# An Investigation into the Bonding Properties of New Generation Ceramic Brackets As Compared to a Stainless Steel Bracket

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# AN INVESTIGATION INTO THE BONDING PROPERTIES OF NEW GENERATION CERAMIC BRACKETS AS COMPARED TO A STAINLESS STEEL BRACKET

by

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A Thesis submitted to the Faculty of the Graduate School,
Marquette University,
in Partial Fulfillment of the Requirements for
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# ABSTRACT
# AN INVESTIGATION INTO THE BONDING PROPERTIES OF NEW GENERATION CERAMIC BRACKETS AS COMPARED TO A STAINLESS STEEL BRACKET

Ami Inoue, D.D.S.

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**Introduction:** More patients are seeking esthetic alternatives for their orthodontic treatment options, which has led to increased use of ceramic brackets in recent years. These brackets were marketed before independent scientific research was completed. Many of the early ceramic brackets used a silane coupling agent to allow for a chemical bond between the bracket and the adhesive resin. Early reports from clinicians of increased bond strengths and iatrogenic tooth damage after bracket removal were common. Manufacturers have made changes to their base designs, relying more on mechanical retention for bond strength. The goal of this study was to test the shear bond strength of two newer generations of mechanically retained ceramic brackets and compare them to a traditional stainless steel bracket.

**Materials and Methods:** Two types of ceramic brackets, Clarity Advanced (3M Unitek, Monrovia, CA), and Avex CX (Opal Orthodontics, South Jordan, UT) and one type of metal bracket, Victory Series MBT (3M, Unitek, Monrovia, CA) were used in this study. Exemption from IRB Application was granted by the Marquette University Institutional Review Board (IRB) on 7-12-13. The shear bond strength of the three groups of brackets were examined after bonding to extracted premolars. Brackets were debonded with a universal testing machine (Instron Corporation, Canton, MA) in a motion parallel to the bracket/tooth interface. Each tooth and bracket was viewed under an optical stereomicroscope at 10x magnification and given an adhesive remnant index (ARI) score. The one way ANOVA and Tukey's post hoc tests were used to determine significant differences in bond strengths, and the Kruskal-Wallis and Mann-Whitney post hoc tests were used to analyze the difference in ARI scores.

**Results:** Statistically significant ($p<0.01$) differences were found between the shear bond strengths of the Victory Series and Clarity Advanced groups, with the Victory Series having a mean strength of 199.4 N and the Clarity Advanced having an average of 136.0 N. Significant ($p<0.0001$) differences in ARI scores were found between the Victory Series and both ceramic groups, with an average score of 1 for the Victory Series and an average score of 2 for both ceramic groups. The two ceramic brackets were not statistically different from each other in bond strength or ARI score.

**Conclusions:** The shear bond strengths of the new generations of ceramic brackets are lower than those of the metal bracket tested, which suggests a safer bond to enamel. Further research on clinical debonding characteristics and behavior intra-orally are needed to support the in vitro results found in this study.

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# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# CHAPTER 1
# INTRODUCTION

The dental specialty of orthodontics has in recent years become more concerned with esthetics. The evolution of the specialty has shown a change in esthetic ideals, and the commonly used materials have also evolved (Britton et al., 1990). Patients are not only concerned with the appearance of their teeth and smile, but also with the appearance of the appliances that will be used. An increase in the number of adults seeking orthodontic treatment in recent years has led to a parallel increase in demand for more esthetic appliances (Russell, 2005).

Many options for appliances to be used in orthodontic treatment are available to practitioners. Historical appliances involved banding every tooth with a metal bracket attached to the band. The development of acid etching enamel and direct bonding by Buonocore removed the need for banding every tooth, and the bonded miniature bracket, much preferred by patients, appeared in the 1960s (Buonocore, 1955; Kusy, 2002). Patient desire for more esthetic options has driven the development of more esthetic materials. The evolution of orthodontic appliances has led to the development of smaller metal brackets, which offer some esthetic advantage, as well as lingual appliances, clear aligner trays, and clear brackets made of ceramic or polymers. Patient surveys conclude that patients find lingual and clear tray appliances more attractive than any fixed appliance, and that ceramic brackets were ranked as more esthetic than metal or self ligating hybrid brackets (Rosvall et al., 2009).

Orthodontic treatment with clear aligner trays, such as Invisalign, is a more visible example of the market’s response to consumer demand with numerous commercials and magazine advertisements aimed directly at consumers. These trays offer treatment with clear overlay trays, although their capabilities in achieving complex movements are limited (Rosvall et al., 2009). Many patients with more advanced treatment requirements end up completing their treatment with conventional fixed appliances (Russell, 2005). Lingual appliances are an alternative esthetic option that may offer more control than the clear trays of Invisalign, with the caveat of more technical difficulties and a decrease in performance as compared to traditional labial appliances (Russell, 2005). Plastic brackets were introduced in the 1970s, but their performance was limited by their lack of strength and dimensional stability (Wang at al., 1997; Kusy, 2002; Graber et al., 2005). Their esthetics were also compromised by discoloration (Bishara et al., 1997; Russell, 2005; Chen et al., 2007).

