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Effect of fiber architecture on flexural characteristics and fracture of fiber-reinforced dental composites

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ABSTRACT

Objective. The aim of this study was to compare and elucidate the differences in damage mechanisms and response of fiber-reinforced dental resin composites based on three different brands under flexural loading. The types of reinforcement consisted of a unidirectional E-glass prepreg (Splint-It from Jeneric/Petron Inc.), an ultrahigh molecular weight polyethylene fiber based biaxial braid (Connect, Kerr) and an ultrahigh molecular weight polyethylene fiber based leno-weave (Ribbond).

Methods. Three different commercially available fiber reinforcing systems were used to fabricate rectangular bars, with the fiber reinforcement close to the tensile face, which were tested in flexure with an emphasis on studying damage mechanisms and response. Eight specimens ($n = 8$) of each type were tested. Overall energy capacity as well as flexural strength and modulus were determined and results compared in light of the different abilities of the architectures used.

Results. Under flexural loading unreinforced and unidirectional prepreg reinforced dental composites failed in a brittle fashion, whereas the braid and leno-weave reinforced materials underwent significant deformation without rupture. The braid reinforced specimens showed the highest peak load. The addition of the unidirectional to the matrix resulted in an average strain of 0.06 mm/mm which is 50% greater than the capacity of the unreinforced matrix, whereas the addition of the braid and leno-weave resulted in increases of 119 and 126%, respectively, emphasizing the higher capacity of both the UHM polyethylene fibers and the architectures to hold together without rupture under flexural loading. The addition of the fiber reinforcement substantially increases the level of strain energy in the specimens with the maximum being attained in the braid reinforced specimens with a 433% increase in energy absorption capability above the unreinforced case. The minimum scatter and highest consistency in response is seen in the leno-weave reinforced specimens due to the details of the architecture which restrict fabric shearing and movement during placement.

Significance. It is crucial that the appropriate selection of fiber architectures be made not just from a perspective of highest strength, but overall damage tolerance and energy absorption. Differences in weaves and architectures can result in substantially different performance and appropriate selection can mitigate premature and catastrophic failure. The study provides details of materials level response characteristics which are useful in selection of the fiber reinforcement based on specifics of application.

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1. Introduction

A range of fillers in particulate form have conventionally been used to improve performance characteristics, such as strength, toughness and wear resistance, Although the addition of fillers and recent changes in composition of resin composites have been noted to provide enhanced wear resistance [1,2], conventional filler based systems are still brittle as compared to metals. Sakaguchi et al. [3] reported that these were prone to early fracture with crack propagation rates in excess of those seen in porcelain. This is of concern since clinical observations have demonstrated that under forces generated during mastication the inner faces of restorations can be subject to high tensile stresses which cause premature fracture initiation and failure [4]. In recent years, fiber reinforcements in the form of ribbons have been introduced to address these deficiencies [5]. By etching and bonding to tooth structure with composite resins embedded with woven fibers adapted to the contours of teeth periodontal splints, endodontic posts, anterior and posterior fixed partial dentures, orthodontic retainers and reinforcement of single tooth restorations can be accomplished. While the science of fiber-reinforced polymer composites is well established, the application of these materials in dental applications is still new and aspects related to material characterization, cure kinetics and even placement of reinforcement are still not widely understood.

Due to the nature of filled polymer and ceramic systems that have been used conventionally, most material level tests designed and used extensively, for the characterization of dental materials, emphasize the brittle nature of materials response. In many cases the tests and the interpretation of results, are not suited to the class of fiber-reinforced polymeric composites, wherein aspects, such as fiber orientation, placement of fabric and even scale effects are extremely important. The difference in characteristics and the need to develop a fundamental understanding of response of continuous fiber and fabric, reinforced dental composites has recently been emphasized both through laboratory and clinical studies. Recent studies have addressed critical aspects, such as effects of fabric layer thickness ratios and configurations [6], fiber position and orientation [7] and even test specimen size [8]. However, the selection and use of continuous reinforcement is largely on an ad hoc basis, with diverse claims being made by manufacturers, without a thorough understanding of the materials based performance demands for the material by the specifics of an application (for example, the fabric architecture required for optimized performance of a post are very different from those for a bridge) or details of response characteristics at levels beyond those of mere “strength” and “modulus”. Further, each fabric is known to respond in different manner to manipulation and drape (i.e. conformance) to changes in substrate configuration [9]. The architecture of the fabrics permits movement of fibers or constraint thereof and even shearing of the structure, to different extents. Weave patterns have also been noted to be important in the selection of composite materials for dental applications based on the specifics of application [10]. Thus, clinically, when each of the different fabric configurations is used to reinforce dental composites, there are manipulation changes that occur to some of the fabric materials. For the biaxially braided material, the fiber orientation can change after cutting and embedment in the composite when adapting to tooth contours. The fibers in the ribbon spread out and separate from each other and become more oriented in a direction transverse to the longitudinal axis of the ribbon. When the leno-weave is cut and embedded in dental composites, the fiber yarns maintain their orientation and do not separate from each other when closely adapted to the contours of teeth. However, due to the orthogonal structure gaps can appear within the architecture providing local areas unreinforced with fiber reinforcement. The unidirectional glass fiber material does not closely adapt to the contours of teeth due to the rigidity of the fibers. It is difficult to manipulate the fibrous material which leaves the final composite material thicker; further manipulation causes glass fiber separation with some visible fractures of the fibers themselves.

