Evaluation of the Load to Failure of Fiber Reinforced Composite Orthodontic Bracket Tie Wings

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Abstract

Esthetic brackets may be provided to patients that desire a less noticeable orthodontic treatment. The brackets are designed to be clear or tooth colored in appearance. However, esthetic brackets are not as dimensionally stable as traditional stainless steel brackets during clinical use. Therefore, tooth movement is not as predictable. Frequent esthetic bracket failures have been reported particularly within the tie wing complex. Objectives of this study were to: 1) design and fabricate a potentially esthetic prototype bracket made of a long glass fiber-reinforced polymer matrix composite, 2) evaluate the static load to initial failure of the tie wings in experimental and conventional orthodontic esthetic brackets (a polycarbonate and ceramic bracket), and 3) determine if the tie wing load to initial failure increased with an increase in fiber content.

The specimen brackets (n=6), classified in groups (A to M), were fabricated in molds made using a vinyl polysiloxane impression of a modified commercially available polycrystalline bracket (Mystique-GAC Intl, Islandia, NY) as a pattern. E-glass fibers (*ever*Stick®-ORTHO, Stick Tech Ltd. Turku, Finland) were incorporated in four different configurations within a di-methylmethacrylate polymer matrix. The amount of E-glass fiber used was doubled for each different configuration. The weight fraction (W_f) of the 2 mm and 4 mm of E-glass fiber was calculated to be 13.75% and 25.82%, respectively. The test groups consisted of: Group A- a commercial polycrystalline bracket (Mystique-GAC Intl, Islandia, NY), Group B- a commercial polycarbonate bracket (Vogue-GAC Intl, Islandia, NY), Group C- a commercial posterior composite (3M ESPE, Z100™) formed into a bracket, Group D- the pure resin (1:1:1 BisGMA, TEDGMA, UDMA) bracket, and Group E- a particulate (80% strontium) filled resin bracket. Groups F and J consisted of

straight E-glass fibers placed perpendicular to the bracket base extending out into the tie wing. Groups G and K consisted of curved E-glass fibers running from the center of the bracket extending out into the tie wing. Groups H and L consisted of chopped E-glass fibers assorted in a random fashion throughout the base and tie wing. Groups I and M consisted of straight E-glass fibers placed in a mesial-distal direction within the tie wing.

Six maxillary right central incisor brackets per group (n=6) were tested to failure with a static load placed directly upon the incisal tie wing complex. The failed brackets were examined with a scanning electron microscope (SEM) to obtain micrographs at magnifications of 20, 50, 150-backscatter electron and secondary electron. The accuracy of glass fiber placement and the failure mechanisms were assessed with the aid of SEM images. The SEM images revealed that the E-glass fibers were able to be manipulated into various shapes for incorporation within the tie wing complex. The fracture line of the FRC prototype brackets progressed in a linear fashion until it reached the area enriched with E-glass fiber. The results ranged from a maximum mean initial load to failure of 101.01 (±19.99) N with Group A (commercial polycrystalline bracket; Mystique-GAC Intl, Islandia, NY) to a minimum mean initial load to failure of 28.17 (±5.20) N with Group-B (commercial polycarbonate filled with 35% alumina bracket; Vogue-GAC Intl, Islandia, NY). Of all the different prototype design configurations, Group-J (straight E-glass fibers (W_f = 25.82%) placed perpendicular to the bracket base extending out into the tie wing) had the highest mean initial failure value- 63.39 (±16.79) N. There was no statistically significant difference between the mean initial failures of the FRC groups at $p<0.05$. All of the FRC groups, except for groups H and L, had load to initial failure values that were greater than the pure resin control group D. The Group B brackets (commercial polycarbonate filled with 35% alumina) were found to fail with loads significantly less than all experimental groups with fiber incorporated except for utilizing random fiber orientation. Further studies on the amount of glass fiber and its placement (closer to site of initial fracture) are needed in order to provide the improved fracture toughness needed for esthetic brackets.

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Introduction

Esthetic orthodontics began with the advancement of adhesive bonding agents (Dorbin 1975, Winchester 1990, Kusy 2002). Improved polymer adhesives and techniques allowed resin adhesive bonding of brackets directly to enamel eliminating the need for stainless steel bands covering the entire middle third of the anterior teeth. Subsequently, reduction in the size of the bondable brackets has allowed even more of the natural tooth structure to be visible. However, the smaller sized brackets did not offer a great esthetic advantage over the conventional sized brackets (Birnie 1990). Manufacturers soon began to construct brackets made of materials other than stainless steel. The bracket materials used included polymers and/or ceramics. These clear, transparent esthetic type brackets were markedly less conspicuous than the stainless steel brackets. Esthetic brackets immediately became a popular option for patients desiring a less noticeable orthodontic appliance.

The early polymer brackets met initial commercial failure due to the poor color stability and minimal resistance to deformation (Dobrin et al. 1975, Alkire 1997, Proffit 2000, Thorstenson 2003). The weak material led to a decrease in effective treatment mechanics during clinical use. Under normal orthodontic forces, the arch wire slot plastically deformed and the tie wings broke (Dorbin et al. 1975, Thorstenson 2003). Early ceramic brackets were color stable and provided adequate torque control. However, they lacked the fracture toughness of stainless steel brackets (Flores et al. 1989, Viazis et al. 1990, Birnie 1990). Ceramic brackets were recommended to be used with caution due to their brittle nature and clinicians were cautioned not to simply consider ceramic brackets as an alternative to stainless steel (Birnie 1990). Esthetic brackets made from a combination of different materials (polymers/metals, metals/ceramics, and ceramics/polymers) improved the clinical performance allowing better acceptance into the orthodontic profession (Kusy 1998). However, the only absolute advantage of these brackets was in appearance (Birnie 1990). The mechanical performance and durability of the stainless steel brackets is far superior. Stainless steel brackets prove to be strong, non-absorbent, biocompatible, and relatively easy to machine (Proffit 2000, Graber 2003). Clinical orthodontists want to be able to offer esthetic brackets that are not only less visible but also similar to the mechanical properties of stainless steel. Currently, there is no esthetic bracket available that is completely satisfactory.

As new brackets begin to be developed and marketed, *in vitro* tests are performed in order to compare and validate the manufacturers' claim in bracket quality. Many published studies thus far have been aimed at determining the fracture strength and deformation of the brackets when subjected to tipping (2nd order), torsion (3rd order), shear and impact forces (Dobrin et al. 1975, Holt et al. 1991, Gunn and Powers 1991, Rhodes et al. 1992, Lindauer et al. 1994, Feldner et al. 1994, Aknin et al. 1996, Alkire et al. 1997, Matasa 1999). Other studies involve the investigation and comparison of bond strength and design features of the different brackets available for clinical use (Joseph et al. 1990, Viazis et al. 1990, Winchester 1991, Bordeaux et al. 1994, Ghosh et al. 1995, Bishara et al. 1999). According to a survey on the clinical performance of ceramic brackets, orthodontists found that one of the most common areas of failure is within the tie wing complex (Gibbs 1992). However, only a single published study focuses specifically on the failure of the bracket's tie wing complex (Johnson et al. 2005). The results of that investigation revealed that both the bracket brand and tie wing configuration were significant factors in the failure of the tie wing under a tensile load. It was also recommended that further improvements in design and manufacturing processes of esthetic brackets were needed to help eliminate the susceptibility of fracture at the tie wing complex.

Materials that are brittle, such as ceramic, undergo minimal deformation when a static load is applied before failure. The associated energy that is absorbed is relatively very small. Ductile materials, such as metals, however tend to absorb a large amount of energy due the resilience and extensive plastic deformation that occurs during failure. The toughness of composite materials may be enhanced by the addition of greater energy-absorption constituents; i.e., glass or organic fibers (Agarwal and Broutman 1990). Fiber reinforced composites (FRC) have been shown to improve mechanical properties of polymers, deliver unique flexibility in design capabilities, and retain ease in a certain degree of fabrication (Giordano 2000). Other advantages of FRC include: lightweight, corrosion resistance, impact resistance, and excellent fatigue strength (Agarwal and Broutman 1990). In order to optimize the use of fibers within a matrix system, composite design principles need to be properly implemented (Dyer 2005). An understanding of the fracture process and associated energy-absorbing mechanisms is essential for the proper design of an effective fiber reinforced composite. A dependable esthetic bracket with both acceptable esthetics for the patient and optimal performance for the orthodontist is still desired.

The aim of this study is to:

1. Design and fabricate a potentially esthetic prototype bracket made of a long glass fiber-reinforced polymer matrix composite.

2. Utilize static load testing to evaluate the initial failure of the tie wings in experimental and conventional orthodontic esthetic brackets (a polycarbonate and ceramic bracket).

3. Determine the effect of fiber content on the load to initial failure of the tie wings in FRC prototype brackets.

Literature Review

In the early 1970's, brackets made of unfilled or neat polycarbonate polymer were first introduced into the field of orthodontics (Dobrin 1975, Feldner et al. 1994, Profitt 2000). Polycarbonates are polymers having functional groups linked together by carbonate groups in a long molecular chain (Graber 2003). These brackets were able to provide a more tooth colored appearance for the patient. However, the initial promise of the brackets was overestimated. It was discovered that the polycarbonate brackets had poor color and dimensional stability during the course of treatment (Alkire 1997, Proffit 2000). Polycarbonate brackets lacked strength and stiffness that resulted in permanent deformation. 'When brackets permanently distort, the energy stored in the arch wire is dissipated in the bracket rather than being transmitted to the intended tooth' (Alkire et al. 1997). This results in a loss of control and efficiency in tooth movement. The arch wire slot tends to plastically deform under normal loads and the tie wings break under simple tipping forces (Dorbin et al. 1975, Thorstenson 2003). The tie wings were identified as the primary site of fracture. Aird found 7.4% of the examined polycarbonate brackets to have fractured tie wings in his *in vivo* and *in vitro* studies (Aird 1987). According to Dobrin et al., unfilled polycarbonate brackets were reported to have high deformation and low torque values as the load increased (Dobrin et al. 1975). The distortion of the arch wire slots also caused an increase in frictional resistance (Thorstenson 2003). As a result, treatment time was extended and the mechanics of tooth movement were compromised. Due to the unfavorable characteristics of the unfilled polycarbonate brackets, manufacturers turned to ceramic as the material of choice.