The demand for an esthetic appliance with acceptable performance has made ceramic brackets one of the most commonly used esthetic appliances (Eliades et al., 1993). Patients like the minimal look of clear or tooth colored brackets, and the strength of the material allows for more control over tooth movement by the clinician. Ceramic brackets were introduced in the 1980s and have gone through significant evolution over the past 30 years (Bishara et al., 1997). Manufacturers have made changes to brackets in response to claims of excessively high bond strength, causing difficulties in bracket removal. Patients also report discomfort during bracket removal. The higher forces used to debond ceramic brackets can also cause them to break or shatter, leaving fragments on the teeth that must be removed with alternative techniques. The changes that have been made, specifically eliminating the silane treatment with a transition to mechanical retention, significantly decreased the bond strength as well as accounts of iatrogenic enamel damage. Even with these latest developments, problems during debonding still persist, including bracket breakage and portions of brackets remaining bonded to the tooth. Another concern with the lower bond strengths is the possibility for more clinical bond failures. The goal to reduce bond strength may have led to problems with insufficient bond strength for clinical use.

The aim of this study was to determine if the most recent ceramic brackets could perform similarly to their metal counterparts in reference to bond strength. The study compared the shear debond strength of two of the most recently developed ceramic brackets with a standard metal bracket, as well as the location of the bond failure. Little research exists on the Clarity Advanced bracket (3M Unitek, Monrovia, CA) and the Avex CX bracket (Opal, South Jordan, UT), while their clinical use is growing. In vitro studies may help predict the clinical strengths and weaknesses of these brackets, as well as evaluate their consistency in debond strength and performance.

# CHAPTER 2
# LITERATURE REVIEW

The introduction of bonded brackets and the reduced need to band anterior teeth, marked the beginning of esthetic orthodontics in the 1960s (Kusy, 2002). In 1955, Buonocore wrote about treating the surface of enamel with acid to make it more receptive to adhesion of acrylic drops. The acid treatment was performed with 85% phosphoric acid for 30 seconds and dramatically increased the adhesion of acrylic filling material by what we now know is due to an increase in surface area (Buonocore, 1955). The success achieved in bonding acrylic to teeth following etching with phosphoric acid was a milestone in esthetic dentistry. Brackets became bondable to teeth instead of attached to bands that fit around the teeth and were hence smaller in size, which was the first major step in creating more esthetic orthodontic appliances.

Orthodontic treatment has for many years been achieved with stainless steel appliances that are attached to the teeth and an assortment of wires of variable size and moduli of elasticity that are then engaged in the tooth-borne appliances. The first orthodontic material that is documented is a gold ligature wire. The use of gold continued throughout the early 20th century, until the deficiencies of the material were pointed out in 1931 at the meeting of the American Association of Orthodontists (Kusy, 2002). Stainless steel was available in the early 1930s but experienced a period of development with the start of World War I. By 1960, stainless steel was accepted as the standard material in orthodontic appliances, due to its desirable stiffness, the ability to make appliances smaller and seemingly more esthetic, and its low friction (Kusy, 2002). Stainless steel also has better strength and springiness than gold, while maintaining a resistance to corrosion (Proffit et al., 2013). Gold universally fell out of favor when stainless steel became part of the market (Kusy, 2002).

A review of orthodontic supply catalogs will illustrate the market dominance of stainless steel in the orthodontic specialty. Manufacturers still make bands, brackets, and wires of the material because of its predictable and reliable properties. Most brackets are either cast or milled from stainless steel, which is then polished to obtain a smooth surface that will be less likely to damage wires that must slide through the bracket (Proffit et al., 2013). The bracket base of most modern stainless steel brackets is welded to the wings of the bracket and has a mesh pad attached to the base, providing mechanical undercuts for retention, and some brackets also include an etched metal surface by lasers or microetching for additional retention (Graber et al., 2005). Some brackets are manufactured using a process called metal injection molding, or MIM, which produces a single piece bracket by combining fine metal particles with organic particles and lubricants that are later removed (Zinelis et al., 2005).

Many studies and clinical application in the mouth over the past twenty years with stainless steel brackets have proven their consistent nature of debond (Kusy, 2002). Whether using chemical cured or light cured resins, stainless steel brackets show similar bond strengths and fracture sites that illustrate a cohesive failure within the resin when shear bond strength is tested (Joseph and Rossouw, 1990). Some studies suggest more precisely that the weakest link in the bond of a metal bracket to enamel is at the bracket adhesive interface, and the predominant pattern of failure when removing stainless steel brackets leaves a majority of the composite bonding material on the tooth. This is described with a high Adhesive Remnant Index (ARI) score, which is an ideal pattern of debond that decreases the risk of enamel damage during bracket removal (Odegaard and Segner, 1988; Blalock and Powers, 1995; Bishara et al., 1997; Soderquist et al., 2006). There are multiple scales used for the ARI score, generally using four to five categories. Lower scores indicate more resin was attached to the bracket after debonding, while higher scores indicate more resin left on the tooth. Thus, a high score with more resin on the tooth reflects a low risk of enamel damage during debond (Odegaard and Segner, 1988; Blalock and Powers, 1995; Bishara et al., 1997; Soderquist et al., 2006). One study suggests that air entrapment within the mesh of the pad and the inability of visible light to cure underneath a metal bracket may be responsible for this weakness, though others claim that transillumination through the enamel allows for complete polymerization of the resin under these brackets (Greenlaw et al., 1989; Bradburn and Pender, 1992; Wang and Meng, 1992). While excess adhesive requires a lengthier removal process, it is generally safer than if the bond between the bracket and adhesive is stronger than the adhesive to enamel. Metal brackets also have the advantage of deformation before the cohesive failure of the resin, which allows the bracket to remain intact during the debonding procedure (Joseph and Rossouw, 1990). Adequate strength during treatment so as to resist distortion while possessing a modulus of elasticity that enables deformation and bending under excess force is one of the positive characteristics of stainless steel, making it a desirable and frequently used material in orthodontics (Bordeaux et al., 1994; Kusy, 2002).