The aim of this study is to experimentally assess the flexural response of three commercial fiber/fabric reinforcement systems available for dental use and to compare performance based on different characteristics and to elucidate differences based on details of fabric architecture and fiber type.

2. Materials and methods

Three different fabric-reinforcing products, all in ribbon form, were used in this investigation. The first is a 3 mm wide unidirectional E-glass prepreg structure with no transverse reinforcement (Splint-It, Jeneric/Petron Inc.[1]) designated as set A, whereas the other two are formed of ultra-high molecular weight polyethylene fibers in the form of a 4 mm wide biaxial braid (Connect, Kerr), designated as set B and a 3 mm wide Leno-weave (Ribbond, WA), designated as set C. The first is a pure unidirectional which intrinsically gives the highest efficiency of reinforcement in the longitudinal direction with resin dominated response in the transverse direction. The second is a biaxial braid without axial fibers, which provides very good conformability and structure through the two sets of yarns forming a symmetrical array with the yarns oriented at a fixed angle from the braid axis. The third architecture has warp yarns crossed pair wise in a figure of eight pattern as filling yarns providing an open weave effect for controlled yarn slippage and good stability.

Multiple specimens of the fabrics were carefully measured and weighed and the average basis weight of the biaxial braid was determined to be 1.03×10^{-4} g/mm^2 whereas that for the leno-weave was 1.42×10^{-4} g/mm^2. It was noted that the unidirectional had an aerial weight of 2.2 times that of the other two. Rectangular test bars of size 2 mm × 2 mm × 48 mm were constructed from layered placement of a flowable composite resin (Virtuoso FloRestore, Demat) in polysiloxane molds, with glass slides held on top with rubber bands and light cured for 60 s using a Kulzer UniXS laboratory polymerization lamp. In the case of sets B and C the fabric was first wetted and

[1] Commercial products are identified for purposes of specification only, and do not imply endorsement, nor do they necessarily imply that the products are the best available for the purpose.

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then placed on the first layer of the flowable composite resin such that the fiber reinforcement was placed between 0.25 and 0.5 mm from the bottom surface (which would be used as the tensile surface in flexural testing). The addition of higher modulus material at or near the tensile surface is known from elementary mechanics of materials to increase flexural performance and has been verified for dental composite materials by Ellakwa et al. [11,12]. Care was taken to maintain alignment of the fibers and fabric structure and not cause wrinkling or lateral movement which would affect overall performance characteristics. The fabric reinforced specimens had only a single layer of reinforcement near the bottom surface with the rest of the specimen having no fiber reinforcement. This general configuration for flexural specimens has been used previously by Kanie et al. [13]. In the current investigation, fiber weight fraction in the single layer was between 37 and 42% but is significantly lower if determined on the basis of the full thickness of the overall specimen. Unreinforced bars of the resin were also fabricated the same way for comparison and were designated as set D.

Eight specimens ($n = 8$) from each set were tested in three-point flexure using a span of 16 mm which provides a span to depth (l/d) ratio of 16, which is recommended by ASTM D 790-03 [14]. It is noted that flexural characteristics can be substantially affected by choice of the l/d ratio which intrinsically sets the balance between shear and bending moment, with shear dominating on shorter spans. Load was introduced through a rounded crosshead indenter placed in two positions—parallel to the test specimen span (P1) and perpendicular to the test specimen span (P2). The load head indenter was of 4 mm total length. This was done to assess effects of load introduction since ribbon architecture had fibers at different orientations. Tests were conducted at a displacement rate of 1 mm/min and a minimum of eight tests were conducted for each set. Loading was continued till either the specimen showed catastrophic rupture or the specimen attained a negative slope of load versus displacement with the load drop continuing slowly past peak to below 85% of the peak load. This level was chosen to exceed the 0.05 mm/mm strain limitation of apparent failure recommended by ASTM D790-03 [14] so as to enable an assessment of ductility of the specimens. Specimens were carefully examined for cracking, crazing and other damage.

The flexure strength was determined as

$$\sigma_f = \frac{3PL}{2bd^2} \quad (1)$$

where P is the applied load (or peak load if rupture did not occur), L the span length between supports and b and d are the width and thickness of the specimens, respectively.