In 1987, the first commercially available orthodontic ceramic bracket was introduced. A ceramic is defined as a compound formed by the union of a metallic and a nonmetallic element. Typically, the ceramic brackets used in orthodontics are made from alumina, which is a hard, strong, and color stable material. Alumina (Al_2O_3) is formed when aluminum is added to steel to remove oxygen dissolved in the steel (Flores et al. 1989). It comes in two major forms: monocrystalline and polycrystalline. Monocrystalline brackets are machined from extrusions of synthetic sapphire. The brackets are first milled using a diamond or ultrasonic cutting technique and then heat-treated to remove imperfections on the surface. Polycrystalline brackets are made by injection molding of tiny alumina particles into a form. The particles are fused together by a heating process and then machined into a bracket design. The monocrystalline brackets tend to be more transparent than the polycrystalline brackets due to less manufacturing impurities. Both of these forms resist staining and color shift better than polycarbonate brackets. Ceramic brackets are also stronger and more stable during orthodontic treatment mechanics. However, there are many disadvantages due to the physical properties of the ceramic material. The properties of ceramics differ from that of stainless steel (Flores et al. 1989, Birnie 1990):

Property	**Monocrystalline**	**Polycrystalline**	**Stainless Steel**	**Enamel**
Hardness(Rockwell)	97.5	82.5	5-35	3.5
Tensile Strength (psi x 1000)	260	55	30-40	
Fracture Toughness (Mpa Pa)	2-4.5	3-5	80-95	

The high hardness value of ceramic material causes serious concern about the possible abrasion of opposing tooth enamel when brackets are placed in the lower arch

(Douglas 1989). In simulated *in vitro* oral environments, it was shown that ceramic brackets caused significantly greater enamel abrasion than stainless steel brackets (Viazis 1990). Another disadvantage of the hardness of the ceramic slot is that it may wear nicks in soft metal arch wires which can increase friction (Bishara 1997).

Tensile strength is defined as the ratio of the maximum load a material can support without fracture when being elongated (Anusavice 2003). The tensile strength of ceramics depends on the surface condition of the material. 'A shallow scratch on the surface of a ceramic will drastically reduced the load required for fracture, whereas the same scratch on a metal surface will have little, if any, effect on fracture under load" (Scott 1988). The elongation of a ceramic at failure is less than 1%, whereas that of stainless steel is roughly 20% (Scott 1988, Viazis 1993, Karamouszos et al. 1997).

Fracture toughness is known as the material's ability to resist the propagation of an existing crack or flaw. The fracture toughness of both forms of alumina is 20 to 40 times less than that of stainless steel (Swartz 1988, Scott 1988). The low fracture toughness of ceramics leads to a higher incidence of breakage. This lack of ductility results in problems during treatment and at debonding, with failures occurring within the bracket or the enamel itself (Viazis et al. 1990).

Methods that have been proposed to reduce enamel damage at the time of ceramic bracket debonding include: mechanical, ultrasonic, and electrothermal. The mechanical method requires the use of specially designed pliers that work either through deformation of the bracket or by stressing the adhesive to cause failure. Failure is thus anticipated at the bracket-adhesive interface or within the adhesive itself. However, since ceramic brackets are much more brittle than stainless steel unwanted failure has been known to occur at the adhesive-enamel interface or within the enamel surface. Therefore, the use of ceramic brackets should be cautioned when bonding to teeth that are compromised by the presence of developmental defects, enamel cracks, and large restorations (Karamouzos et al. 1997). Ultrasonic debonding technique may decrease the chance of enamel damage and bracket failure at the expense of increased chair time and equipment cost. Electrothermal debonding involves heating the bracket while applying a tensile force to the bracket. However, excessive heat may potentially cause pulpal irritation and possible necrosis. Regardless of the technique used to debond ceramic brackets, special care and consideration should always be taken due to the extreme high hardness value and low fracture toughness of the ceramic material.

The clinical performance of the ceramic bracket is highly dependent upon the precision of the manufacturing process (Karamouzos et al. 1997). Even the slightest imperfections or impurities can cause crack propagation within the brittle material (Swartz 1988). Scratches on the surface of the ceramic may drastically reduce the load required to fracture the material (Karamouzos et al. 1997). Flores's found ceramic brackets to be less tolerant of surface flaws than metal brackets (Flores et al. 1989). However, since polycrystalline brackets are manufactured with more initial surface flaws, additional scratches did not seem to affect the strength of the bracket. It is advocated that care should be taken when inserting and removing the arch wires during adjustment procedures. The surface roughness of the ceramic slot can significantly increase frictional resistance of arch wires. A decrease in canine retraction rate was estimated at 25% to 30% when compared with stainless steel brackets (Bishara 1997). It has been reported that under all conditions tested, stainless steel brackets generate lower frictional forces than ceramic brackets (Karamouzos et al. 1997).

Esthetic brackets made purely of one type of material have proved to be unsuccessful in orthodontics. Therefore, different classes of materials were combined to try to enhance the performance and quality of the orthodontic bracket. The benefit of combining these materials is to produce a final product that is superior to either of its principle components alone (Kusy 1998). The composition of a composite material may include: polymers, metals, and ceramics. Each of these materials may serve as matrices or reinforcement. The properties of the resultant composite depend on the contribution of each of the components. Typically, a dental composite is made by the controlled addition of pretreated solid filler particles to a liquid/molten matrix of a synthetic resin that is then formable. Orthodontic ceramic particulate reinforced polymer matrix composite brackets are typically made by injection molding (Graber 2003).

Ceramic material fillers (15% to 30%) are added to the composition of polycarbonate to further increase the strength and reduce the staining of the polycarbonate polymer (Bazakidou 1997). However, Feldner found that ceramic reinforcement alone did not appear to have any significant clinical effect on strengthening the polycarbonate matrix and that excessive distortion still resulted from heavy clinical torquing forces (Feldner et al. 1994). Precision-made stainless steel slot inserts were incorporated in the polycarbonate bracket design to help decrease the friction of the arch wires as well as prevent slot deformation and torque loss (Feldner 1994, Bazakidou 1997, Thortenson 2003). According to the study by Alkire, reinforcement of the slot with a metal insert was more effective than the addition of ceramic filler in reducing the distortion of the bracket (Alkire et al. 1997).

Modifications have also been made to ceramic brackets to improve their quality and performance. Smoother slot surfaces (metallic or ceramic/plastic) were added to help reduce the frictional resistance during sliding mechanics. The addition of a metal slot may help strengthen the bracket during routine orthodontic torquing forces (Bishara 1997). In order to decrease the brittleness and roughness of the ceramic, a layer of silica is coated on the bracket's surface. To help prevent enamel damage during debonding, flexible plastic bases have been added to ceramic brackets. The resilient plastic material can absorb some excess energy, converting it to strain and thus resisting penetration into the enamel (Matasa 1999). Researchers have concluded that mechanically retained bracket bases provide adequate bond strength and less enamel damage at debond compared to bracket bases with chemical adhesion (Wang et al. 1997). A vertical debonding slot and stress concentrator has been incorporated in the design of many current ceramic brackets to help create a more consistent failure mode during bracket removal (Bishara 1997).

There have been a number of *in vitro* and *in vivo* tests performed on esthetic brackets. A majority of these tests include determining the fracture strength and deformation of the brackets when subjected to tipping (2^{nd} order), torsion (3^{rd} order), shear, and impact forces (Dobrin et al. 1975, Holt et al. 1991, Gunn and Powers 1991, Rhodes et al. 1992, Lindauer et al. 1994, Feldner et al. 1994, Aknin et al. 1996, Alkire et al. 1997, Matasa 1999). Lindauer concluded that arch wire tipping forces were unlikely to cause significant failure of ceramic brackets during clinical use (Lindauer et al. 1994). Other 2^{nd} order tests reported wide variations in force magnitudes at bracket fracture (Gunn and Powers 1991, Rhodes et al. 1992). The distance component of the total applied moments needs be considered in order to provide more accurate results (Lindauer et al. 1994).

Esthetic brackets are more likely to fail when previously weakened by direct trauma or surface defects during and after manufacturing (Viazis et al. 1993). Torque forces tend to act more across the depth of the bracket with forces separated by smaller distances. Therefore, the generated force tends to be the greatest at the tie wings of the brackets (Holt et al. 1991). Overall, the fracture resistance of ceramic brackets during normal arch wire activation appears to be adequate for clinical use (Holt et al. 1991, Lindauer et al. 1994). However, excessive forces that are not controlled will ultimately lead to bracket failure due to the material's properties (Flores et al. 1989, Rhodes et al. 1992). Other studies on esthetic brackets involve the investigation and comparison of bond strength and design features of the different brackets available for clinical use (Joseph et al. 1990, Viazis et al. 1990, Winchester 1991, Bordeaux et al. 1994, Ghosh et al. 1995, Bishara et al. 1999). Ghosh used the finite element method to conclude that esthetic brackets with rounded corners and no sharp edges produced a more regular stress distribution and less stress overall (Ghosh et al. 1995). Currently, manufacturers have adopted these guidelines for esthetic bracket construction. Despite the various laboratory tests, these brackets still proved to be unreliable and unpredictable during clinical use compared to stainless steel brackets (Dobrin et al. 1975, Holt et al. 1991, Gunn and Powers 1991, Rhodes et al. 1992, Lindauer et al. 1994, Feldner et al. 1994, Aknin et al. 1996, Alkire et al. 1997, Matasa 1999).

Orthodontic forces are expressed within the arch wire slot and tie wing complex (Profitt 2004, Graber 2005). The tie wings of ceramic brackets can be a stress concentration site that may fail during orthodontic treatment. The strength and stability of the tie wing complex is crucial in providing the most optimal and effective tooth movement

(Artun 1997). The tie wings have been found to fracture when subjected to simple torquing and tipping forces (Rhodes 1992). Fracture of the tie wings occurred in almost 4% of the sample (n= 49) in Artun's post-treatment evaluation of multi-bonded ceramic brackets (Artun 1997). Broken tie wings can affect the clinical performance and extend the treatment time. The fractured pieces of the ceramic bracket may also pose a health risk to the patient if aspirated. There are many different design configurations for the brackets' tie wing complex. The most common forms include true twin and semi-twin. The only true twin ceramic bracket is made of monocrystalline since it has the greatest tensile strength (Birnie 1990). The polycrystalline brackets are designed in a semi-twin configuration in which bulk is added between the mesial and distal tie wings. This increase in thickness of the tie wing complex may cause difficulties in clinical application when tying in arch wires (Artun 1997). The patient may also experience added discomfort as well as increased difficulty with oral hygiene.