The desire for more esthetic brackets helped propel the development of the plastic bracket in the 1970s (Bordeaux et al., 1994; Kusy, 2002). Plastic brackets are most often made of an injection-molded polymer called polycarbonate, a material that lacks strength and stability (Wang et al., 1997; Kusy, 2002; Graber et al., 2005). These brackets have fallen out of popular use due to distortion caused by water absorption and creep, unstable slot size, and staining (Britton et al., 1990; Bordeaux et al., 1994; Blalock and Powers, 1995; Wang et al., 1997; Graber et al., 2005; Chen et al., 2007). The brackets also require the use of a plastic primer when using diacrylate cements (Blalock and Powers, 1995). Attempts to improve the performance of the brackets have been unsuccessful in overcoming their weaknesses. Polycarbonate brackets have been reinforced with ceramic and fiberglass fillers to increase the strength and decrease the distortion, in addition to lining the slot with metal to increase rigidity (Bishara et al., 1999; Russell, 2005). These changes have improved the technical specifications of the brackets, but the problems with torque movements and resisting distortion remain, leaving their clinical performance less than satisfactory (Russell, 2005). The limited studies of bond strength of polycarbonate brackets demonstrated significantly lower bond strength for polycarbonate versus ceramic brackets. The location of bond failure for polycarbonate brackets in the study cited showed a similar debond behavior to metal brackets with most of the adhesive remaining on the enamel (Ozcan et al., 2008).

The limiting physical properties of esthetic polycarbonate brackets led to further development of esthetic appliances and the introduction of ceramic brackets in the mid-1980s (Kusy, 2002; Chen et al., 2007). These brackets are made from either a single crystal, also called monocrystalline sapphire, or of polycrystalline aluminum oxide

(Kusy, 2002; Graber et al., 2005; Russell, 2005; Chen et al., 2007; Reddy et al., 2013). Brackets made of polycrystalline zirconia have also been developed, and they are reported to have the greatest toughness of ceramics, but they do not exhibit the same translucent characteristic of the alumina ceramics and are used less frequently (Kusy, 2002; Russell, 2005).

The difference between the two types of alumina brackets is in the manufacturing process. Monocrystalline brackets are machined from a single crystal of aluminum oxide that has been heated and cooled slowly. Polycrystalline brackets use either injection molding or a sintering process that blends aluminum oxide particles with a binder, creating a mixture that is formed into a shape from which the bracket is then machined and heated to remove the imperfections and stresses that are created by the cutting process. Injection molding removes the cutting process from manufacturing and therefore eliminates structural imperfections and the need to heat the brackets after machining (Bordeaux et al., 1994; Russell, 2005). Monocrystalline ceramics are the more translucent of the two types of alumina brackets, and therefore might be considered more esthetic, but they are also more susceptible to the propagation of cracks from any imperfections or scratches (Russell, 2005).

Some of the positive features of ceramics include its color stability and resistance to staining, as well as its strength and resistance to deformation and slot distortion (Chaconas et al., 1991; Merrill et al., 1994; Bishara et al., 1997; Kukiattrakoon and Samruajbenjakul, 2010). The nature of the ceramic also lends itself to brittleness, which is due to low fracture toughness and may be considered the limiting physical property of the material (Bordeaux et al., 1994; Bishara et al., 1997). This property alone makes the material more prone to fracture during debonding, as well as fracture of the bracket and/or wings during treatment (Chaconas et al., 1991; Bishara et al., 1997; Theodorakopoulou et al., 2004; Russell, 2005). Numerous studies on the debonding characteristics of ceramic brackets have shown a propensity for bracket fracture when applying force to debond the bracket (Chaconas et al., 1991; Eliades et al., 1993; Bishara et al., 1997; Liu et al., 2005; Kitahara-Céia et al., 2008). The facture toughness of alumina ceramic brackets has been reported at 3.0 to 5.3 MPa x $m^{1/2}$ while the fracture toughness of steel is around 80 to 90 MPa x $m^{1/2}$ (Kusy, 1990; Bordeaux et al., 1994). The difference between the two materials is marked and a cause for concern when applying force to remove orthodontic brackets that are bonded to teeth. Increased friction is another drawback when using ceramic brackets, as they show the highest amount of friction when used with any type of arch wire except nickel-titanium (Kusy, 2002).

The low fracture toughness of alumina ceramics necessitates a bulkier design with a larger profile and wings to resist fracture, a characteristic that is generally considered unesthetic and undesirable (Kusy, 2002). Without adequate mass of material, especially in the mono-crystalline bracket types, the tie-wings had a propensity to break while tying in a wire, or when torque was added to the arch wire. Another consequence of a larger profile was the increased incidence of wear and chipping of maxillary teeth opposing ceramic brackets that were bonded to the lower incisors and canines (Kusy, 2002).

