight ratio compared to metals, sometimes even by 20% [4]. With improved characteristics, these materials can be transferred to the oral environment which in some aspects seems to be even more hostile than the outer space. The first significant results in this research field appeared in the early ’80s through the use of carbon fibers and especially aramid (Kevlar, DuPont, Wilmington, Delaware). They are not randomly oriented like short fibers, but carefully aligned to form a unidirectional tape [3].

The most common dental composites are particulate filler composites (PFC), consisting of a resin matrix (continuous phase) and fillers (particles of various materials and size). The glass fibers as fillers for composite resin matrix were used in the earlier version of today’s FRC (short fibers). When fibers are used to reinforce dental composite (continuous long fibers) the resulting material is both a particulate and a laminate composite and is termed a fiber-reinforced composite [5]. Hence fiber-reinforced composites can be classified into two types: discontinuous short fibers and continuous aligned fibers with anisotropic properties. The reinforcing component provides strength and stiffness, and the matrix supports the reinforcement and provides workability. The most often applied fibers in dental practice are: glass fibers, carbon fibers and synthetic fibers as aramid and polyethylene.

The fibers are the constituent that confers strength properties to various stresses. Compared to the matrix, the maximum stress to which the material can hold is far superior and at the same time the elongation is diminished. The matrix shows a greater elongation and a higher strength that ensures that the fibers break before the entire matrix fails. In areas subjected to high stress, the restorative materials used should have high flexural strength, high elastic modulus and low deformation as well as high impact and fatigue resistance [6].

We emphasize however that the composite material is a unitary system in which the two phases work together as the elongation-effort diagram suggests. Additionally, their modulus of elasticity can be modified, adjusting the fiber/matrix ratio, location and orientation of the fibers. Considering this aspect, the fiber reinforced composites (FRCs) should minimize the stress level at the tooth-restoration interface and improve the biomechanical properties of the pontic and of the retainers [7].

After 30 years of sustained development of physical, chemical and biomechanical properties, FRCs have currently a variety of applications in dentistry: fixed and removable prosthodontics (including repairing of fractured porcelain veneers, repairing and reinforcing of removable acrylic resin prosthesis), periodontology (periodontal splints), orthodontics (retainers and space maintainers), and restorative dentistry (root canal posts) [6-13]. However,

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Product	*Manufacturer*	*Geometrical parameters*	*Type of material and chemical composition*	*Batch number*
Construct	Kerr Corporation, Orange, CA, USA	2mm	Ultra-high strength, cold gas plasma-treated silanated biaxial braided polyethylene fibres	5137531
		3mm		5137532
Dentapreg PFM	ADM A.S., Brno, Czech Republic	3 x 0.3 x 60 mm – 10700 fibres	Multidirectional (braided) E-glass fibre	03-022014
Dentapreg PFU		2 x 0.3 x 60 mm – 8400 fibres	Unidirectional S2-glass fibre	02-022014
Construct Resin	Kerr Corporation, Orange, CA, USA	-	Fumed silica, grounded barium alumina-borosilicate, dimethacrylate resins, silane	4823032
Filtek Z250	3M ESPE, St. Paul, MN, USA	-	Microhybrid composite BIS-GMA,UDMA, BIS EMA	647812
Zetaplus	Zhermack, Badia Polesine, Italy	-	Polysiloxane condensation silicon	158882

Table 1
MATERIALS USED IN THE STUDY

Group (n=5)			1	2	3	4	5	6
	Filtek Z250 (Control)	F						
A	Filtek Z250+ Construct 3 mm		C3T	C3C	C3H	C3V	C3U	
B	Filtek Z250+ Construct 2 mm		C2T	C2C	C2H	C2V		C2D
C	Filtek Z250+ Dentapreg 3 mm		D3T	D3C	D3H	D3V		
D	Filtek Z250+ Dentapreg 2 mm		D2T	D2C	D2H	D2V		D2D
		Control	*Tension*	*Compres-sion*	*Middle Horizontal*	*Middle Vertical*	*U-shape*	*Double*

Table 2
THE SPECIMENS DIVIDED IN 21 GROUPS ACCORDING TO THE TYPE AND THE WIDTH OF THE FIBRE

current designs of FRC bridges do not provide an adequate lifespan, the survival rate being reported as 73.4% at 4.5 years [9]. The most plausible reason is the insufficient information regarding the effect of design parameters on mechanical performance of FRC bridges [14] this factor explaining also the practitioners' and technicians' reluctance in using this prosthesis.

In testing the mechanical behavior of FRC systems, many different materials, methods and aims were employed [6]. Consequently, the results obtained from the comparison between different methodologies were shown to be inconsistent, especially when different specimen dimensions, fiber thickness, location and orientation are considered [15–18]. The systems architecture is also referred to as *cross-sectional arrangement or design* [19].