Fiber Reinforcement

The improvement in the mechanical properties of a material is called reinforcement. There has been ongoing advancement in the reinforcement of materials used in the field of dentistry. An effective method for improving the mechanical properties of polymer materials has been successfully accomplished by the use of fibers (Giordano 2000). For more than 40 years, fibers have been incorporated into resin based materials for dental prosthetic use (Goldberg and Burstone 1992). Fiber reinforcement has been known to reduce the brittleness of a material, allowing better resistance to stress in multiple directions (Giordano 2000). Its uses in dentistry include: dental cements, dental splints, root posts, denture bases, and crown/bridge restorations (Brown 2000). When used intraorally, fibers need to be biocompatible, non-toxic, and dimensionally stable (Goldberg and Burstone 1992).

Composite design principles need to be considered when incorporating fibers within a matrix system (Dyer 2005). These design principles are: 1) the selection of the materials, 2) the amount of the materials, 3) the interface/adhesion between the materials, and 4) the physical arrangement of the materials (Barbero 1998; Hull 1990, Behr 2000). The performance and mechanical properties of fiber reinforcement composite (FRC) is critically influenced by these factors. Manipulations of different design schemes are needed in order to produce the most optimal composite material (Barbero 1998, Herakovich 1998).

Selection of Materials:

A fiber is described as being a thin, flexible structure with a length at least 100 times greater than its diameter (Vallittu 1996, Brown 2000). The fibers that are used in reinforcement may be metallic, ceramic, or polymeric. Different types of fibers are desired depending on the specific need. The types of fibers commonly used in dental reinforcement include: 1) glass, 2) carbon, 3) aluminum and sapphire whiskers, 4) Kevlar, and 5) ultra high molecular wt. polyethylene- (UHMWPE). The best esthetic qualities seem to be found when using polyethylene fiber and glass fiber (Vallittu 1996). Glass fibers are a common choice for dental applications because they adhere well to di-methacrylates (Ellakwa et al. 2002). The fibers are contained within a matrix that serves as protection and distribution to load forces. Dental fiber reinforcement material primarily comes pre-impregnated within a di-methacrylate based resin system. The compatibility of the selected fiber and matrix system is essential for successful composite construction.

Volume Fraction of Constituent Materials:

The overall behavior of a composite is primarily determined by the constituent volume fraction (Agarwal and Broutman 1990, Herakovich 1998). Since there are different densities of fibers, the quantity of the fiber is typically defined in volume percent not weight percent (Vallittu 1999, Behr et al. 2000). Alteration in the amount of reinforcement may affect the mechanical properties of the composite. The relationship between the amount of reinforcement and the composite mechanical properties has generically been termed the rule of mixtures (Barbero 1998).

The rule of mixtures is expressed in the formula (Agarwal and Brautman 1980):

$E_c = E_f V_f + E_m V_m$, where E, V, f, and m represent modulus, volume fraction, fiber, and matrix, respectively.

As the amount of fibers increase, the mechanical properties of the composite shift toward the properties of the fiber. However, a higher volume of fiber may cause the impregnation of the fibers with the matrix to be more difficult (Chai et al. 2005).

Interface/Adhesion of Constituent Materials:

Complete impregnation and adhesion of the fibers are needed in order for the material to behave properly (Beech 1972, Vallittu, 1996). Weak boundaries within the composite structure must be avoided. The adhesion mechanism can be influenced by the compatibility of the matrix with the reinforcement material (Hull 1990). It is important to eliminate any voids between the fiber and matrix material. The voids created from poorly impregnated fibers may serve as oxygen reserves. Radical polymerization of the matrix is inhibited by the oxygen which in turn decreases the strength of the composite (Vallittu 1999).

Glass fibers are usually coated with a silane coupling agent to allow better adhesion to the matrix material (Hull 1900, Vallittu 1993, Miettinen et al. 1999, Behr et al. 2000). The silane molecule attaches to the surface of the glass fiber through a siloxane bridge creating a chemical bond. The bonding link with the matrix is formed from the silane's oroanofunctional group (Kim and Mai 1998). The number and type of chemical bonds formed helps to determine the strength of bond between the reinforcement fiber and the matrix (Hull 1990).

When designing a FRC for intraoral use, one must consider the influence of water sorption. The overall strength and long term stability of the adhesion between the fibers and the resin matrix can potentially be affected by water sorption (Lassila et al. 2002, Chai et al. 2005). "Disruption of the bond between the matrix and glass fiber is caused by the leaching of 'glass forming' oxides from the fiber surface and by the reversible hydrolytic degradation of the polysiloxane network obtained by hydrolysis and poly-condensation of silane coupling agents" (Miettinen et al. 1999).

Arrangement of Constituent Materials:

The fibers may be assembled in a continuous, unidirectional form or scattered discontinuously as whiskers. The strength and stiffness of FRC depends primarily on the orientation of the fibers with respect to the direction of load (Hyer 1998, Chong et al. 2003). Unidirectional fibers may be positioned either parallel or perpendicular to the applied stress. When loads are perpendicular, the fiber is properly utilized and the tensile strength of the FRC is the highest. Fibers oriented parallel to the loading conditions lead to an undesirable matrix dominated effect. "Predicting the loading situation may allow the designer to place the strongest reinforcement in the correct direction." (Vishu 1998)

Discontinuous fibers experience a transfer of stress through shear force at the fiber/matrix interface. Even though discontinuous fibers are easier to process because of injection molding, control of their orientation and achievement of high fiber volume has been difficult to manage (Isaac 1999). Further studies have shown that fiber orientation and position are critical to strength of the structure (DeBoer et al. 1984, Chong and Chai 1995, Vallittu 1998). In 2003, Dyer showed that position and fiber orientation influenced the load to cause initial and final failure (Dyer et al. 2003). The primary purpose of fiber reinforcement is the achievement of optimal loading force transferred from matrix to the fiber material (Behr 2000).

Failure and Damage:

Fiber reinforced composites (FRC) may undergo many local failures prior to final breakage or failure (FF). The beginning of the damage process is termed initial failure (IF) (Barbero 1998, Herakovich 1998, Hull 1990). Damage accumulation occurs when additional local failures develop with increasing load or time (Herakovich 1998). Typically, the first sign of internal damage is the micro-cracking of the matrix. The initial failure is depicted on a stress/strain diagram as the first abrupt change in the curve (Hull 1990). Measures of initial failure may provide qualitative results that may correspond better to failures seen in intra-oral use (Dyer 2005). A zero (or negative) slope of applied stress/strain diagram reveals that the material has reached its final failure (FF) (Herakovich 1998). The final failure of a composite structure is when it starts to perform inadequately and thus becomes non-functional in its use.

Fiber reinforced materials have been used in orthodontics as adjuncts for active tooth movement, fixed retainers, space maintainers, temporary post-orthodontic fixation devices, and post-traumatic stabilization splints (Burstone et al. 2000). Manufacturers have been known to reinforce plastic brackets with glass, polymer fiber, and mineral filler. Fiber reinforcement technology may lead to the development of a bracket that has the mechanical performance desired by the orthodontist and the esthetic appearance desired by the patient. With the understanding of fiber reinforced composite design principles, the proper amount of fibers may be strategically placed in the area most susceptible to bracket failure; the tie wing complex.

Study Objectives:

Fiber reinforced composite can be a material with properties that are esthetically pleasing while maintaining optimal functional properties (Goldberg and Burstone 1992). With the increasing demand of orthodontic treatment among adults, the continued development of a quality esthetic appliance is essential. Therefore, with the advancement, development, and knowledge of fiber-reinforced composite material design, a new reliable esthetic orthodontic bracket could possibly be manufactured.

Specific Aims:

1. Design and fabricate a potentially esthetic prototype bracket made of a long glass fiber-reinforced polymer matrix composite.
2. Utilize static load testing to evaluate the initial failure of the tie wings in experimental and conventional orthodontic esthetic brackets (a polycarbonate and ceramic bracket).
3. Determine the effect of fiber content on the load to initial failure of the tie wings in FRC prototype brackets.

Materials and Methods:

An upper right central ceramic (polycrystalline) bracket without a metal slot (Mystique-GAC Intl, Islandia, NY) was chosen as the design pattern for the fabrication of the test brackets. The configuration of the bracket was semi-twin with a slot size of .022". The gingival tie wing complexes of the ceramic brackets were removed using a 30 micron coarse high speed diamond bur (Brassler). A 0.012 inch stainless steel wire (Ligature Tie, GAC Intl, Islandia, NY) was placed in the arch wire slot to protect against scratching during tie wing removal (Figure 1). The modified bracket was inspected with 10X magnification (Nikon Microscope Model) to confirm the absence of any surface damage close to the incisal tie wings. A single bracket free of any defect was then selected from a sample of five cut brackets to be used as a model for the fabrication of the prototype brackets. The modified ceramic bracket was placed on a glass slab with the mesh pad down. An impression was made using a clear, transparent vinyl polysiloxane impression material (Memosil-2®). Once the impression material was set (2 minutes), it was cut down to a 1 cm X 1" X 1" pad. A total of ten molds were fabricated. Each mold was inspected using 10X magnification (Nikon Microscope Model). The most accurate impressions of the modified ceramic bracket were used as the negative mold for the fabrication of the prototype brackets.

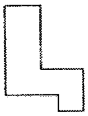
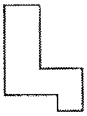
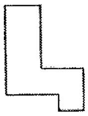
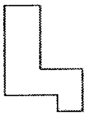
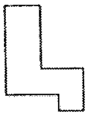
The prototype brackets composed of long E-glass fiber reinforced polymer matrix composite were compared to (Table I): a commercial polycrystalline bracket (Mystique-GAC Intl, Islandia, NY), a commercial polycarbonate (filled with 35% alumina) bracket (Vogue-GAC Intl, Islandia, NY), a fabricated bracket made of Z100™ commercial restorative (3M ESPE) composite, and a laboratory prepared particulate (80% strontium) filled resin bracket. The control group consisted of a non-reinforced pure resin system (1:1:1 BisGMA*, TEDGMA†, UDMA‡) bracket. Note: BisGMA is typically diluted with TEDGMA in order to obtain clinically acceptable handling properties (Krause et al. 1998).