While the tangent modulus of elasticity is often used to determine the modulus of specimens, by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve to measure the slope, m, which is then used as

$$E_f = \frac{mL^3}{4bd^3} \quad (2)$$

in the current case a majority of the specimens show significant changes in slopes very early in the response curve indicating microcracking and non-linearity. Since these occur fairly early the modulus determined from the initial tangent has significant statistical variation. In order to determine a more consistent measure of modulus the secant modulus of elasticity as defined in ASTM D790-03 [14] is used herein, with the secant being drawn between the origin and the point of maximum load to determine the slope m, which is then used in Eq. (2). This also has the advantage of providing a characteristic that incorporates the deformation capability, thereby differentiating between specimens that reach a maximum load at low deformation (such as, the unreinforced composite and the unidirectional reinforced composite) and those that show significant deformation prior to attainment of peak load (such as, the specimens reinforced with the braid and leno-weave).

The matrix material is generically more brittle than the fiber and usually has a lower ultimate strain. Thus, as the specimen bends the matrix is likely to develop a series of cracks with the initiation and propagation of cracks depending not just on the type and positioning of the reinforcement, but also on the strain capacity of the neat resin areas. It is thus of use to compute the strain in the composite under flexural load and this can be determined as

$$\varepsilon_f = \frac{6dD}{L^2} \quad (3)$$

where D is the midspan displacement.

The toughness of a material can be related to both its ductility and its ultimate strength. This is an important performance characteristic and is often represented in terms of strain energy, U, which represents the work done to cause a deformation. This is essentially the area under the load-deformation curve and can be calculated as

$$U = \int_0^{x_1} P\,dx \quad (4)$$

where P is the applied load and x is the deformation. In the case of the present investigation, two levels of strain energy are calculated to enable an assessment of the two response types. In the first, strain energy is computed to the deformation level corresponding to peak load (which is also the fracture load for sets A and D). In the case of specimens that show significant inelastic deformation (sets B and C) strain energy is also computed till a point corresponding to a deformation of 11.5 mm at which point the load shows a 15% drop from the peak. Post-peak response in flexural has earlier been reported by Alander et al. [8].

3. Results

The application of flexural loading was seen to result in two different macroscopic forms of response. In the case of specimens from sets A and D (reinforced with a unidirectional fabric and unreinforced) failure was catastrophic, in brittle fashion, at peak load, whereas in the case of specimens from sets B and C the attainment of peak load was followed by a very slow decrease in load with increasing displacement, representative of inelastic or plastic, deformation. Typical response curves are shown in Fig. 1 as an example.

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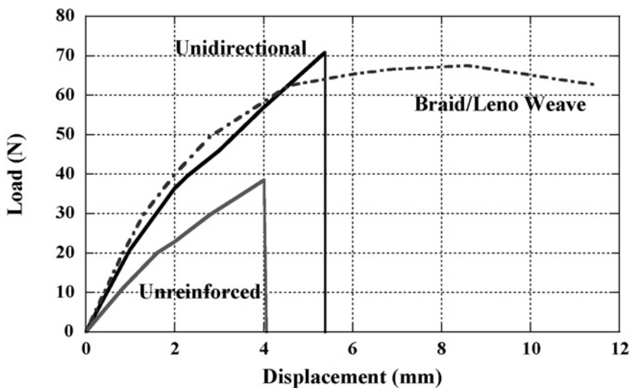

Fig. 1 – Typical flexural response.

The variation in flexural strength (plotted here in terms of stress at peak load) with type of specimen and load introduction method is shown in Fig. 2. The highest strength was achieved by specimens with the braided fabric wherein on average a 125% increase over the unreinforced specimens was attained. Statistical analysis with ANOVA and Tukey's post hoc test revealed that method of load introduction did not affect the results and that further there were no significant differences in overall peak strength results between sets A and B (specimens containing the unidirectional and braided fabrics). Significant differences ($p < 0.003$) were noted between sets B and C. It is, however, noted that in sets B and C, failure did not occur at the peak load, with load slowly decreasing with increase in midpoint deflection. A comparison of flexural stresses for these systems at peak load and load corresponding to a deflection of 11.5 mm is shown in Fig. 3. As can be seen the two systems show significant inelastic deformation with drops of only 12.8, 12.1, 11.7 and 9.5% from the peak, emphasizing the stable, ductile and non-catastrophic, post-peak response in these systems.

A comparison of secant modulus (measured to the peak load) for the different sets is shown in Fig. 4. As can be seen, with the exception of the unidirectional system, the apparent moduli were lower than that of the unreinforced specimens. It is also noted that although the Tukey post hoc tests do not show a significant difference due to orientation of load

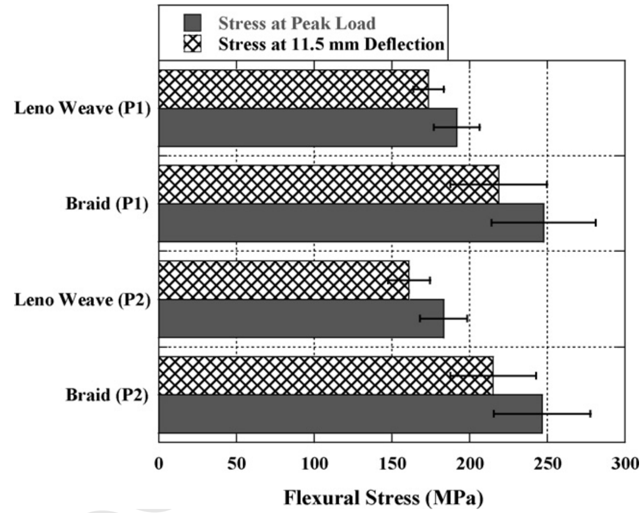

Fig. 3 – Comparison of flexural stresses in specimens having non-catastrophic failure modes.