The aim of this study is to assess the flexural strength and the flexural modulus of two fiber reinforcement systems with different cross-sectional design.

Experimental part

Materials and methods

In the context of using the same packable microhybrid composite (Filtek Z250, 3M ESPE) two different brands of fiber reinforcing products in ribbon-form and pre-impregnated were used in the study: Construct (Kerr) and Dentapreg (ADM) (table 1).

The evaluated parameters, related to the cross-sectional design, were: (1) different types of fibers reinforcement - glass and polyethylene, (2) different architecture of the fibers - unidirectional and braided, (3) different widths of the fiber - 2 and 3 mm and (4) different position of the fiber.

Details of the materials used in this experimental study are given in table 1.

Specimen preparation

Four main categories of five (n=5) ISO Standard 4049/2000 [20] specimens were created, according to the fibre reinforcement type and dimension (table 2). A polysiloxane condensation silicon mold was used. The mold was obtained after impression record of a rectangular stainless steel bar-shape specimen of 2 x 2 x 25 mm standard size [21].

The tested specimens for the groups *Control, Tension, Compression, U-shape and Double* were constructed placing first the fibre in polysiloxane mold followed by the composite, slightly pressed against the fibre using a glass slide, with a polyester film interposed between the glass and the mold. For the 3 mm fibres, their fitting into a 2 mm sample width change the initial disposition of the fibre within the fabric; the fibres in the ribbon are getting closer to each other and they become more oriented in longitudinal direction related to the longitudinal axis of the sample.

For the *U-shape* group, the braided fibres were placed against the bottom and lateral walls of the mold. This type of placement changes the initial disposition of the fibre within the fabric; the fibres in the ribbon spread out and separate from each other and become more oriented in transversal direction related to the longitudinal axis of the sample. For the *Double* groups, two layers of 2 mm fabric were placed on the bottom of the mold.

The tested specimens for the groups *Middle horizontal* and *Middle vertical* were constructed starting with an increment of 1 mm thickness of composite resin. The fibre was placed on top of the composite and then a second increment of composite was placed to fill the mold, slightly pressed against the fibre using a glass slide, with a polyester film interposed between the glass and the mold. In the case of groups A and B, the fabric was first wetted and then placed on the first layer of composite resin.

The light-curing of the specimens was performed in two phases. Each phase consisted of 60 s of light-exposure: 20 s for each third of the beam length. The LED curing light unit had 1100 mW/cm^2 power and 430-480 nm wavelength and its tip was positioned at 5 mm distance from the specimen.

After removing the specimens out of the mold, the dimensional parameters were assessed using a digital calliper with 0.01 mm accuracy. The material excess was removed from the edges with a scalpel blade. When necessary, the specimens were finished with a silicon carbide grinding paper, until the dimensions of 2.0 ± 0.1 mm x 2.0 ± 0.1 mm x 25.0 ± 1 mm were obtained without touching the fibre surfaces. Test specimens out of dimensional tolerance which could not be adjusted were rejected and new ones were prepared. All the procedures were performed by the same person in order to calibrate the protocol. The specimens were stored at room temperature for 24 h before mechanical testing.

Mechanical testing

The three point bend test is a short duration test that allows to determine the internal stress that occurs in the mass as a result of external forces action and of the following factors: test load speed, crosshead speed, sample deformation speed, ultimate bending force that each sample can hold, the ultimate strength, the deformation and the flexural rigidity; the diagram of the force variation in relation with time and deformation is obtained.

Five specimens (n=5) from each set were subjected to three-point bending test using ISO 4049 flexural test and a universal testing machine WDW-5CE type. The flexural strength and the flexural modulus from the measured deflection of the specimens were assessed.

The specimens have been tested by static short duration loads at a cross-head speed of 0.1mm/min, at room temperature and in normal humidity conditions. The load was applied at the middle of the test specimen perpendicular to the long axis, with a rounded-ended striker and with a distance of 20.4 mm between the two supports. Loading was removed when either sample showed catastrophic rupture or a negative slope of load vs. displacement was recorded after the peak load, with the load values dropping continually below 85% of the peak load [22].

The maximum stress at the beam surface is [23]:

$$\sigma_{\max} = \frac{M_{\max} \cdot h/2}{I_z} \quad (1)$$

where: M_{max} - maximum bending moment;

I_z - moment of inertia;

h - height of the test specimen.

In these specific conditions, the maximum bending moment in the beam is located in the middle of the test specimen and is equal to $M_{max} = Fl/4$; therefore the location of the maximum tensile and compressive flexural stresses is also in the middle of the beam, on the lower surface of the sample for the tension and upper surface of the sample for the compression.

The moment of inertia for a rectangular cross section beam is: $I_z = bh^3 / 12$, where b is the width of the test specimen.