*2,2-bis (p-2 hydroxy-3 methacryloxy propoxy phenyl) propane

†Triethylene-glycol dimethacrylate

‡ Urethane dimethacrylate

Table I. Comparison and Control Brackets Tested

Group	Pictogram	Matrix	Reinforcement/W_f	Brand/Manufacturer
A		Polycrystalline	Silica lined arch wire slot	Commercial Bracket; Mystique- GAC International, Islandia, NY
B		Polycarbonate	35% alumina	Commerical Bracket; Vogue- GAC International, Islandia, NY
C		BisGMA, TEDGMA	100% Zirconia/Silica	Z100™ restorative (3M ESPE) composite
D		1:1:1 BisGMA, TEDGMA, UDMA	NONE	Laboratory constructed non-reinforced pure resin
E		1:1:1 BisGMA, TEDGMA, UDMA	80% wt. strontium filler	Laboratory constructed particulate filled resin

Particulate (80% strontium) filled resin construction:

A set amount of non-reinforced pure resin (1:1:1 BisGMA, TEDGMA, UDMA) was weighed out. This amount was used as a reference point (20%) to calculate the amount of strontium [Sr(Ix-24505)RWG(5-PD027)0300005193;1000 g from Bisco, May 26, 2003] needed to get an 80% wt. strontium/resin construction.

The formula of the composition of the total resin/filler is written below:

20% resin (28.6009 g) + 80 % filler-Sr (76.26907 g) = 100%: total resin/filler

The Z100™ restorative (3M ESPE) composite bracket was fabricated using a composite warmer and plastic instrument. The 80% strontium filled resin bracket and the non-reinforced pure resin bracket were both fabricated by syringe injection into the mold. All fabricated brackets were cured under a *bell*Glass *HP* TEKLITE (Kerr Sybron, Orange, CA) (200 mW/cm^2) for one minute per side at a distance of 10 cm.

Fiber arrangement:

The fiber reinforcement material consisted of unidirectional E-glass (~65% wt./ BisGMA and PMMA matrix) (*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland). Four different patterns of E-glass fiber were configured within a non-reinforced pure resin matrix by a hand lay-up process. A pictogram derived from the cross-section of the modified ceramic bracket was used to illustrate the orientation of the fibers (Figure 2).

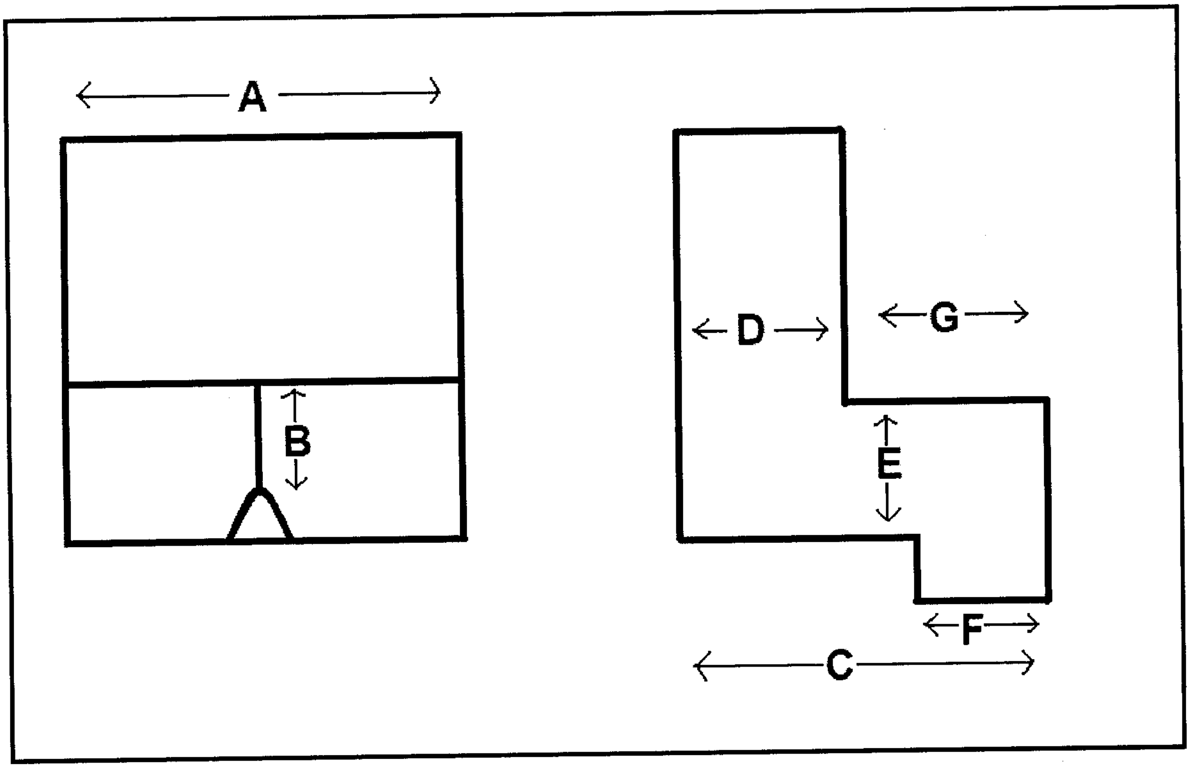
Fiber weight and weight fraction:

The E-glass fibers were cut into 2 mm and 4 mm pieces. The average weight of the 2 mm pieces was 0.00276 g. The average weight of the 4 mm pieces was 0.00530 g. The average weight of the fabricated test brackets with 2 mm of E-glass fiber was 0.02007 g (W_f= 13.75%) The average weight of the fabricated test brackets with 4 mm of E-glass fiber was 0.02053 g (W_f= 25.82%).

Bracket measurements:

The specimens in each sample group were measured in seven different dimensions using a digital caliper (Digital Caliper model No. 14-648-17, Traceable, Friendswood, TX) accurate to 0.001 inch per inch (table II). All fabricated test brackets were constructed using the molds made from the modified commercial polycrystalline bracket (Mystique-GAC Intl, Islandia, NY). Therefore, all of the bracket dimensions are similar except for the commercial polycarbonate (filled with 35% alumina) bracket (Vogue-GAC Intl, Islandia, NY).

Table II. Bracket Measurements



Bracket Dimensions	Mean Value (mm)	Standard Deviations
A	3.603 (3.469*)	±0.0386 (±0.0321*)
B	0.816 (0.409*)	±0.0633 (±0.0277*)
C	2.104 (2.102*)	±0.0268 (±0.0175*)
D	1.050 (1.284*)	±0.0290 (±0.0107*)
E	0.911 (0.766*)	±0.0859 (±0.0217*)
F	0.861 (0.733*)	±0.0649 (±0.0462*)
G	1.054 (0.818*)	±0.0387 (±0.0169*)

Note: values marked with * indicates measurements of the commercial polycarbonate (filled with 35% alumina) bracket (Vogue-GAC Intl, Islandia, NY)

Bracket Failure Testing:

The test brackets were placed in a vise and aligned with the bracket base facing upward to ensure consistent orientation (Figure 3). A small amount of clear photopolymerizable urethane dimethacrylate (UDMA) gel (Triad Gel, Dentsply, York, PA) was used on the base of the brackets to help promote adhesion. The aligned test brackets were then imbedded in a block of uncured silica-reinforced UDMA material (Triad, Dentsply, York, PA). A one minute initial cure of the UDMA block was completed using a Triad Visible Light Curing Unit (Dentsply, York, PA). The testing blocks were then removed from the vice and cured for an additional five minutes each.

The testing blocks were placed in a holding vise and secured to an Instron Universal Testing machine (Model TT-B Universal Testing Instrument, Instron Engineering Corporation, Canton, MA). A 50-pound load cell was used on the Instron machine. Before testing, the machine was calibrated and re-zeroed between each sample group of test brackets. The load testing for the sample groups was performed on the same day to provide consistent calibration and reading of the machine as well as to prevent discrepancies between sample groups.

A rod with a beveled tip (chisel type mounting) was used to make a line contact force upon the incisal tie wings of the brackets (Figure 4). A polyacetate spacer was used to position the loading head 0.2 mm from the bracket slot, to maintain consistency between samples and to avoid any binding of the loading rod. Only contact with the incisal tie wings was desired and expected. The sharpness of the rod's beveled tip was examined and maintained after each group tested to ensure consistent results.

The load on the tie wings increased at a cross head speed of 0.01 inch/minute until initial fracture of the bracket. The tie wing failure point was measured at the maximum amplitude of the deflection on a recording device. The results recorded were the load to initial failure (in pounds). The pound values (lbs.) were then converted to Newtons (N).

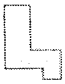
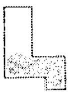
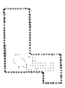
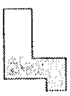
SEM Image Preparation:

Scanning Electron Microscopy (SEM) images (magnification- X35) of each bracket used in testing were made to investigate the initial surface quality and fiber impregnation. SEM images were also taken on the groups of brackets (Group G, L, and K) that had the tie wing complex retained after initial failure. The SEM images of these test brackets were used to help determine the area and mode of failure. Each type of bracket tested (Groups A to M) was embedded with a clear photopolymerizable urethane dimethacrylate (UDMA) gel (Triad Gel, Dentsply, York, PA). The embedded brackets were placed in a Triad Visible Light Curing Unit (Dentsply, York, PA) and cured for five minutes. Cuts (top to bottom) were then made within the tie wing complex of each bracket using a Struers Accutom-5 (Struers Inc., Cleveland, Ohio) machine. The disc size used was 0.006". The cut bracket specimens were then coated with gold via a Denton Vacuum Desk II (Denton Vacuum, Moorestown, New Jersey) machine's sputter coater to make the surfaces conductive. The mounted bracket specimens were coated according to the recommended coating procedure. Each bracket specimen was analyzed with the JXA- 6400 Electron Probe Microanalyzer (JEOL USA, Inc., Peabody, Massachusetts) to help determine the accuracy of bracket construction and glass fiber adhesion and placement.

Statistical Analysis:

The initial load to failure in pounds was compared using a One-Way Analysis of Variance (ANOVA) with the groups as the dependent variable. Only the initial failure of the tie wing complex was recorded and analyzed. A Post-hoc Tukey test was then used to find significant differences between the groups. Significant difference was established at the alpha=0.05 level.