indenter, the level for the unidirectionals is only 0.1022 compared to 1 for the others. Removal of a single outlier from P1 results in $p < 0.007$ indicating a strong effect of orientation of the indenter with the secant modulus being 17.7% lower with the indenter placed parallel to the fibers, which results in splitting between fibers and uneven fracture with less pullout.

As was noted previously, both the unreinforced samples (set D) and the unidirectional prepreg reinforced specimens (set A) failed in catastrophic fashion at deformation levels significantly less than those at which the other two sets reached the inelastic peak. Since sets B and C did not fracture but showed large deformation with some partial depth cracking through the matrix it is important to be able to compare the levels of strain attained on the tension face using Eq. (3). This comparison is shown in Fig. 5 at the level of peak load (which is the fracture/failure load for sets A and D). While the addition of the unidirectional to the matrix resulted in an average strain of 0.06 mm/mm which is 50% greater than the capacity of the unreinforced matrix, the addition of the braid and leno-weave resulted in increases of 119 and 126%, respectively, emphasizing the higher capacity of both the UHMW polyethy-

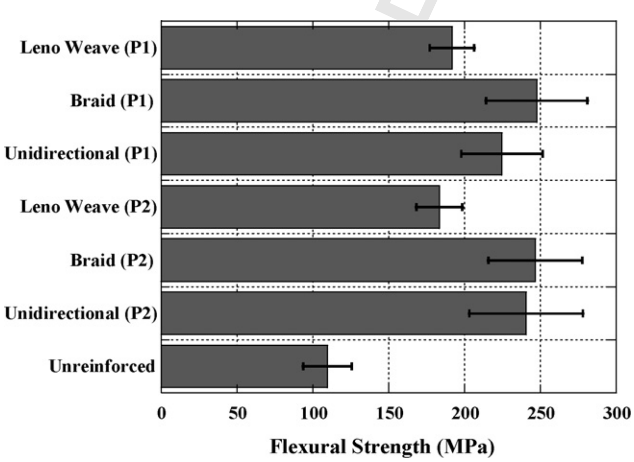

Fig. 2 – Flexural strength at peak load.

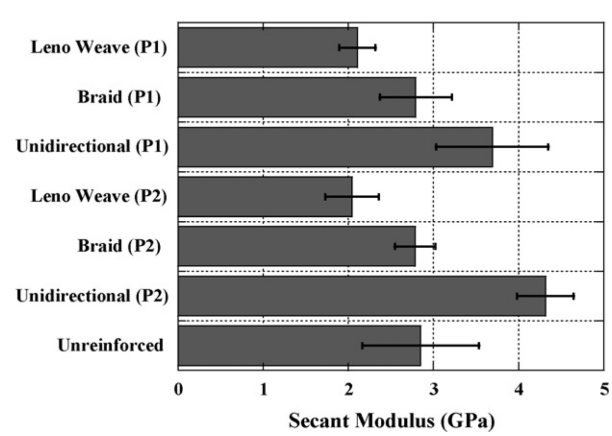

Fig. 4 – Comparison of secant moduli under flexural loading.

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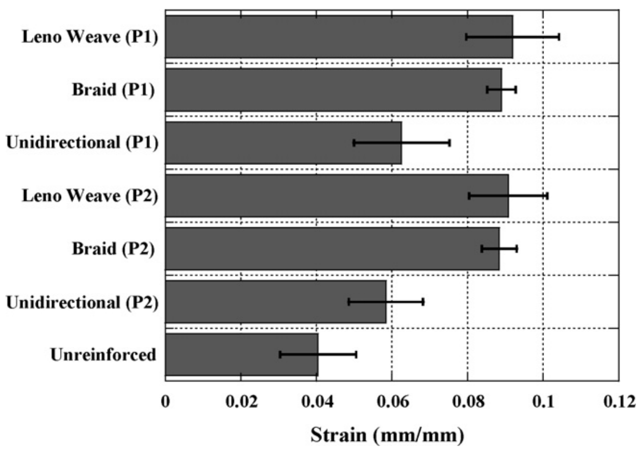

Fig. 5 – Comparison of strain capacity at peak load.

lene fibers and the architectures to hold together without rupture under flexural loading. It should be noted, as a reference, that the strain at the point at which the tests on sets B and C were stopped, at a midpoint deflection of 11.5 mm, was 0.135 mm/mm, which represents a 233% increase over the level attained by the unreinforced matrix. The use of the Tukey post hoc test indicated insignificant difference between the braid and leno-weave reinforced specimens (p between 0.9896 and 0.9999 for the four combinations of comparison possible).