Substitution of M_{max} and I_z into equation (1) gives:

$$\sigma_{\max} = \frac{3}{2} \cdot \frac{F \cdot l}{b \cdot h^2} \quad (2)$$

where: F - maximum load.

The maximum deflection of the beam is [1]:

$$f_{\max} = \frac{F \cdot l^3}{48 \cdot E \cdot I_z} \quad (3)$$

where: l - the distance between the supports.

Substitution of I_z into equation (3) gives the following formulae for the flexural modulus (E):

$$E = \frac{F \cdot l^3}{4 \cdot f_{\max} \cdot bh^3} \quad (4)$$

where: f_{max} - the maximum deflection of beam.

Statistical methods

Mean data values and SDs were calculated for initial and final flexural strength and for initial and final flexural modulus. The initial flexural strength (IFS) corresponds to the first cracks appeared in the sample, which are usually initiated in the tension part of the samples. The final flexural strength (FFS) corresponds to the peak load, which for some samples coincides with the catastrophic failure.

One-way analysis of variance (ANOVA) and Tukey post hoc multiple comparisons test were used to determine the significance of the difference between mean values of calculated flexural strength and modulus of elasticity for each main category. All tests were performed at a significance level of $\alpha = 0.05$.

Results and discussions

Under flexural conditions simulated in this experiment, the principal stress on the superior aspect of the beam is compressive, while that on the inferior aspect is tensile. Two failure patterns were noticed: the first one - catastrophic failure, in brittle fashion, at peak load, and the second one – representative for plastic deformation, with an increasing displacement after the peak load, corresponding to a slow decrease in load. The specimens were tested until fracture failure occurred or 4 mm midpoint deflection was attained.

It was noticed that for the samples without reinforcement on the tension side, the first fracture line appeared along the axis of the force, on the inferior part of the composite. The crack evolved up to the junction layer between the fibre and the composite veneer and then the fracture spread along the fibre. For the samples with reinforcement on the tension side, cracks appeared at the compression side - the superior part of the composite. The fracture failure describes two patterns: the complete transversal separation of the specimens in two parts and the delamination of the composite, while maintaining the fibre integrity (fig. 1 - 6).

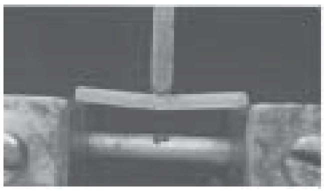

Fig. 1. Construct – compression side

Fig. 2. Construct fibre – U-shape

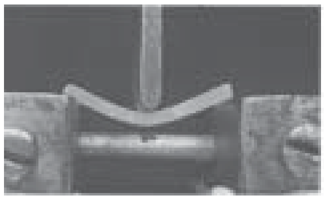

Fig. 3. Construct – middle vertical

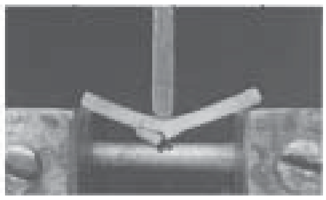

Fig. 4. Construct – middle vertical

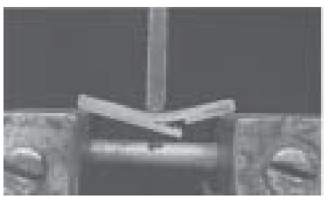

Fig. 5. Dentapreg – middle horizontal

Fig. 6. Dentapreg – tension

The initial flexural strength (IFS) and initial flexural modulus (IFM) values were calculated based on the initial loads, equivalent to the initial fracture force and the initial deflection of the specimens. The final flexural strength (IFS) and the final flexural modulus (IFM) values were calculated based on the maximum loads, equivalent to the peak load and the final deflection of the specimens (max. 4.5 mm). It must be pointed out that for the samples which were

Table 3
ONE-WAY ANALYSIS OF VARIANCE - INITIAL FLEXURAL STRENGTH (MPa)

SUMMARY				
Groups (n=5)	Sum	Average	Variance	SD
C3T	208,16	69,39	2094,81	45,77
C3C	149,66	49,89	1298,22	36,03
C3V	97,75	32,58	2,92	1,71
C3H	163,67	54,56	2007,20	44,80
C3U	1378,77	459,59	351,41	18,75
D3T	406,32	135,44	719,35	26,82
D3C	118,70	39,57	259,32	16,10
D3V	185,72	61,91	1011,49	31,80
D3H	69,96	23,32	9,57	3,09
C2T	87,20	29,07	0,18	0,42
C2C	147,70	49,23	1674,53	40,92
C2V	336,34	112,11	171,62	13,10
C2H	86,34	28,78	29,19	5,40
C2D	89,50	29,83	1,59	1,26
D2C	164,39	54,80	2001,86	44,74
D2T	84,47	28,16	0,49	0,70
D2V	84,13	28,04	0,41	0,64
D2H	71,20	23,73	0,40	0,64
D2D	88,51	29,50	0,25	0,50
F	67,37	22,46	0,31	0,56