Table III. FRC Brackets Tested

Group	Pictogram	Matrix	Reinforcement/W_f	Brand/Manufacturer
F		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 13.75\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland
G		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 13.75\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland
H		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 13.75\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland
I		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 13.75\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland
J		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 25.82\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland
K		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 25.82\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland
L		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 25.82\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland
M		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass (~65% wt./BisGMA and PMMA matrix $W_f = 25.82\%$	*ever*Stick-ORTHO; Stick Tech Ltd., Turku, Finland

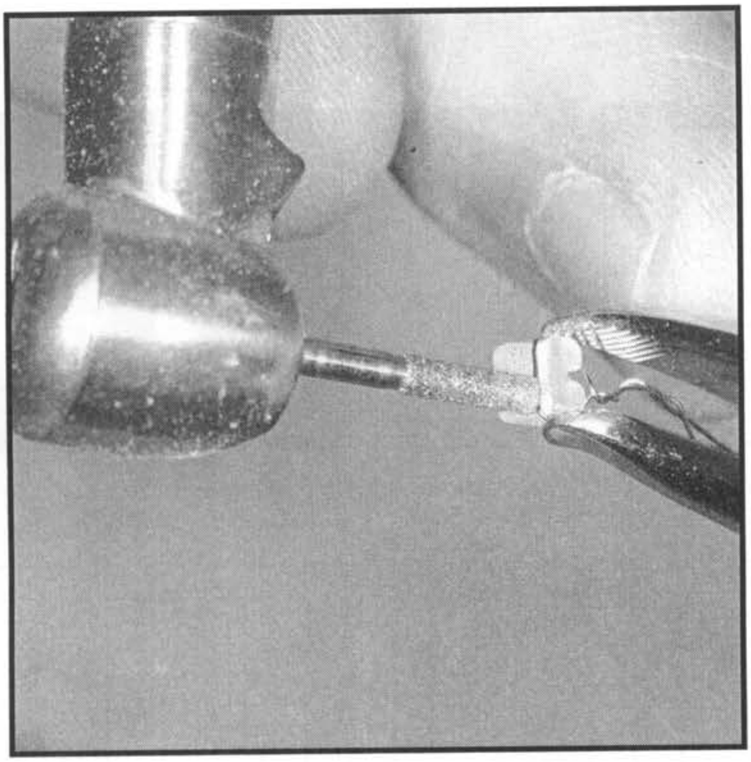


Figure 1. Removal of gingival tie wings with diamond bur; incisal tie wing protected with ligature tie

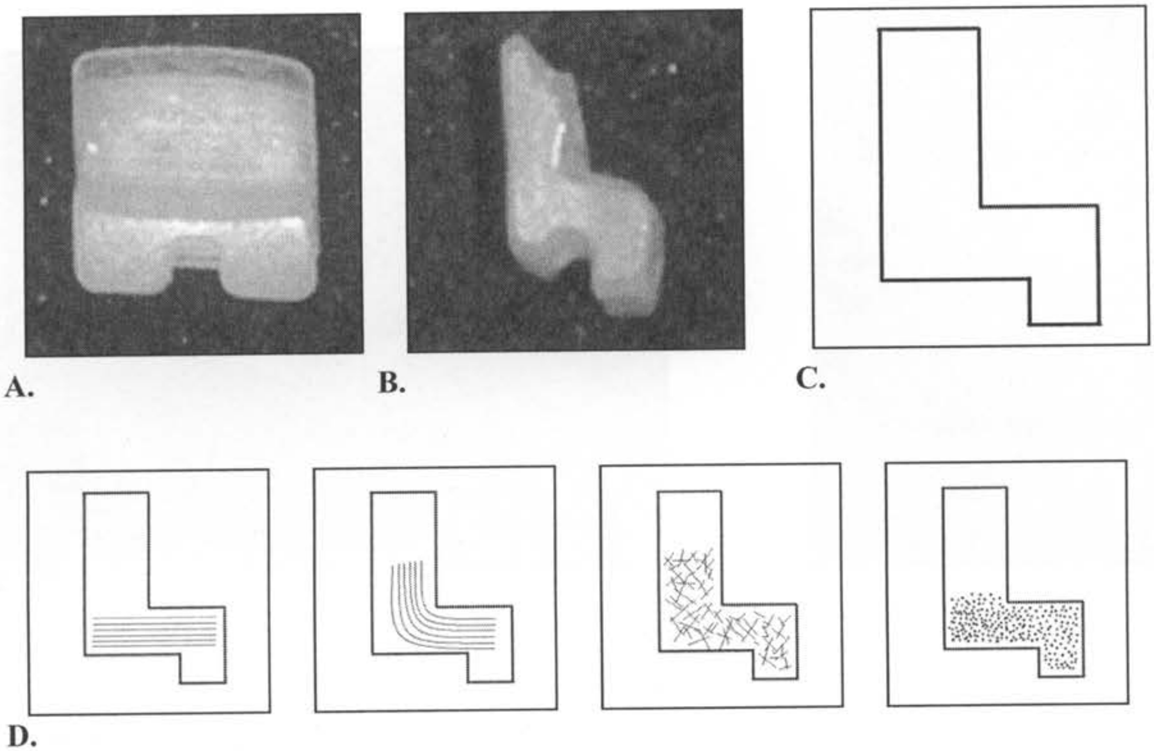
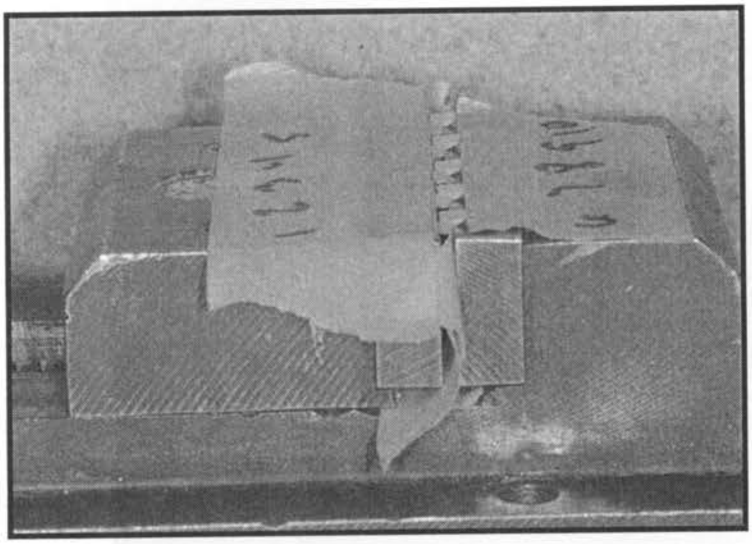
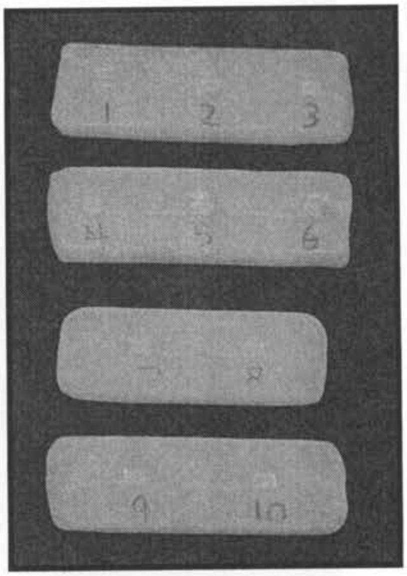


Figure 2. Photograph of modified commercial polycrystalline bracket (Mystique- GAC Intl, Islandia, NY). A.) frontal view of the modified bracket, B.) cross-sectional view of the modified bracket, C.) pictogram of the cross-sectional view of the modified bracket, D.) pictograms of the four different patterns of E-glass fibers tested



A.



B.

Figure 3. A.) Test brackets loaded and aligned into a vice with the bracket base facing upward; B.) Brackets embedded in UDMA blocks

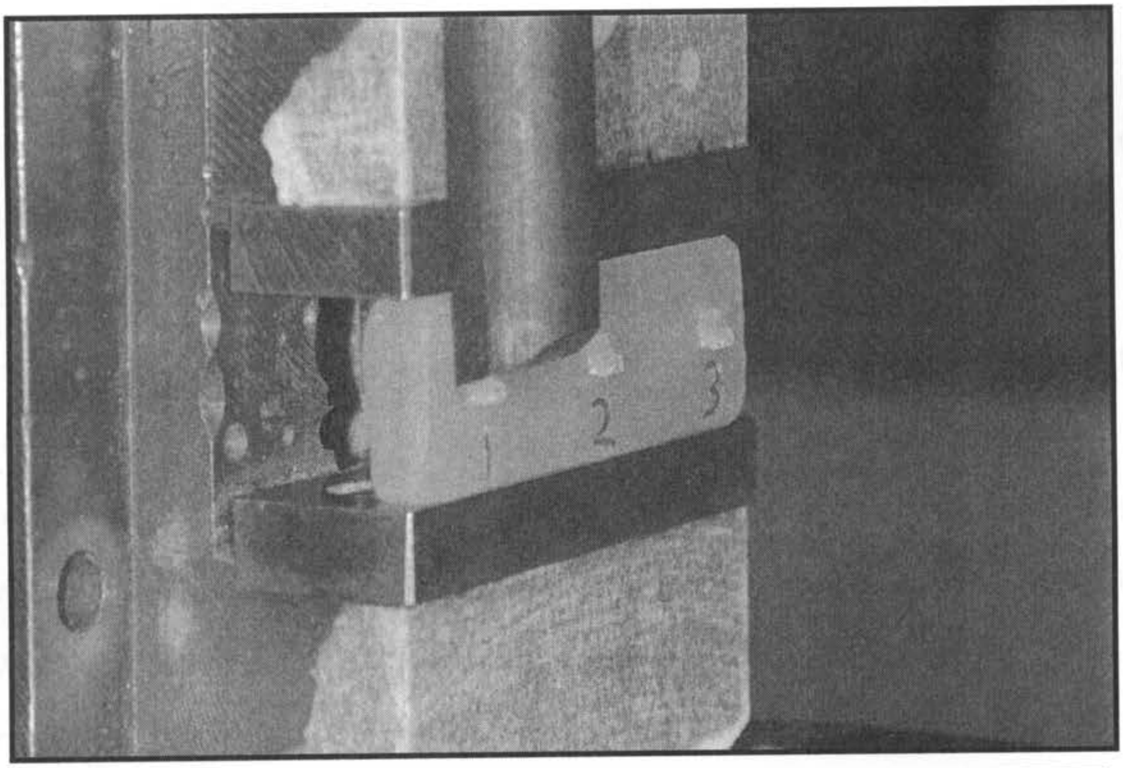


Figure 4. Rod with a beveled tip (chisel type mounting) used to make a line contact with the incisal tie wings of the brackets

Results

All of the samples remained in the UDMA block during the static load testing. None of the samples pulled out of the block or exhibited any movement in the block. The mean initial failure values for each bracket type are listed in Table IV and presented in Figure 10. There was no statistically significant difference between the mean initial failures of the FRC groups at $p<0.05$. The Group A brackets (commercial polycrystalline bracket; Mystique-GAC Intl, Islandia, NY) had the highest mean initial failure value of all the groups tested. The Group B brackets (commercial polycarbonate (filled with 35% alumina) Vogue-GAC Intl, Islandia, NY) had the lowest mean initial failure value of all the groups and was found to be significantly different with Group A, F, G, J, and K. Groups F (W_f= 13.75%) and J (W_f= 25.82%) consisted of straight fibers placed perpendicular to the bracket base extending out into the tie wing. Groups G (W_f= 13.75%) and K (W_f= 25.82%) consisted of curved E-fibers running from the center of the bracket extending out into the tie wing. Only the FRC prototype brackets in the experimental groups H and L (random oriented fibers) had mean load to initial failure values (41.15 N and 41.52 respectively) that were less than the pure resin control group D (42.26 N).