Alumina ceramics are by nature an inert material, rendering them unable to be chemically bonded to any adhesive resin that is used (Bishara et al., 1997; Theodorakopoulou et al., 2004; Russell, 2005; Kitahara-Céia et al., 2008). Lack of a chemical bond caused early ceramic bracket manufacturers to use a silane-coupling agent to mediate a chemical bond between the ceramic and resin (Bishara and Trulove, 1990; Britton et al., 1990; Bishara et al., 1997; Theodorakopoulou et al., 2004; Russell, 2005; Chen et al., 2007; Habibi et al., 2007; Reddy et al., 2013). One end of the silane molecule bonds strongly to acrylic resins while the other end binds to glass (silica). The inert aluminum oxide bracket crystals must be coated with a layer of glass in order for the silane to work as a coupler, therefore each bracket was coated with silica glass on the base to allow this coupling (Bishara & Trulove, 1990). The strength of the silane bond to the silica base of the bracket is stronger than the enamel bond to the resin, which forces the bond failure into the enamel resin interface, a less desirable clinical outcome, increasing the risk for failure within the enamel itself (Bishara and Trulove, 1990; Habibi et al., 2007; Kitahara-Céia et al., 2008).

Many of the early reports of silane modified ceramic brackets confirmed a clinical finding of greater bond strengths than necessary and an increase in enamel damage during bracket removal. Most literature reports higher bond strengths for chemically retained brackets than mechanically retained ceramic brackets (Bordeaux et al., 1994; Wang et al., 1997; Kusy, 2002; Russell, 2005; Habibi et al., 2007; Ozcan et al., 2008), though one study by Merrill et al. (1994) reported no significant difference between chemically retained and mechanically retained brackets. The risk of damage to teeth has even led some researchers to examine the method of debonding brackets, looking toward lasers, chemical treatments, ultrasonic instruments, and electrothermal treatments to facilitate the process without damaging teeth (Bishara and Trulove, 1990; Chen et al., 2007). Others theorize that changing the enamel treatment with different etching techniques may help avoid enamel damage (Britton et al., 1990).

The clinical drawbacks discussed above have led to a change in ceramic bracket design, particularly in the method of retention used in the bracket base (Chen et al., 2007). While some studies report mechanical retention and associate weak bonds in the earliest ceramic brackets (Odegaard & Segner, 1988), most studies report that early ceramic brackets quickly moved to use of the silane coupler to produce the chemical retention described above (Bishara and Trulove, 1990). The increased iatrogenic damage necessitated a redesign in retention, with a later move to mechanical retention features in the base of the bracket. One attempt to decrease the bond strength involved the attachment of a flexible polycarbonate base to the bracket wings, but this decreased the bond strength too dramatically to be clinically useful (Olsen et al., 1997; Bishara et al., 1999). The incorporation of a metal insert in the slot of the ceramic brackets was an attempt to increase the resistance to fracture when applying force to remove brackets (Bishara et al., 1999). One of the advantages of the metal insert was a decrease in friction between the archwire and the bracket (Bishara et al., 1997; Chen et al., 2007). Manufacturers then started making grooves and slots in the bases of the brackets to increase surface area available for mechanical interlocking (Bordeaux et al., 1994). More recent developments have resulted in base designs that include mechanical ball base, dimpled, and silane coated buttons (Chen et al., 2007; Russell, 2005). The apparent roughness of these designs is readily visible to the naked eye on the base of the brackets.

Previous studies comparing chemically and mechanically retained ceramic brackets found a significant difference in failure pattern between the two retention types. The chemically retained brackets showed the silane layer reinforced the adhesive, which fractures at a higher level than the enamel, and thus were more likely to result in enamel failures during debond. The mechanically retained brackets without silane treatment minimized enamel fracture and increased the amount of adhesive remaining on the tooth after debond (Harris et al., 1992; Eliades et al., 1993). Recent literature reports that even mechanically retained ceramic brackets have greater bond strengths than metal brackets (Reddy et al., 2013). In an evaluation of the bond strength of ceramic brackets to glazed aluminous and fluorapatite ceramics, it was found that bead base ceramic brackets, a mechanical retention design, showed the highest shear bond strength of the brackets studied (Kukiattrakoon and Samruajbenjakul, 2010).

In further attempts to improve the debond performance of ceramic brackets, 3M Unitek (Monrovia, CA) added a vertical slot to the base of their polycrystalline alumina Clarity bracket to encourage a predictable bracket failure that would eliminate excess stress during debond (Bishara et al., 1997; Liu et al., 2005; Chen et al., 2007). The more recent version of the bracket is the Clarity Advanced, which no longer has a metal insert in the bracket slot, but still incorporates the vertical score line in the base for easy debonding. The manufacturer of the Clarity Advanced brackets, like many others, have specific instructions detailing the recommended method for debonding their brackets, and claim that the specific pliers designed for debonding change the direction of stress on the enamel, making it safer for the tooth (Viazis et al., 1990; Theodorakopoulou et al., 2004). They also warn against bonding the ceramic brackets to any compromised teeth with large restorations. The bracket is claimed to use a smaller grain crystal than the original Clarity (with metal inserts) when making the injection molded brackets, contributing to increased strength, and allowing for a smaller bracket. Retention is achieved via a microcrystalline mechanical-locking bonding surface which appears as roughness to the naked eye (3M Unitek, 2014). While there are reports in published literature about the Clarity brackets with metal inserts, there have been few, if any, publications that tested the Clarity Advanced brackets.