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	534538,2	19	28133,59	48,35974	1E-21	1,852892
Within Groups	23270,25	40	581,7562			
Total	557808,5	59				

Table 4
ONE-WAY ANALYSIS OF VARIANCE - FOR FINAL FLEXURAL STRENGTH, AT PEAK VALUE (MPa)

SUMMARY				
Groups (n=5)	Sum	Average	Variance	SD
C3T	1282,22	427,41	2803,12	52,94
C3C	266,01	88,67	12,67	3,56
C3V	647,76	215,92	641,63	25,33
C3H	610,17	203,39	3018,93	54,94
C3U	1623,98	541,33	2302,02	47,98
D3T	379,71	156,11	1726,91	41,56
D3C	289,44	96,48	3523,16	59,36
D3V	375,55	125,18	0,81	0,90
D3H	447,94	149,31	1847,04	42,98
C2T	1132,22	377,41	2063,26	45,42
C2C	301,59	100,53	100,90	10,04
C2V	588,03	196,01	1222,34	34,96
C2H	566,25	188,75	472,33	21,73
C2D	854,98	284,99	25,00	5,00
D2C	366,16	122,05	279,79	16,73
D2T	730,66	243,55	429,97	20,74
D2V	546,09	182,03	331,33	18,20
D2H	348,68	116,23	24,09	4,91
D2D	524,00	174,67	16,33	4,04
F	67,37	22,46	0,31	0,56

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	893666,09	19	47035,06	49,159	7E-22	1,8529
Within Groups	38271,64	40	956,791			
Total	931937,73	59				

fractured in one stage the initial and the final flexural strength were the same (especially for unreinforced samples and for some of glass-fibre reinforced samples).

The ANOVA test was performed in the first step to determine if any significant differences exist between group means. The Tukey test was run to find which group means exhibit a significant difference.

All the reinforcements increased to some extent both initial and final flexural strength. The best results, in both cases, were manifested by C3U (459.59±18.75 MPa - initial and 541.33±47.98 MPa - final).

For the initial flexural strength, significant improved performances were demonstrated also by D3T (135.44±26.82 MPa) and C2V (112.11±13.10 MPa). The lack of statistical significance for the other cross-sectional designs can be correlated with the large variance of the determinations.

The evaluation of the final tensile strength reveals that the braided polyethylene fibres assure a better flexural strength compared with glass-fibres. In the groups of Construct fibres, one can notice that the disposition of the fibres is the main factor that makes the difference, the dimension being the second one (tables 5 and 6). The best cross-sectional design is *U-shape* followed by the placement of the fibres on the tensile side (*Tension* groups): C3T = 427,41±52,94 MPa and C2T = 377,41±45,42 MPa. Also, C2D (*Double* fibres on tensile side) showed an increased toughness (284,99±5,0 MPa), but significantly lower than C2T.

It is already commonly accepted that the placement of the fibres, disregarding their type, on the tensile side, improves the flexural strength of the samples [6, 14, 18, 24, 25]. In this case, the fracture pattern for polyethylene fibres samples changes to more ductile and elongated compared to the glass-fibres or unreinforced samples for

Tabel 5
TUKEY'S MULTIPLE COMPARISON TEST (TUKEY'S HSD) - PAIR-WISE COMPARISON BETWEEN MEANS FOR INITIAL FLEXURAL STRENGTH. STATISTICALLY SIGNIFICANT DIFFERENCES ARE HIGH-LIGHTED