All fabricated brackets were constructed without major visible voids or surface flaws. SEM images revealed that: 1) There was a uniform distribution of material within the brackets made from the Z100™ commercial restorative (3M ESPE) composite (Figure 5), 2) The laboratory prepared particulate (80% strontium) filled resin brackets consisted of a homogenous mixture of particulate with resin (Figure 6), and 3) The E-glass fibers were able to be manipulated into various shapes for incorporation within the tie wing complex (Figure 7).

The initial site of failure of each of the bracket specimens was at the junction of the bracket base and tie wing extension. The SEM images revealed that the static load placed on tie wing complex did not produce any surface damage on the slot wall (Figure 8). Two separate zones of materials existed within the FRC prototype brackets: 1) Resin only and 2) Resin/fiber. The fracture line of the FRC prototype brackets progressed in a linear fashion until it reached the area enriched with E-glass fiber (i.e., resin/fiber zone; Figure 9).

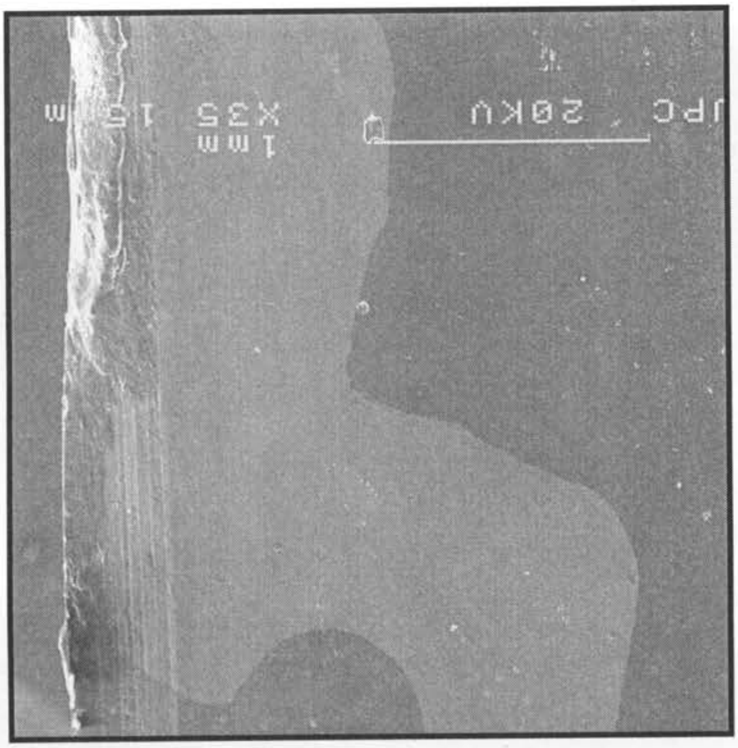


Figure 5. Uniform distribution of material within the bracket made from Z100™ commercial restorative (3M ESPE) composite (Group C) (X35).

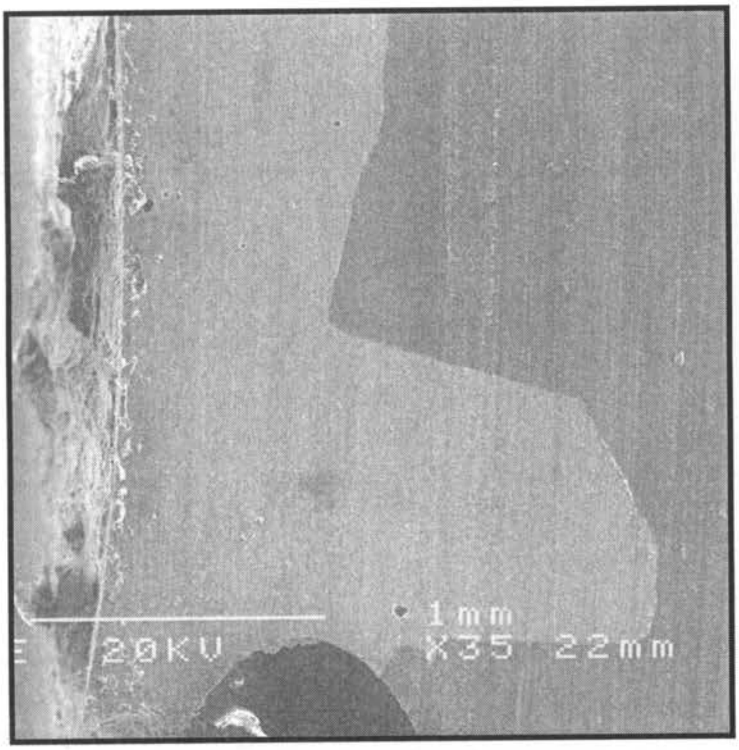


Figure 6. Homogenous mixture of particulate (80% strontium) with resin (X35).

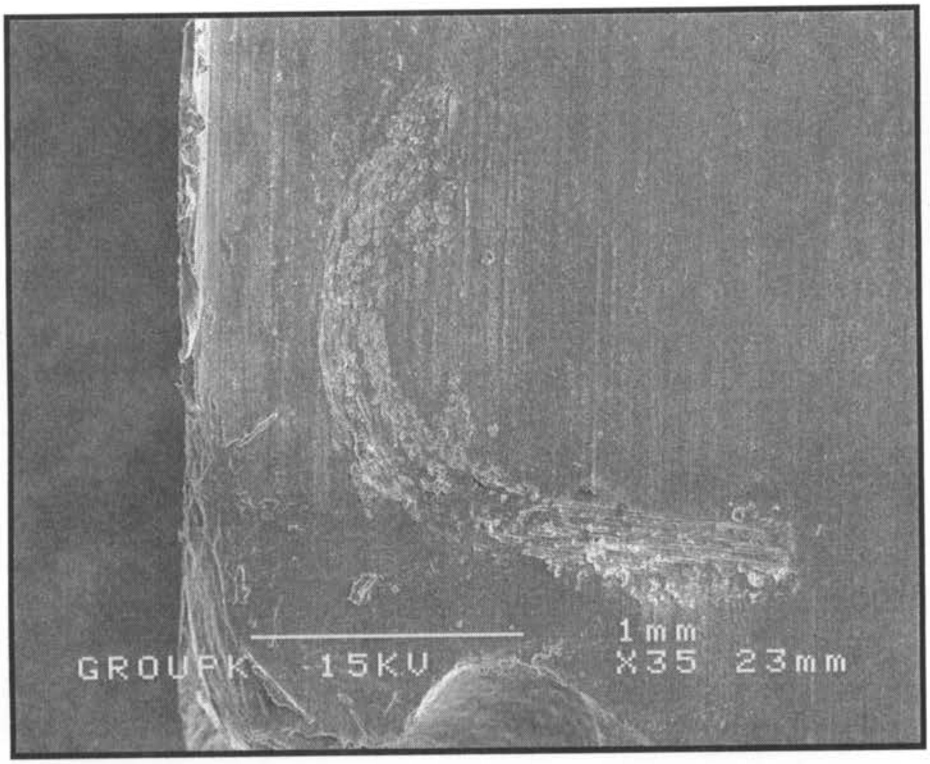


Figure 7. Manipulation of E-glass fibers within the di-methacrylate resin matrix of the brackets (X35).

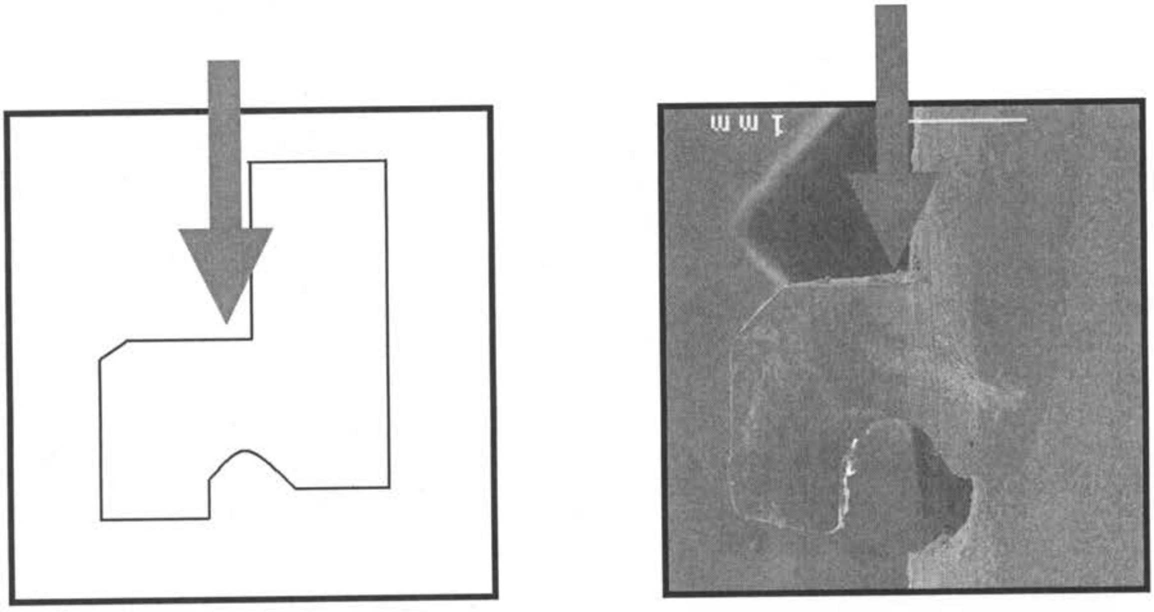


Figure 8. Diagram and SEM image of the static load configuration. Red arrow indicates the direction of force upon the bracket. No surface damage to arch wire slot wall by rod. Initial site of fracture starts at the junction of the base and wall of the arch wire slot (X20).