Another new ceramic bracket that has little published data is the Avex CX from Opal Orthodontics (South Jordan, UT). This bracket is also made of polycrystalline aluminum oxide, and the manufacturer cites a unique surface treatment or roughening of the bonding pads along with retention grooves to provide mechanical retention and safe debonds (Opal Orthodontics, 2014). The surface treatment appears as two elliptical grooves cut into the base of the bracket oriented in an occlusal-gingival direction. They also note an increased shoulder between the wings of the bracket, which increases strength and decreases the chance of fracture during debonding (Opal Orthodontics, 2014). They do not have a specific instrument made to debond the brackets, a notable difference from the Clarity Advanced brackets.

The difference in debond technique makes a comparison in bond strength difficult as the Clarity Advanced brackets are designed to purposely fail in the middle and the Avex CX brackets are designed to be removed as one piece without failure. Most study designs test the shear bond strength with a Universal Testing Machine, thereby making it the standard method of evaluating the bond strength (Chen et al., 2007; Finnema et al., 2010). Some studies have examined the debond strength when using different pliers, which may provide more insight to their clinical performance (Bishara et al., 1999, Chen et al., 2007).

# CHAPTER 3
# MATERIALS AND METHODS

This study compared the shear debond strengths of the Victory series metal brackets (3M Unitek, Monrovia, CA), Clarity Advanced ceramic brackets (3M Unitek, Monrovia, CA), and Avex CX ceramic brackets (Opal Orthodontics, South Jordan, UT). Each of the three groups had a sample size of fifteen brackets. A photo of the brackets used is shown in Figure 1 from the labial surface and in Figure 2 from the bracket base.

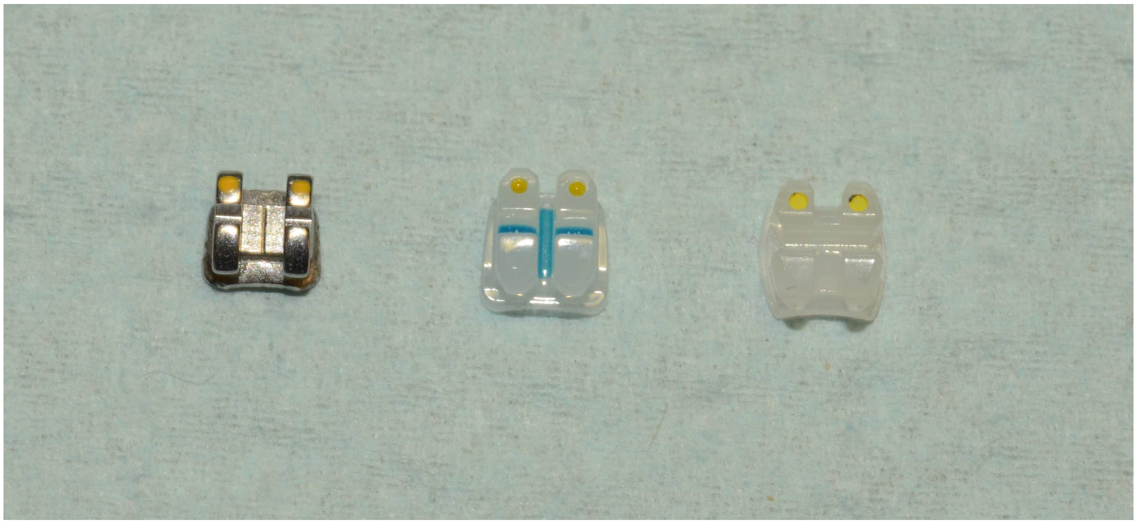

Figure 1: View of the labial surface of brackets used in this study from left to right: Victory Series, Clarity Advanced, and Avex CX.

Forty-five extracted human premolars that had been previously collected (use in this study was approved without submission of an IRB Application for Human Subjects Research as determined by the Marquette University Institutional Review Board on 7-12-2013) and stored in distilled water were randomly assigned to each of the three groups. The teeth were inspected and showed no signs of enamel irregularities or previous bonding on their facial surfaces.

Brackets were bonded according to the Opal Orthodontics protocol, using their etchant (Opal Etch), bonding agent (Opal Seal), and cement (Opal Bond MV). Each tooth was pumiced for 10 seconds with oil free and fluoride free pumice, then rinsed and dried with oil free air. Teeth were etched with 37% phosphoric acid on their facial surface for 20 seconds, then rinsed for 15 seconds and air dried with oil free air. The teeth were air dried, and a chalky appearance of etched enamel was verified. Next, a thin layer of Opal Seal was painted onto the base of the bracket and the etched surface of the tooth and thinned with a gentle stream of air. Opal Bond MV was applied to the base of each bracket, which was positioned in the middle of the facial surface of the tooth, and all flash was removed before curing with an LED curing light for 10 seconds.