Groups		C3U	D3T	C2V	C3T	D3V	D2C	C3H	C3C	C2C	D3C	C3V	C2D	D2D	C2T	C2H	D2T	D2V	D3H	D2H	F
	Average	459,59	128,81	112,11	69,39	61,91	54,80	54,56	49,89	49,23	39,57	32,58	29,83	29,50	29,07	28,78	28,16	28,04	26,39	23,73	22,46
C3U	459,59	0,00																			
D3T	128,81	330,78	0,00																		
C2V	112,11	347,48	16,69	0,00																	
C3T	69,39	390,20	59,42	42,73	0,00																
D3V	61,91	397,68	66,90	50,21	7,48	0,00															
D2C	54,80	404,79	74,01	57,32	14,59	7,11	0,00														
C3H	54,56	405,03	74,25	57,56	14,83	7,35	0,24	0,00													
C3C	49,89	409,70	78,92	62,23	19,50	12,02	4,91	4,67	0,00												
C2C	49,23	410,35	79,57	62,88	20,15	12,67	5,56	5,32	0,65	0,00											
D3C	39,57	420,02	89,24	72,55	29,82	22,34	15,23	14,99	10,32	9,67	0,00										
C3V	32,58	427,01	96,22	79,53	36,80	29,32	22,21	21,98	17,30	16,65	6,98	0,00									
C2D	29,83	429,76	98,97	82,28	39,55	32,07	24,96	24,73	20,05	19,40	9,73	2,75	0,00								
D2D	29,50	430,08	99,30	82,61	39,88	32,40	25,29	25,05	20,38	19,73	10,06	3,08	0,33	0,00							
C2T	29,07	430,52	99,74	83,05	40,32	32,84	25,73	25,49	20,82	20,17	10,50	3,51	0,76	0,44	0,00						
C2H	28,78	430,81	100,03	83,33	40,61	33,13	26,02	25,78	21,10	20,45	10,79	3,80	1,05	0,72	0,29	0,00					
D2T	28,16	431,43	100,65	83,96	41,23	33,75	26,64	26,40	21,73	21,08	11,41	4,43	1,68	1,35	0,91	0,62	0,00				
D2V	28,04	431,55	100,77	84,07	41,34	33,86	26,75	26,52	21,84	21,19	11,52	4,54	1,79	1,46	1,03	0,74	0,11	0,00			
D3H	26,39	433,20	102,42	85,72	42,99	35,51	28,40	28,17	23,49	22,84	13,17	6,19	3,44	3,11	2,68	2,39	1,76	1,65	0,00		
D2H	23,73	435,85	105,07	88,38	45,65	38,17	31,06	30,82	26,15	25,50	15,83	8,85	6,10	5,77	5,33	5,05	4,42	4,31	2,66	0,00	
F	22,46	437,13	106,35	89,66	46,93	39,45	32,34	32,10	27,43	26,78	17,11	10,13	7,38	7,05	6,61	6,32	5,70	5,59	3,94	1,28	0,00

Tabel 6

TUKEY'S MULTIPLE COMPARISON TEST (TUKEY'S HSD) - PAIR-WISE COMPARISON BETWEEN MEANS FOR FINAL FLEXURAL STRENGTH. STATISTICALLY SIGNIFICANT DIFFERENCES ARE HIGH-LIGHTED

Groups		C3U	C3T	C2T	C2D	D2T	C3V	C3H	C2V	D2V	D2D	D3H	D3T	D3V	D2C	D2H	C2H	C2C	D3C	C3C	F
	Average	541,33	427,41	377,41	258,85	243,55	215,92	203,39	196,01	182,03	165,33	149,31	126,57	125,18	122,05	116,23	104,69	100,53	96,48	88,67	22,46
C3U	541,33	0,00																			
C3T	427,41	113,92	0,00																		
C2T	377,41	163,92	50,00	0,00																	
C2D	258,85	282,50	168,58	118,58	0,00																
D2T	243,55	297,77	183,85	133,85	15,27	0,00															
C3V	215,92	325,40	211,48	161,48	42,91	27,63	0,00														
C3H	203,39	337,93	224,01	174,02	55,44	40,16	12,53	0,00													
C2V	196,01	345,31	231,39	181,40	62,82	47,54	19,91	7,38	0,00												
D2V	182,03	359,29	245,37	195,38	76,80	61,52	33,89	21,36	13,98	0,00											
D2D	165,33	375,99	262,07	212,07	93,49	78,22	50,59	38,06	30,68	16,70	0,00										
D3H	149,31	392,01	278,09	228,10	109,51	94,24	66,61	54,08	46,70	32,72	16,02	0,00									
D3T	126,57	414,75	300,84	250,84	132,28	116,98	89,35	76,82	69,44	55,46	38,76	22,74	0,00								
D3V	125,18	416,14	302,22	252,22	133,64	118,37	90,74	78,21	70,83	56,85	40,15	24,13	1,39	0,00							
D2C	122,05	419,27	305,35	255,36	136,77	121,50	93,87	81,34	73,96	59,98	43,28	27,26	4,52	3,13	0,00						
D2H	116,23	425,10	311,18	261,18	142,60	127,33	99,69	87,17	79,79	65,81	49,11	33,09	10,34	8,96	5,83	0,00					
C2H	104,69	436,63	322,71	272,71	154,13	138,86	111,23	98,70	91,32	77,34	60,64	44,62	21,88	20,49	17,36	11,53	0,00				
C2C	100,53	440,79	326,88	276,88	158,30	143,02	115,39	102,86	95,48	81,50	64,80	48,78	26,04	24,65	21,52	15,70	4,16	0,00			
D3C	96,48	444,85	330,93	280,93	162,35	147,08	119,44	106,91	99,53	85,55	68,85	52,83	30,09	28,70	25,57	19,75	8,22	4,05	0,00		
C3C	88,67	452,65	338,74	288,74	170,16	154,88	127,25	114,72	107,34	93,36	76,66	60,64	37,90	36,51	33,38	27,56	16,02	11,86	7,81	0,00	
F	22,46	518,87	404,95	354,95	236,37	221,10	193,48	180,93	173,55	159,58	142,88	126,86	104,11	102,73	99,60	93,77	82,24	78,07	74,02	66,21	0,00