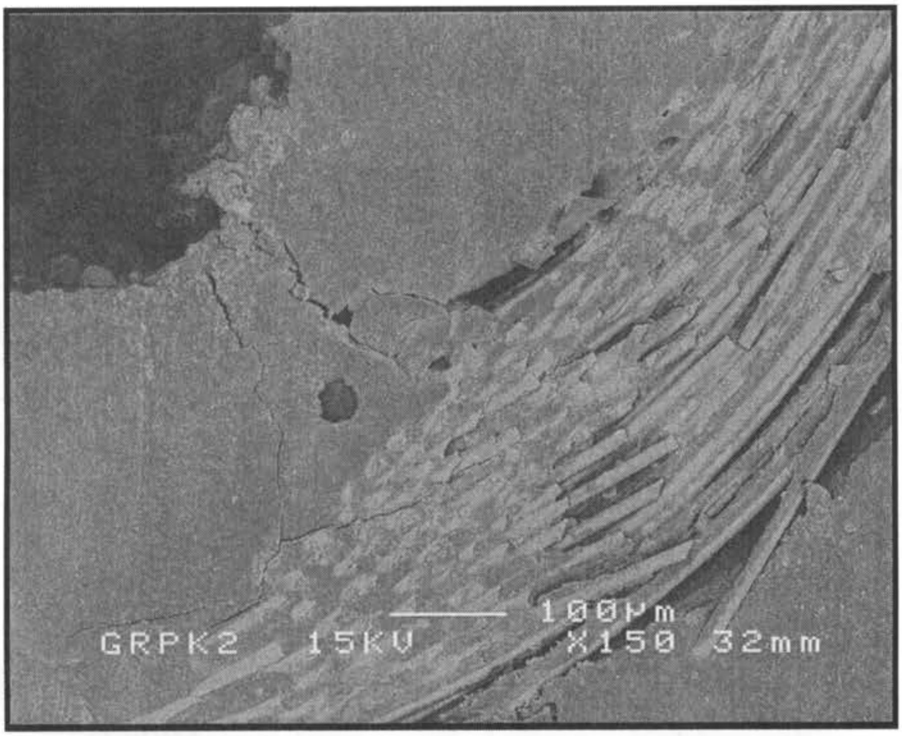
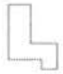
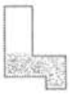


Figure 9. Propagation of fracture within di-methacrylate resin rich area and resin/fiber area (X150).

Table IV. Mean initial failure values of the tested brackets (n=6)

Group	Pictogram	Matrix	Reinforcement/W_f	Mean Initial Failure value (Newtons)	Standard Deviations	Range
A		Polycrystalline	Silica lined arch wire slot	101.01	±19.99	73.40-127.89
B		Polycarbonate	35% alumina	28.17	±5.20	20.02-35.59
C		BisGMA, TEDGMA	100% Zirconia/Silica	45.74	±10.85	33.36-62.28
D		1:1:1 BisGMA, TEDGMA, UDMA	NONE	42.26	±8.02	27.80-48.93
E		1:1:1 BisGMA, TEDGMA, UDMA	80% wt. strontium	49.08	±2.91	44.48-53.38
F		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=13.75%	57.27	±10.96	45.59-72.28
G		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=13.75%	62.09	±11.48	48.93-75.62
H		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=13.75%	41.15	±7.44	33.36-54.49
I		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=13.75%	45.22	±11.46	35.59-66.72
J		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=25.82%	63.39	±16.79	53.38-92.30
K		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=25.82%	56.34	±7.63	51.15-71.17
L		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=25.82%	41.52	±8.37	34.47-57.83
M		1:1:1 BisGMA, TEDGMA, UDMA	Unidirectional E-glass W_f=25.82%	54.68	±10.03	43.37-70.06

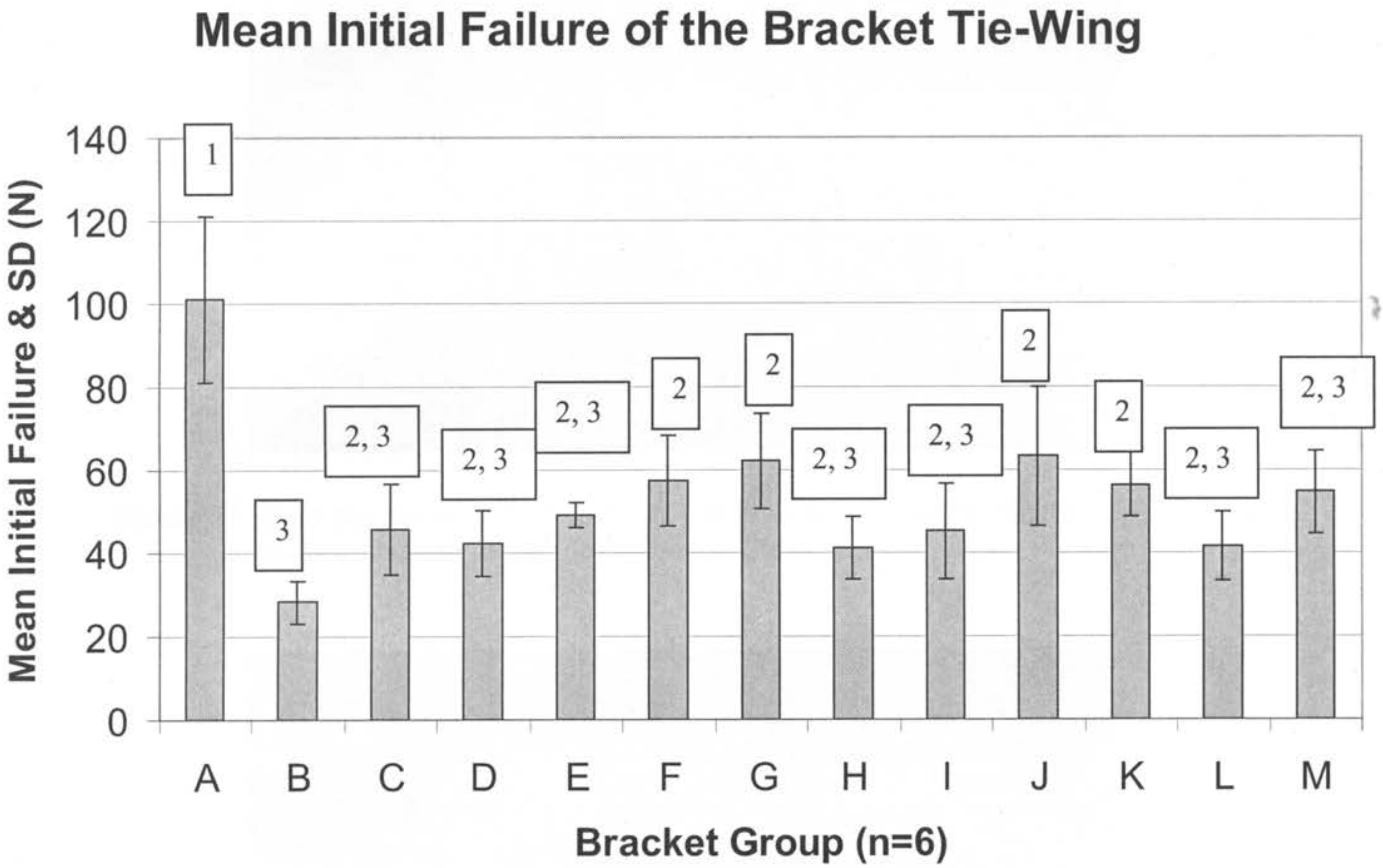


Figure 10. Bar Graph of Mean Initial Failure of the Bracket Tie-Wing.
Statistical ANOVA with Post-hoc Tukey test at $p < 0.05$.
Y-bars designate Standard Deviation.
The numbers above the Y-bars signify statistical groups.
Statistically, the bracket groups with the same number are not significantly different.

Figure 11. Poor placement of E-glass fibers within tie-wing complex; fibers located far from initial site of fracture (X50).

Figure 12. Random orientation of E-glass fibers. Di-methacrylate resin-rich areas present (X50).

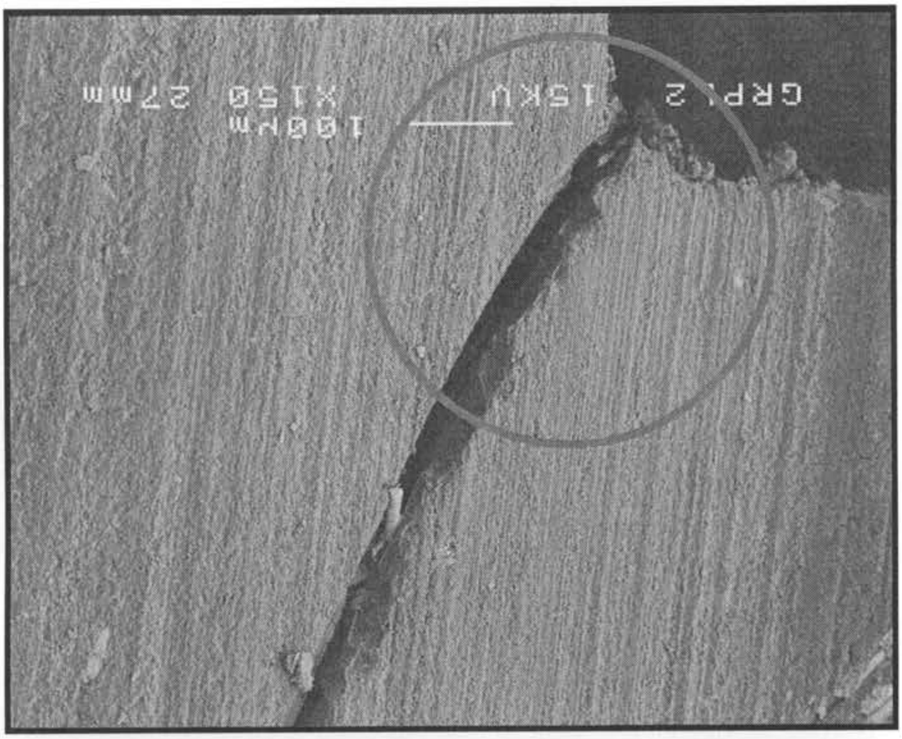


Figure 13. Junction of the base and wall of arch wire slot- the initial site of fracture. Area where ideal fiber placement is needed (X150).