In any application where impact, abrasion or excessive movement is possible, an important characteristic of the material is the level of energy absorbed prior to failure. Figs. 6 and 7 compare the strain energy at peak load (the failure point for sets A and D) and corresponding to a deflection of 11.5 mm (taken to be the predefined level for sets C and D which show inelastic deformation), respectively. As seen in Fig. 6 the addition of the fiber reinforcement substantially increases the level of strain energy in the specimens with the maximum being attained in set B (braid reinforced) under load condition P2. In this configuration there is a 433% increase in energy absorption capability above the unreinforced case. Overall the braided specimens show the highest level of absorption, followed by the leno-weave reinforced specimens, with the unidirectional reinforced specimens hav-

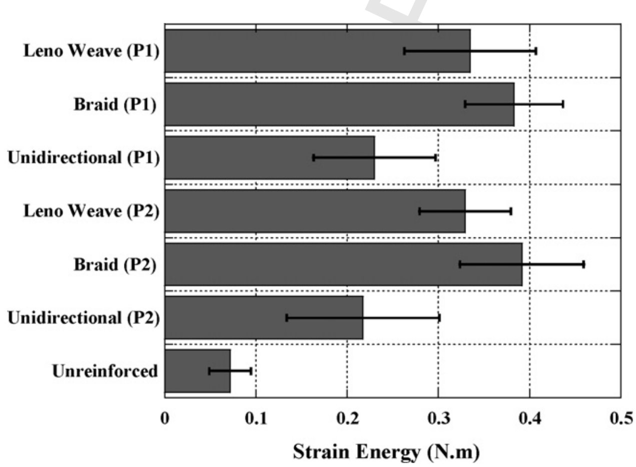

Fig. 6 – Comparison of energy absorption at peak load.

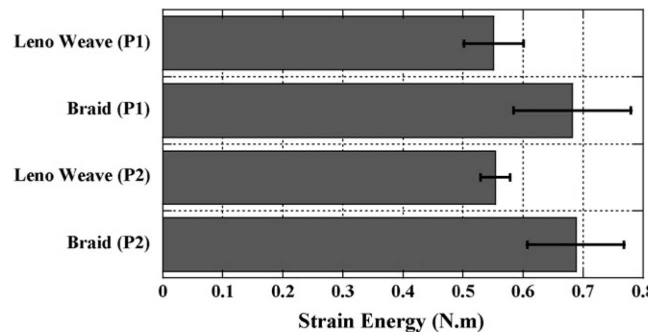

Fig. 7 – Comparison of post-peak strain energy determined at a deflection of 11.5 mm for specimens with non-catastrophic failure modes.

ing the lowest increase which is still 203% (for configuration P1) greater than the level attainable by the unreinforced specimens. The use of the Tukey post hoc test indicates there is insignificant difference between the characteristics of the specimens reinforced by the braided and leno-weave UHMW polyethylene fibers (p between 0.5337 and 0.7205 for the four possible comparison pairs). It is of interest to note that the strain energy increases substantially when considered up to the 11.5 mm level of deflection. In this case, however, the Tukey post hoc test indicates that while there is insignificant effect of load configuration (sets P1 and P2) there is a significant difference between the braid and leno-weave reinforced specimens (at the highest level $p = 0.0046$ for the comparison pair of B-P1 and R-P2 and at the lowest level of $p = 0.023$ for the comparison pair of B-P2 and R-P1).

4. Discussion

Three different fabric configurations, each having very different characteristics, were used to reinforce a polymeric dental composite. Results were assessed through the use of a simple flexural test which is conventionally used in characterization of fiber-reinforced dental composites. Although the test is well established it should be noted that the configuration only assess one of the loading conditions seen clinically. During mastication, for example, the system (dental restoration and substructure) see often sees a flexural stress among multi-directional stresses which develop as a result of loading. While simple to conduct, the test is significantly influenced by the choice of support-span to depth ratio. The maximum modulus is known to be reached at a ratio of 50 [15] with the use of ratios smaller than 60 resulting in interlaminar shear stress development which reduces both strength and modulus in well-laminated specimens. Karmarker showed for fiber-glass reinforced dental composites that the flexural modulus decreased when the span to depth ratio was less than 14 [16]. However, a number of tests reported in the literature have used shorter ratios resulting in characterizations that are affected by the configuration itself. Xu et al. [6] reported tests in flexure on specimens of size of 2 mm × 2 mm × 10 mm span, which essentially results in a short-beam-shear type configuration which tests an interlaminar, rather than flexural, stress configuration due to the high effect of shear along the span. Vallitu