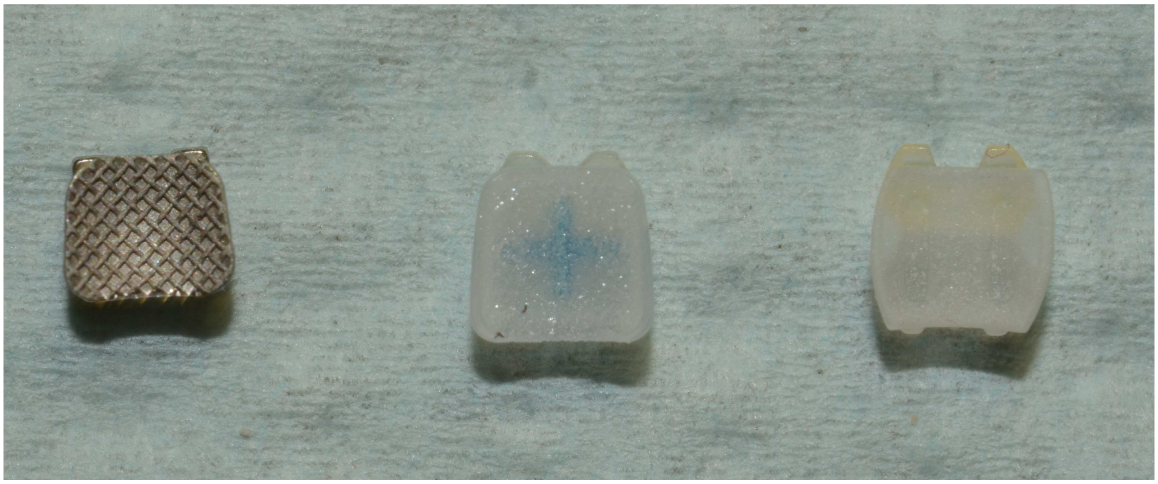

Figure 2: View of bracket base of the brackets used from left to right: Victory Series, Clarity Advanced, and Avex CX. Note the surface texture and vertical score line of the Clarity Advanced and the retention grooves of the Avex CX.

Bonded teeth were stored for 24 hours in distilled water before mounting them in acrylic blocks. Each tooth was suspended in the center of a PVC cylinder by a wire tied in the bracket slot, then mounting acrylic was added to cover the greatest convexity of the tooth, leaving the bracket and facial tooth surface exposed. Photos of the setup and a mounted tooth are seen in Figures 3 and 4, respectively.

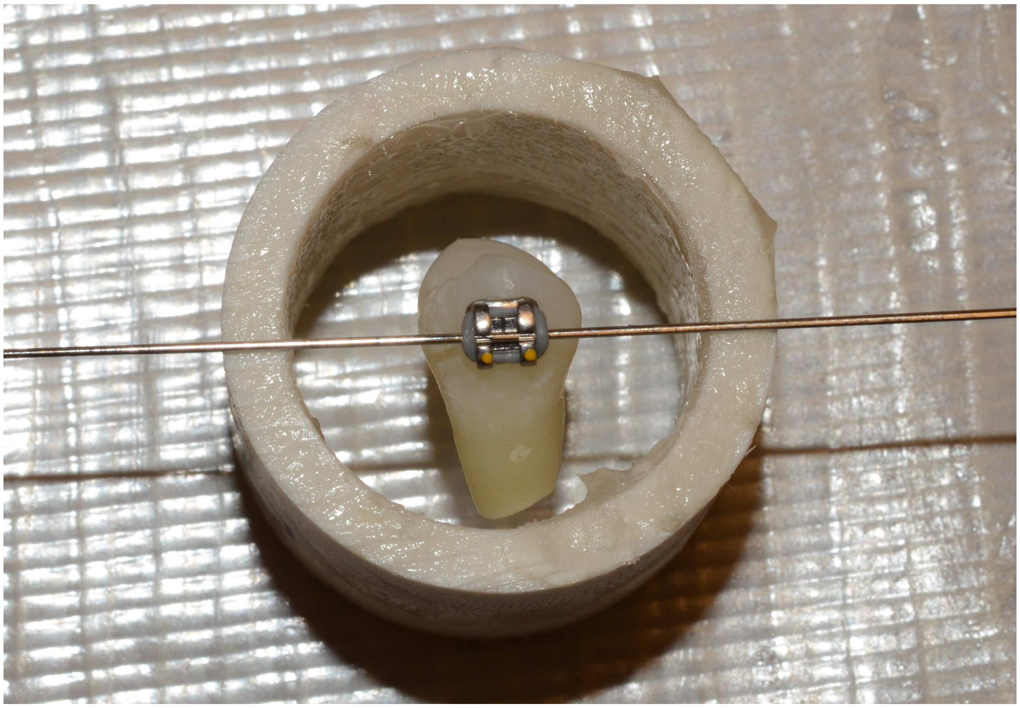

Figure 3: Bonded tooth suspended in a PVC cylinder before adding acrylic.