which the fracture is brittle and instantaneous. From the clinical point of view this ductile fracture behaviour should allow the possibility of prolonging the intraoral life-span of the fibre-reinforced bridges by allowing some repairs to be performed. In this particular situation, the difference between the initial flexural strength and the final flexural strength becomes relevant. This is not the case when the rupture is sudden: no intra-oral interventions are possible and the initial flexural strength becomes the most important factor in clinical surviving of the FRC bridges.

The placement of the C fibres on the compression side, either 2 or 3 mm, improved the flexural strength but not in a statistically significant manner. This is the case for all the fibres placed in the compression side of the samples. For these situations, the mechanical performances of the samples are dictated mainly by the mechanical properties of the veneering composite [14, 24, 25]. The same goes for the middle horizontal disposition of the fibres where there are no remarkable improvements and, supplementary, the thickness of the veneering composite at the inferior part of the sample plays an important role. In these situations, after the failure of the inferior layer of the composite, the tensile stress is transferred completely to the fibre.

Another aspect that is worth mentioning, even if not statistically significant, is the position of the fibre in the middle of the sample. The vertical orientation (*Vertical* groups), parallel to the force direction, seems to work better in terms of flexural strength than horizontal (*Horizontal* groups). This seems to be in contradiction with the findings of other studies [24, 26, 27].

Regarding the initial flexural modulus, no statistically significant correlations of E were found for the cross-sectional designs tested in this study, except for D2D which proved highly rigid (41.4±2.6 MPa) (table 7-10).

Overall, for both the initial and final flexural modulus, the glass-fibres seem to increase the flexural modulus. Also, placing the fibres on the pressure side (*Compression* groups) increases the flexural modulus, while placing the fibres on the tension side (*Tension* groups) increases the

Table 7

ONE-WAY ANALYSIS OF VARIANCE - INITIAL FLEXURAL MODULUS (GPa)

SUMMARY				
Groups (n=5)	*Sum*	*Average*	*Variance*	*SD*
C3T	14,81	4,94	1,207	1,10
C3C	34,16	11,39	100,873	10,04
C3V	37,90	12,63	199,477	14,12
C3H	13,25	4,42	0,048	0,22
C3U	14,74	4,91	0,308	0,55
D3T	12,10	4,03	0,353	0,59
D3C	18,05	6,02	27,218	5,22
D3V	40,38	13,46	45,841	6,77
D3H	9,81	3,27	0,015	0,12
C2T	16,44	5,48	8,635	2,94
C2C	28,78	9,59	120,730	10,99
C2V	12,28	4,09	0,226	0,47
C2H	40,41	13,47	23,838	4,88
C2D	28,80	9,60	0,281	0,53
D2C	47,88	15,96	58,047	7,62
D2T	39,40	13,13	1,796	1,34
D2V	31,47	10,49	0,626	0,79
D2H	27,71	9,24	7,632	2,76
D2D	124,50	41,50	6,750	2,60
F	14,14	4,71	3,172	1,78

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4002,18	19	210,6411	6,938575	1,47E-07	1,852892
Within Groups	1214,144	40	30,3536			
Total	5216,324	59				

Table 8

ONE-WAY ANALYSIS OF VARIANCE - FINAL FLEXURAL MODULUS (GPa), AT THE PEAK VALUE

SUMMARY				
Groups (n=5)	*Sum*	*Average*	*Variance*	*SD*
C3T	17,05	5,68	0,20	0,44
C3C	9,49	3,16	0,07	0,26
C3V	5,94	1,98	0,13	0,36
C3H	5,26	1,75	0,04	0,19
C3U	14,02	4,67	0,28	0,53
D3T	7,33	2,68	1,05	1,03
D3C	5,67	1,88	0,58	0,76
D3V	10,18	3,39	1,12	1,06
D3H	8,52	2,42	0,01	0,10
C2T	13,19	4,40	0,12	0,34
C2C	8,48	2,83	0,07	0,27
C2V	5,34	1,78	0,14	0,37
C2H	4,38	1,46	0,06	0,25
C2D	15,09	5,03	0,01	0,09
D2C	18,55	6,18	0,83	0,91
D2T	18,52	6,17	0,02	0,15
D2V	9,49	4,37	0,02	0,15
D2H	15,11	2,54	0,23	0,48
D2D	15,29	5,10	0,25	0,50
F	8,04	2,68	1,20	1,10

ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	138,1911	19	7,273216	17,98772	5,87E-14	1,852892
Within Groups	16,17374	40	0,404343			
Total	154,3648	59				

Tabel 9

TUKEY'S MULTIPLE COMPARISON TEST (TUKEY'S HSD) - PAIR-WAYS COMPARISON BETWEEN MEANS FOR INITIAL FLEXURAL MODULUS. STATISTICALLY SIGNIFICANT DIFFERENCES ARE HIGH-LIGHTED

Groups		D2D	D2C	C2H	D3V	D2T	C3V	C3C	D2V	C2D	C2C	D2H	D3C	C2T	C3T	C3U	F	C3H	C2V	D3T	D3H
	Average	41,50	15,96	13,47	13,46	13,13	12,63	11,39	10,49	9,60	9,59	9,24	6,02	5,48	4,94	4,91	4,71	4,42	4,09	4,03	3,27
D2D	41,50	0,00																			
D2C	15,96	25,54	0,00																		
C2H	13,47	28,03	2,49	0,00																	
D3V	13,46	28,04	2,50	0,01	0,00																
D2T	13,13	28,37	2,82	0,33	0,33	0,00															
C3V	12,63	28,87	3,33	0,84	0,83	0,50	0,00														
C3C	11,39	30,11	4,57	2,08	2,07	1,75	1,25	0,00													
D2V	10,49	31,01	5,47	2,98	2,97	2,64	2,14	0,90	0,00												
C2D	9,60	31,90	6,36	3,87	3,86	3,53	3,03	1,78	0,89	0,00											
C2C	9,59	31,91	6,37	3,88	3,87	3,54	3,04	1,79	0,90	0,01	0,00										
D2H	9,24	32,26	6,72	4,23	4,22	3,90	3,40	2,15	1,25	0,36	0,36	0,00									
D3C	6,02	35,48	9,94	7,45	7,44	7,12	6,62	5,37	4,47	3,59	3,58	3,22	0,00								
C2T	5,48	36,02	10,48	7,99	7,98	7,65	7,15	5,91	5,01	4,12	4,11	3,76	0,54	0,00							
C3T	4,94	36,56	11,02	8,53	8,52	8,20	7,69	6,45	5,55	4,66	4,65	4,30	1,08	0,54	0,00						
C3U	4,91	36,59	11,05	8,56	8,55	8,22	7,72	6,47	5,58	4,69	4,68	4,32	1,10	0,57	0,03	0,00					
F	4,71	36,79	11,25	8,76	8,75	8,42	7,92	6,67	5,78	4,89	4,88	4,52	1,30	0,77	0,23	0,20	0,00				
C3H	4,42	37,08	11,54	9,05	9,05	8,72	8,22	6,97	6,07	5,19	5,18	4,82	1,60	1,06	0,52	0,50	0,30	0,00			
C2V	4,09	37,41	11,87	9,38	9,37	9,04	8,54	7,29	6,40	5,51	5,50	5,14	1,92	1,39	0,84	0,82	0,62	0,32	0,00		
D3T	4,03	37,47	11,93	9,44	9,43	9,10	8,60	7,35	6,46	5,57	5,56	5,20	1,98	1,45	0,90	0,88	0,68	0,38	0,06	0,00	
D3H	3,27	38,23	12,69	10,20	10,19	9,86	9,36	8,12	7,22	6,33	6,32	5,97	2,75	2,21	1,67	1,64	1,44	1,15	0,82	0,76	0,00

Tabel 10

TUKEY'S MULTIPLE COMPARISON TEST (TUKEY'S HSD) - PAIR-WAYS COMPARISON BETWEEN MEANS FOR INITIAL FLEXURAL MODULUS. STATISTICALLY SIGNIFICANT DIFFERENCES ARE HIGH-LIGHTED