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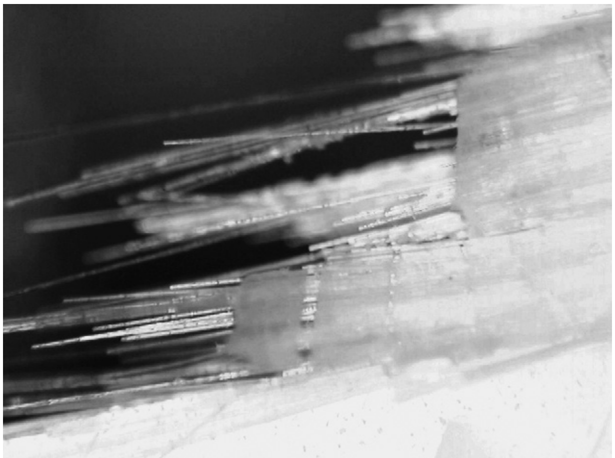

Fig. 8 – Optical micrograph showing fiber rupture and pull-out in unidirectionally reinforced specimen.

in a study that raised concerns regarding fiber–matrix bond used a span-to-depth ratio of 11.67 and noted that improvement in flexural strength was only modest and that fracture toughness was decreased based a study of SEM images [17]. It should be noted that at smaller *l*/*d* ratios failure is initiated by interlaminar fracture with non-unidirectional reinforcements being affected significantly more than pure unidirectional lay-ups and that results obtained using smaller *l*/*d* ratios can be erroneous and misleading due to the introduction of shear and interlaminar dominated stress states.

In a fiber-reinforced composite, it is known that the use of a unidirectional reinforcement provides significant enhancement of strength and stiffness in the fiber direction with very minor changes from the matrix properties in the transverse direction. This architecture has the maximum efficiency of translation of fiber characteristics to composite performance. As reported in the preceding section the flexural stiffness of the resulting composites are the highest. The fibers carry the load and since these are aligned along the test span failure in bending is seen to take place through rupture of the fibers towards the tensile surface. Prior to failure the strains in the resin cause the formation of stress crazes and fiber–matrix debonding. Fracture is catastrophic and is accompanied by pull-out as seen in Fig. 8, with fiber surfaces beyond the fracture plane being fairly clean of adhered matrix. The matrix on the tensile surface is also seen to crack with delamination at the fiber surface level. Crazing is primarily through longitudinal microcracking which is unconstrained due to lack of transverse reinforcement induced restraint. Due to the dominance of stiffness in one direction the strain enhancement over the unreinforced polymeric resin composite is the least of the three architectures considered (about 50% compared to a 119 and 126% enhancement due to the braid and leno-weave architectures, respectively). This also results in the strain energy being the least. While Ellakwa et al. reported that the positioning of the fiber reinforcement affected both strength and strain energy [11], it is emphasized that the effect is not just based on position of the reinforcing ribbon vis-a-vis the thickness, but also on the details of the fabric architecture, with woven and braided architectures having significantly higher strain energy capacity due to the interlocking nature of the fabric which allows local points of intersection and sliding.

Since the unidirectional has no fibers in the transverse direction, there is a lack of constraint to transverse movement which has been reported to cause significant distribution of fibers during clinical placement, thereby decreasing fiber efficiency since the orientation is not maintained. In addition there is potential for splitting of the matrix between fibers once the composite has cured under loads that are not perfectly perpendicular to the fiber direction. In this study loads were introduced through indenters aligned both parallel and perpendicular to the span. In general very few differences were found in response based on alignment of the load-tup, indicating that at the scale used the representative cell was larger than the footprint of the load-tup. Resulting in an average load being introduced irrespective of the orientation. The only notable exception was in case of the secant modulus which provides an indication of stiffness, wherein the secant modulus of the unidirectionally reinforced specimens with the indenter placed parallel to the fibers was 17.7% lower than that resulting from perpendicular placement, which can be attributed to splitting between fibers and uneven fracture with less pullout. In addition the load at the point of first non-linearity in the response was 14.6% lower, although there was insignificant difference in load at failure.

As noted earlier, the braid and leno-weave reinforced specimens did not fail through rupture, which was also noted by Davy et al. [18]. The specimens underwent large irreversible deformation with substantial midpoint deflection and levels of tensile strain (Fig. 5) that could be considered as being beyond the level of "failure" recommended by ASTM D790 [14]. This combined with the high levels of strain energy absorbed by the specimens (Figs. 6 and 7) indicates a higher level of toughness associated with these architectures as compared to the unreinforced matrix and the unidirectionally reinforced specimens. This is attributable to the nature of the fabric architectures wherein fiber bundles are woven across each other in predetermined patterns, both allowing for slippage and for entrapment of microcracks in local regions bounded by these fibers. The intersecting nature of the fiber architectures with areas of crimp and overlap serve as crack arrestors. These characteristics are important since they provide a level of damage tolerance which may be crucial in cases where there is uncertainty regarding the orientation and extent of imposed load, as well as where impact and abrasion resistance are required. Unlike the failure surface seen in Fig. 8 associated with the unidirectional reinforcement, the mechanism of progressive damage in these architectures is one of flexural cracking in the matrix on the tensile surface. These cracks are spaced 2–4 mm apart and delineate the areas of excessive strain and curvature under flexural load. In the case of the leno-weave, since a percentage of the fibers are essentially in the longitudinal direction the cracks are bridged by these fibers, holding the faces together and preventing further growth of the crack and arresting through-thickness cracking. A close-up of a bridged area is shown in Fig. 9 and it can be seen that the matrix in contact with the middle fiber bundle on the right of the crack face is showing indications of debonding and stress-crazing. The fibers are essentially act-