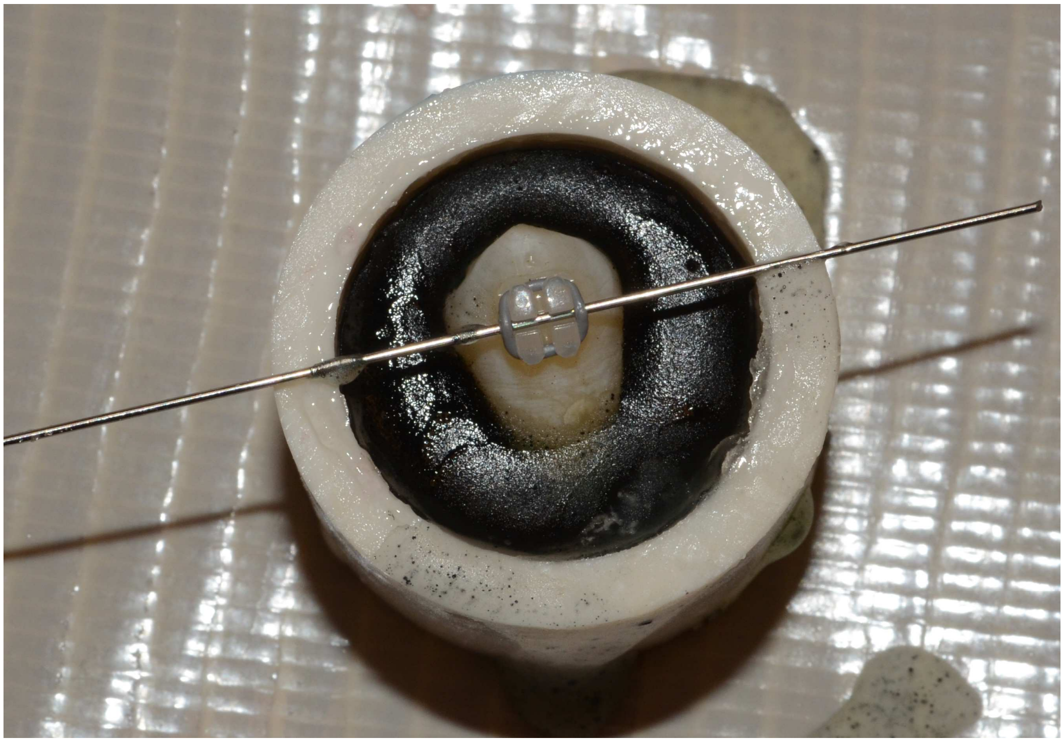

Figure 4: Sample of a freshly mounted sample in the PVC cylinder with acrylic covering the height of contour.

After mounting, teeth were again stored in distilled water at 37 degrees Celsius for 24 hours before debonding. Teeth were debonded with a Universal Testing Machine (Instron Corporation, Canton, MA). Each cylinder was mounted with the bonded surface parallel to the cutting blade of the machine, which is depicted in Figure 5. The blade was positioned to debond in the mesial distal direction at the tooth-adhesive interface as seen in Figure 6 with a crosshead speed of 0.1 mm per minute. The maximum force before debond was recorded for each sample and results are depicted in Figure 7. Teeth and brackets were then examined under 10x magnification after debond and an adhesive remnant index (ARI) score was recorded for each.

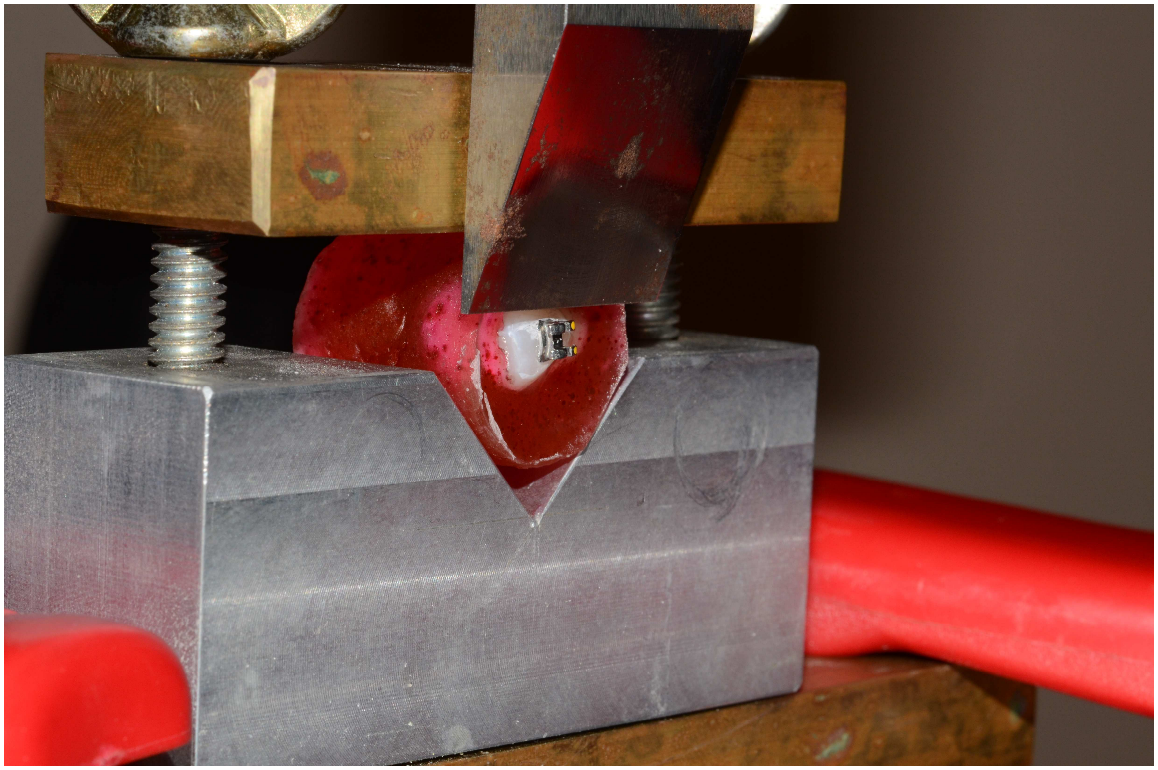

Figure 5: View of the blade of the Instron machine paralleled to the surface of the tooth at the bracket to tooth interface.