Figure 14. Residual resin attached to E-glass fibers gives indication of proper adhesion (X1,000).

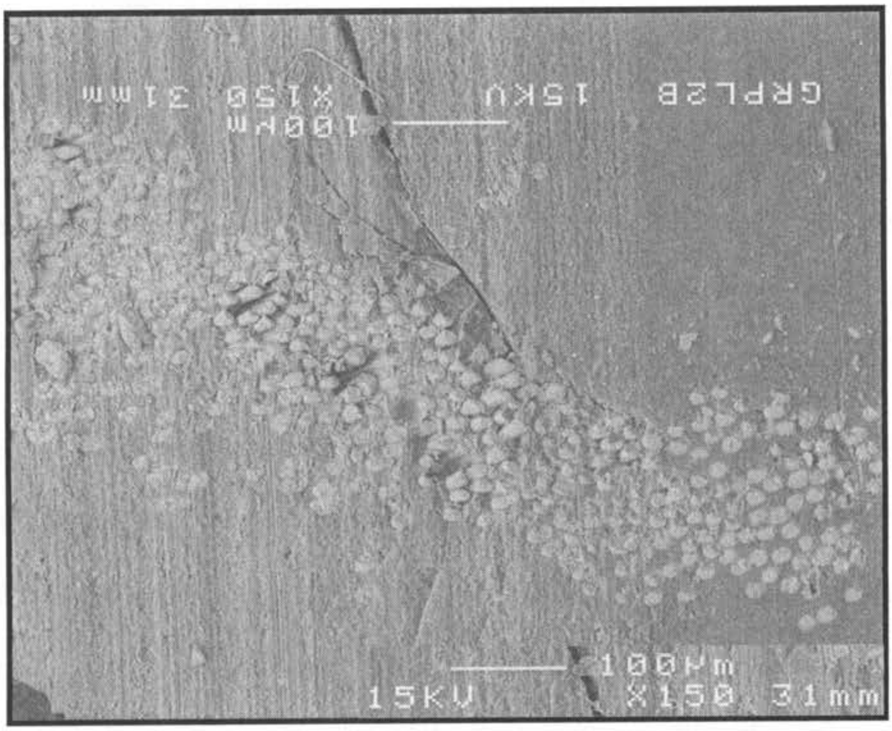


Figure 15. Adequate interfacial bond between E-glass fibers and di-methacrylate resin matrix resulting in deflection of crack propagation (X150).

Discussion:

This test used a new method for testing the affect of fiber reinforcement on tie wing fracture resistance. An acceptable testing method should 1.) not introduce major experimental errors, 2.) be repeatable, and 3.) be readily duplicated (Flores et al. 1989). All of these criteria were met with the present study. As with many other *in vitro* studies, the design of this experiment did not exactly replicate forces involved with the clinical failures of esthetic brackets do to the fact that a static load was placed at one point on the tie wing extension until failure. It is understood that in a clinical situation, there is more of a dynamic interaction of forces within the arch wire slot. Forces may also be intermittent due to the active tooth movement of various treatment mechanics and arch wire progression. The static loading condition, however, provided a preliminary understanding of the proper orientation and location of the E-glass fibers within the tie wings of the brackets. This allowed for screening of multiple fiber orientation designs prior to more complex testing. Since little is known on the manipulation of fiber placement for reinforcement of esthetic brackets, the basic static load test was essential to provide insight on how and why initial failure occurs.

Proper design and engineering principles need to be applied when fibers are used for dental appliances. The challenge of fiber incorporation is the implementation of a high degree of reinforcement while meeting the requirements of esthetics, ease of construction, stability, and biocompatibility in the oral environment (Goldberg and Burstone 1992). Fiber geometry and orientation has been found to influence the mechanical properties of the composite structure (Agarwal and Broutman 1990, Callister 1996). The four different patterns of E-glass fiber within the experimental brackets were: 1) Straight fibers placed perpendicular to the bracket base extending out into the tie wing (Group F and J), 2) Curved fibers running from the center of the bracket extending out into the tie wing (Group G and K), 3) Chopped fibers assorted in a random fashion through out the base and tie wing (Group H and L), and 4) Straight fibers placed in a mesial-distal direction within the tie wing (Group I and M).

The slightly lower mean initial load to failure values in the FRC prototype brackets (groups H and L) may be due to the fact that the random oriented fibers were not incorporated in the most optimal areas within the tie wing complex (Figure 11). All of the other FRC prototype groups had higher mean load to initial failure values compared to the pure resin control group (D). The E-glass fibers were able to reinforce the polymer matrix increasing the load to initial failure of the tie wing complex. Among the FRC groups, one of the brackets in group J (straight fibers running perpendicular from the bracket base) had the highest load to initial failure value (92.30N) perhaps due to the fibers being located closer to the initial site of fracture.

The increase in fiber volume fraction also proved to increase the load to initial failure of the FRC brackets. This occurred for all of the groups except for groups G and K. The increased amount of curved fibers was unable to be manipulated close to the initial site of failure by the hand lay-up technique. Regardless of the volume fraction, there was great difficulty in controlling the accuracy of the random fiber distribution in groups H and L. Unfortunately, the chopped glass fibers did not concentrate close to the site of fracture initiation. Since the overall behavior of a composite is primarily determined by the constituent volume fraction (Agarwal and Broutman 1990, Herakovich 1998), the amount of fibers within the brackets may have been too low to achieve optimal reinforcement. The low weight fraction of fiber within the tie wing complex resulted in areas that were only enriched with resin (i.e., resin zone; Figure 12). The areas of pure resin seemed to be the most at risk for fracture.

As expected, SEM results showed that the hand-lay up process produced small defects during fabrication that included: voids, resin rich zones, misaligned fibers, and regions of poor adhesion. These defects were not excessive or consistent in the brackets. According to Goldberg and Burstone, hand placement of fibers can be tedious and almost impossible to attain reproducibility (Goldberg and Burstone 1992).

It has been suggested that manufacturing flaws and surface defects introduced during treatment may potentially accentuate bracket failure (Viazis et al. 1993, Russell 2005). 'When a failure is initiated, a part of the total strain energy is released as a wave that propagates from the failure site throughout the structure (Giordano et al. 1998). As in Dyer's study, the first sign of FRC internal damage was the micro-cracking of the resin rich zone (Dyer 2003). In this test, SEM results showed that the fracture line progressed in a linear fashion until it reached the fiber rich area of the bracket. Crack propagation is described as being an enlargement, extension, or travel of a crack through a material, resulting in fracture of a ceramic material (Viazis et al. 1993). The start and propagation of the fracture seemed to indicate that the placement of the E-glass fibers needed to be moved closer to the site of initiation (Figure 13).

There are several mechanisms involved in the fracture process of a fibrous composite during the propagation of a crack. The fibers that lie ahead of the crack remain intact while the ones near the tip of the crack may undergo high stress and immediately break. If a matrix crack is unable to propagate across the fibers, then the fibers may actually debond from the matrix material prior to breaking. This type of failure is termed fiber debonding. In this experiment, there was residual resin attached to the fibers after the fracture (Figure 14). The crack at the fiber break was allowed to travel within the resin matrix which resulted in fiber debonding. Another type of failure that may occur at the fiber-matrix interface is fiber pullout. This occurs when a crack, initiated at a fiber break, is unable to propagate into the matrix material. The fibers are pulled out of the matrix rather than fractured at the plane of fracture indicating an inadequate fiber/matrix bond. Upon specimen evaluation, fiber pullout does not seem to occur in the FRC prototype brackets. This is likely due to the proper interfacial bond established between the E-glass fibers and the resin matrix. The fibers used in this experiment were coated with silane prior to placement during its manufacturing process. The fiber/matrix bond caused the crack propagation to deflect from the original path and move transversely within the fiber network (Figure 15). The fibers absorbed the energy of the fracture and decreased the crack propagation (Agarwal and Broutman 1990).

Fiber reinforcement can only successful if the loading forces can be transferred from the matrix to the fibers (Behr et al. 2000). The addition of fibers within a matrix can be a potential method of influencing the failure mode thus increasing the toughness of a composite material. However, the results of this study did not reveal a statistically significant increase in the initial failure of the tie wings when reinforced with E-glass fibers of different configurations and weight fractions. There were individual load to initial failure values within the FRC bracket groups that approached the mean value of the commercial polycrystalline bracket (Mystique-GAC Intl, Islandia, NY). This suggests that more accurate and consistent placement of the E-glass fibers is needed in order to provide results that are statistically comparable to current ceramic brackets.

A limitation of the present study was that the brackets were tested dry at ambient temperature which does not resemble oral conditions. Both moisture and body temperature may have a negative effect on the FRC brackets. Vallitu (2000) found that after just four weeks in water, the ultimate transverse strength of a composite may be reduced by 27% relative to its dry transverse strength. It is possible that after water storage, the brackets tested in this study may have a similar loss of strength. Further investigation is necessary in this area.

The SEM images revealed that the affects of altering the fiber volume fraction needs to be further tested. The amount of fiber to be used may be limited due the small bracket size and shape. However, the percent of fiber in a bracket could be increased. An increase in fiber content may cause a decrease in the amount of resin matrix which could lead to more voids and incomplete impregnation. The need for better placement of the fibers was also evident in the SEM images. E-glass fibers should be placed in closer proximity to the site where fractures are known to start and then tested to determine if greater reinforcement and strength is achieved. As mentioned above, strategically placed fibers within the tie-wing complex may allow for optimal mechanical properties of the material. By predicting the loading situation and understanding the failure mode, it may be possible for a lesser amount of fiber to be ideally located in order to provide the most adequate effect in reinforcement (Vishu 1998).

Conclusions:

- It was possible to design and test a new esthetic FRC bracket.
- The prototype FRC brackets with unidirectional E-glass fibers had a higher load to initial failure of the tie wing than the commercially available alumina-reinforced polycarbonate bracket- Group B.
- Within the confines of this test configuration, the commercially available polycrystalline bracket (Mystique-GAC) had the highest load to initial failure of the bracket tie wing- 101.01 N (±19.99).
- Of all the different prototype design configurations, the group with unidirectional E-glass fibers placed perpendicular to the bracket base had the highest load to initial failure mean value- 63.39 N (±16.79).
- Further studies on the amount of glass fiber and its placement (closer to site of initial fracture) are needed in order to provide the improved fracture toughness needed for esthetic brackets.
- Testing methodology allowed for investigation of the at risk portion of the orthodontic bracket.

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