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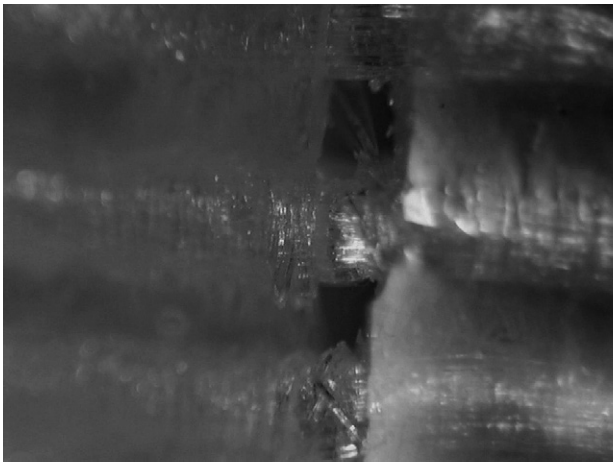

Fig. 9 – Optical micrograph showing bridging of a flexural crack by bundles in the leno-weave.

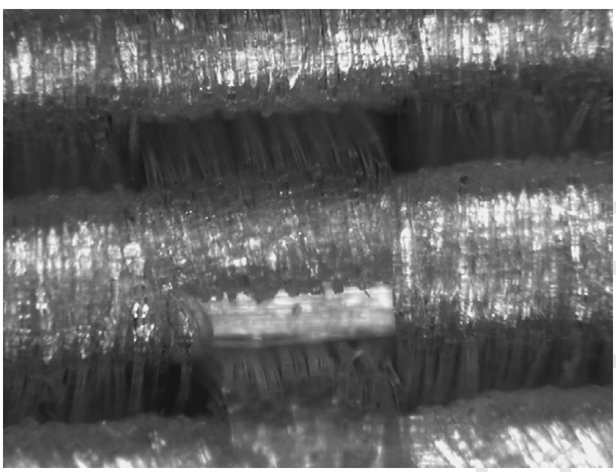

Fig. 10 – Rupture of transverse fiber at an intersection within the leno-weave.

ing as staples internal to a crack holding the faces together and preventing further fracture. Fig. 10 shows a close-up of the structure of the leno-weave indicating breakage of the transverse fibers in a local area. In the case of the braided fabric since the fiber bundles essentially overlap each other at angles (Fig. 11) in a non-orthogonal structure the cracks are of smaller width and are greater in number and at closer spacing. However, again these are held together as they approach the reinforcement by the fibers which act as crack arrestors. The ability to distribute the stresses through the interacting fibers and bundles in the braided ribbon results in the absorption of the highest level of strain energy, especially after attainment of the peak load. This behavior is advantageous in stress redistribution and in ensuring that externally imposed stresses are distributed over the largest possible substrate area, thereby decreasing the level of shear stress which could otherwise cause debonding of the restoration from the substrate.

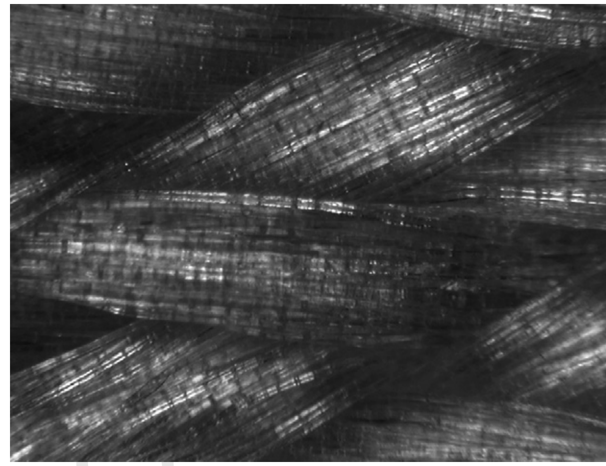

Fig. 11 – Architecture of braided specimen showing fiber undulation and interlock.

While the values of performance characteristics are important in the selection of a material system, the consideration of scatter in data is of equal importance, since a material with large statistical variation would not be as desirable as one that has more consistent results. The scatter in data not only depends on the dental composite matrix and cure conditions, but also on the type of fiber reinforcement used. Fennis et al. [19], for example, reported that woven fabric reinforcements gave more consistent results than unidirectionals. The characteristics of variation for the strength at peak load (ultimate load for materials A and B) for materials considered in the current investigation are listed in Table 1. The values of the Weibull shape and scale parameters, α and β, are approximated as

$$\alpha \approx \frac{1.2}{\mathrm{COV}} \tag{5}$$

Table 1 – Characteristics related to scatter of flexural strength at peak load

Material set	Mean strength (MPa)	Standard deviation (MPa)	Weibull shape parameters (α)	Weibull scale parameters (β)
Unreinforced	109.69	16.02	8.22	116.33
Unidirectional (P2)	240.61	37.54	7.69	255.99
Braid (P2)	246.71	31.09	9.52	259.87
Leno-weave (P2)	183.30	15.21	14.46	190.04
Unidirectional (P1)	224.69	26.74	10.08	236.10
Braid (P1)	247.67	33.44	8.89	261.69
Leno-weave (P1)	191.84	14.58	15.79	198.34