Groups		D2C	D2T	C3T	D2D	C2D	C3U	C2T	D2V	D3V	C3C	C2C	F	D3T	D2H	D3H	C3V	D3C	C2V	C3H	C2H
	Average	6,18	6,17	5,68	5,10	5,03	4,67	4,40	4,37	3,39	3,16	2,83	2,68	2,68	2,54	2,42	1,98	1,88	1,78	1,75	1,46
D2C	6,18																				
D2T	6,17	0,01																			
C3T	5,68	0,50	0,49																		
D2D	5,10	1,09	1,08	0,59																	
C2D	5,03	1,15	1,14	0,65	0,06																
C3U	4,67	1,51	1,50	1,01	0,42	0,36															
C2T	4,40	1,79	1,78	1,29	0,70	0,63	0,28														
D2V	4,37	1,81	1,80	1,31	0,72	0,66	0,30	0,02													
D3V	3,39	2,79	2,78	2,29	1,70	1,64	1,28	1,00	0,98												
C3C	3,16	3,02	3,01	2,52	1,93	1,87	1,51	1,23	1,21	0,23											
C2C	2,83	3,35	3,34	2,86	2,27	2,20	1,85	1,57	1,55	0,57	0,34										
F	2,68	3,50	3,49	3,00	2,41	2,35	1,99	1,72	1,69	0,71	0,48	0,15									
D3T	2,68	3,51	3,50	3,01	2,42	2,36	2,00	1,72	1,70	0,72	0,49	0,15	0,01								
D2H	2,54	3,64	3,63	3,14	2,55	2,49	2,13	1,85	1,83	0,85	0,62	0,28	0,14	0,13							
D3H	2,42	3,76	3,75	3,26	2,68	2,61	2,25	1,98	1,95	0,97	0,74	0,41	0,26	0,26	0,13						
C3V	1,98	4,20	4,19	3,70	3,12	3,05	2,69	2,42	2,39	1,41	1,18	0,85	0,70	0,70	0,57	0,44					
D3C	1,88	4,31	4,30	3,81	3,22	3,15	2,80	2,52	2,50	1,52	1,29	0,95	0,80	0,80	0,67	0,54	0,10				
C2V	1,78	4,40	4,39	3,91	3,32	3,25	2,89	2,62	2,59	1,62	1,39	1,05	0,90	0,90	0,77	0,64	0,20	0,10			
C3H	1,75	4,43	4,42	3,93	3,34	3,28	2,92	2,64	2,62	1,64	1,41	1,08	0,93	0,92	0,79	0,67	0,23	0,12	0,03		

flexural strength. This is in agreement with the findings of other research studies [14, 24]. A meta-regression study pointed out a lower flexural modulus of polyethylene reinforced specimens, regardless the dimension, impregnation, manufacturer or type of composite [6].

The rich scientific literature on the subject of FRC is motivated by the researchers' belief that these restorations have a great potential. It is unanimously accepted that there is a lack of knowledge in this field due to its novelty and the existing research is either insufficient or inconclusive. A simple transfer of the research methodology from the field of physics, chemistry, plastics or ceramics to composites does not seem to offer the expected answers for an improved application of these composites in the oral cavity.

Unfortunately the scientific literature does not contain studies that demonstrate clearly enough the relation between the biomechanical performance of the materials and their clinical utilization. Moreover, given the particularity of these materials i.e. their anisotropy and the fact that their biomechanical properties vary in accordance to the fiber/resin ratio, to the fiber's position, orientation and type and to the composite type, the variability of these materials is very high. This opens the way for an extraordinary potential leading to new research and promising results.

Some other factors that make these materials difficult to manage and that have an influence on the biomechanical properties are: fiber surface treatment, impregnation of fibers with resin, water absorption of the matrix and the adhesion between fiber and matrix. For example, the composite matrix allows diffusion and absorption of water, resulting in a decrease of strength and stiffness. The greatest reduction in strength is reported to be in the first 4 weeks of water storage [28].

Various studies have shown that framework design, flexural and fatigue properties, and load-bearing capacities of FRCs have improved [14, 29, 30]. In most studies of dental FRCs, an ISO standard-size bar of the composite material (2mm x 2mm x 25mm) is tested to failure by three-point or four-point load. Such studies usually find that the material's strength is significantly improved by the addition of the reinforcement fibers, but the conclusion usually is that the strength of the resulting structure is still not perfectly suitable for dental restoration. "Such a conclusion does not correlate well with the excellent clinical success achieved by numerous practitioners. Fiber-reinforced dental composite may not work on paper but works extremely well in the mouth." [5]. On the other hand, other authors state that the selection and use of continuous reinforcement is largely on an ad hoc basis. There are diverse claims made by manufacturers, a lack of a thorough understanding of the materials based, and also not a deep understanding of the material required performances for specific applications [22]. The potential of these metal replacing restorations, with all disadvantages that they carry, allow minimal preparation with exceptional aesthetic results at very affordable costs, in a short time. This is very motivating and appealing to many specialists and patients. Nevertheless the high variability of materials and techniques combined with the execution sensitivity and overall the reported survival rate can be discouraging for many practitioners.

It is known with certitude that the failure behavior, stiffness and toughness of FRC bridges are dependent on the components of the composite system and their spatial relation. Considering these aspects, it is a matter of time until the optimum design will be properly described in order to ensure the success of this type of restorations.

Conclusions

The cross-sectional design plays an important role in biomechanical performances of FRC restorations. Within the limitations of the present study, it was found that the toughness of the studied FRC systems increased in the case of tensile side placement of the fibers. The U-shape placement of biaxial braided polyethylene fibers on the tensile side of the samples presented the best flexural strength.

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