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Table 2 – Strength characteristics

Material set	Mean flexural strength (MPa)	Strength at 10% probability of failure (MPa)	Predicted mean tensile strength (MPa)
Unreinforced	109.69	88.46	58.72
Unidirectional (P2)	240.61	191.06	125.32
Braid (P2)	246.71	205.18	139.93
Leno-weave (P2)	183.30	162.65	119.63
Unidirectional (P1)	224.69	188.88	130.18
Braid (P1)	247.67	203.16	136.80
Leno-weave (P1)	191.84	172.00	128.44

and

$$\beta = \frac{\mu}{\Gamma(1 + 1/\alpha)} \quad (6)$$

following Ref. [20] where COV is the coefficient of variation (determined as the standard deviation divided by the mean), μ the mean value and Γ is the gamma function. A low value of the Weibull shape parameter is generally associated with broader flaw distributions and brittle materials. The lowest values of coefficient of variation and correspondingly the highest values of the Weibull shape parameter, are shown by the specimens reinforced with the leno-weave fiber ribbon. It is noted that the highest coefficient of variation, 0.156, is seen with the unidirectional reinforced material system, tested with the load-tup in the parallel direction (set P1), which is higher than that of the unreinforced material (COV = 0.146). Thus, the leno-weave reinforced material has significantly greater consistency and less scatter, in flexural strength. The increase in consistency or reliability, can be traced to the details of the architecture of the leno-weave which provides a greater extent of resistance to shearing or deformation, of the fabric during manipulation and adaptation prior to polymerization, without loss in conformability, than the other two reinforcements. It is emphasized that in the fiber-reinforced composites, especially those laminated by a manual process as required in adapting them to the tooth substrate, individual fibers and fiber bundles can move significantly from their intended locations resulting in fiber wrinkling and waviness, as well as non-uniformity in fiber volume fraction across the surface of the composite, all of which will result in scatter in performance characteristics. The lower scatter indicates a greater resistance to local variations during the lay-down and polymerization process.

Design is often undertaking through the selection of a suitable probability of failure and a 10% probability was used previously by Chong and Chai in comparing failure load of veneered glass fiber-reinforced composites and glass infiltrated alumina with and without zirconia reinforcement [21]. Use of the same level of probability of failure (B10) in conjunction with the Weibull parameters listed in Table 1 provide estimates of strengths as listed in Table 2.

Although the flexural strength and other characteristics of flexural response are often used in the screening of dental materials [22], the selection of a material should be based on performance characteristics required by the specifics of application. These characteristics are in most cases different from those related to flexure and could include tensile strength, impact resistance and shear characteristics, each of which necessitates additional testing. However, it is possible to estimate the tensile strength from flexural tests using Weibull theory and assuming the same probability of failure in flexure and tension. A relationship between the tensile stress, σ_t and the flexural stress, σ_f, can be derived following Lavoie [23] as

$$\sigma_t = \sigma_f \left[\frac{1}{2(\alpha + 1)^2} \frac{V_b}{V_t} \right]^{1/\alpha} \quad (7)$$

where V_b and V_t are volumes in flexure and tension, respectively, and α is the Weibull modulus. The factor $1/2(m+1)^2$ serves to transform the specimen volume in flexure, which has an intrinsic stress gradient into an equivalent uniformly stressed volume in tension. Considering equal volumes the values of tensile strength for the materials considered in this investigation are listed in Table 2. It should be noted that the values are determined from the stresses at peak load, which represents rupture for sets A and B only and that the difference in placement of the load-tup has no significance in a longitudinal tensile tests. Thus, averaging across load cases P1 and P2 would provide a better estimate of tensile strength and this results in predicted values of 58.72, 127.75, 138.37 and 124.04 MPa, for the unreinforced, unidirectional prepreg reinforced. Braid reinforced and leno-weave reinforced, dental composites, respectively.

5. Summary

It is shown that the response of fiber-reinforced dental composites should be assessed on the basis of a number of response characteristics and that the details of fabric architecture can substantially affect overall response. It is shown that the material system having the highest flexural stiffness does not necessarily have the highest strength or the greatest capacity for energy absorption. Scatter in strength is seen to depend on the details of reinforcement architecture and the tight nature of the leno-weave is shown to result in significantly lower scatter and higher Weibull modulus. A simple statistical method is used to predict tensile strength based on flexural strength and Weibull characteristics enabling the estimation of two critical characteristics from a single test. It is emphasized that selection of a system should be based on the pre-definition of actual characteristics needed for an application and that these characteristics can change based on the specifics of the application.

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