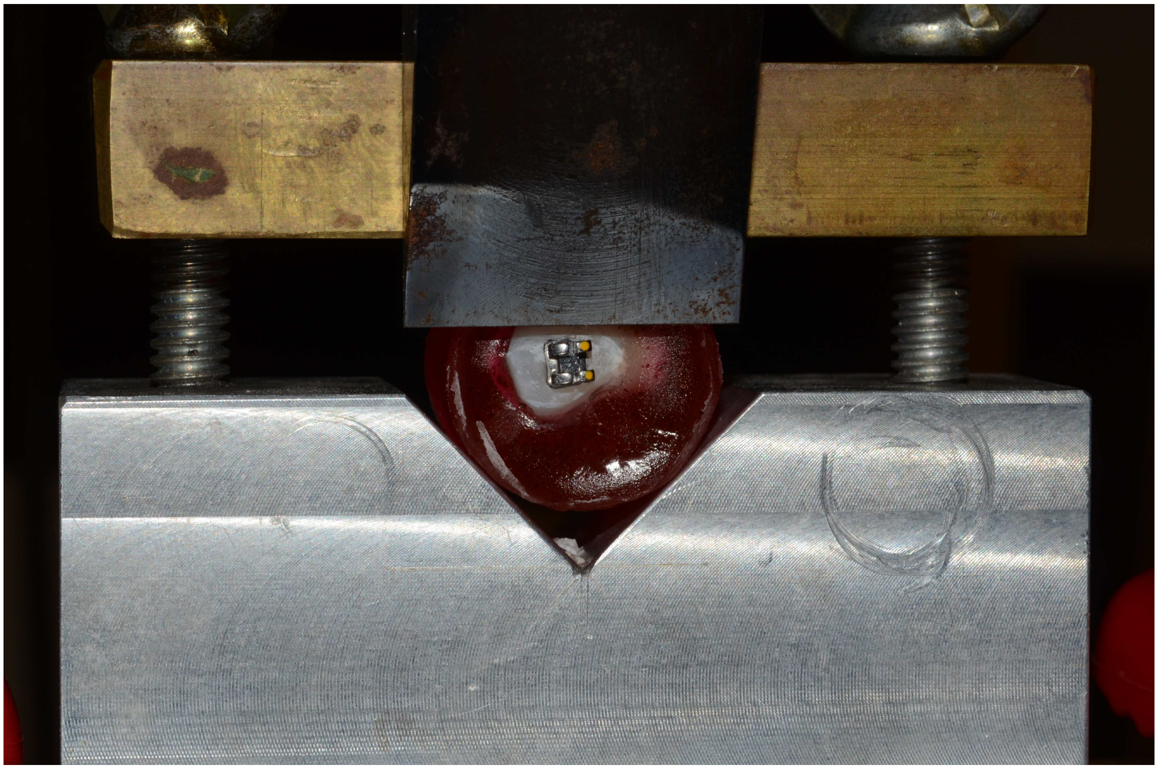

Figure 6: View of the Instron machine with the blade positioned to debond in a mesial distal direction.

Collected data was analyzed using a one way ANOVA to determine significance of shear bond strength values. The Tukey’s post hoc test was used to determine which groups were statistically different from the ANOVA test. The Kruskal-Wallis test was used to analyze the ARI scores and determine significance. The post hoc analysis used the Mann-Whitney test to determine which groups were different. A Weibull analysis was also completed to predict the probability of failure of each group.

# CHAPTER 4
# RESULTS

Of the 45 brackets that were debonded, there was one enamel fracture noted with the Avex CX bracket. The shear bond strength for this bracket specimen was not used for statistical analysis because the bracket itself was still bonded to the tooth. Two Clarity Advanced brackets fractured in a manner that varied from the intended fracture along the vertical scribe line. All of the other Clarity Advanced brackets either debonded as a single piece or one half of the bracket debonded up to the vertical scribe line, leaving the other half of the bracket still attached to the tooth. The remaining Victory and Avex CX brackets were debonded intact.

The force values of each bracket were measured in kgf and multiplied by the acceleration of gravity for a force value in N. The maximum force recorded for each sample is depicted in Figure 7. The kgf values are reported in Table 1 and the converted values are reported in Table 2. The average value for the Victory series was 199.4 N ± 77.4 N; the Clarity Advanced was 136.0 N ± 33.4 N, the Avex CX was 178.7 N ± 32.6 N, which are shown in Table 3. A one way ANOVA test was used to determine if any of these values were significantly different from one another and returned a test statistic of F=5.611 and a p value of 0.007. The Tukey's post hoc test results are detailed in Table 4 and determined the Victory Series to be significantly different from the Clarity Advanced group.

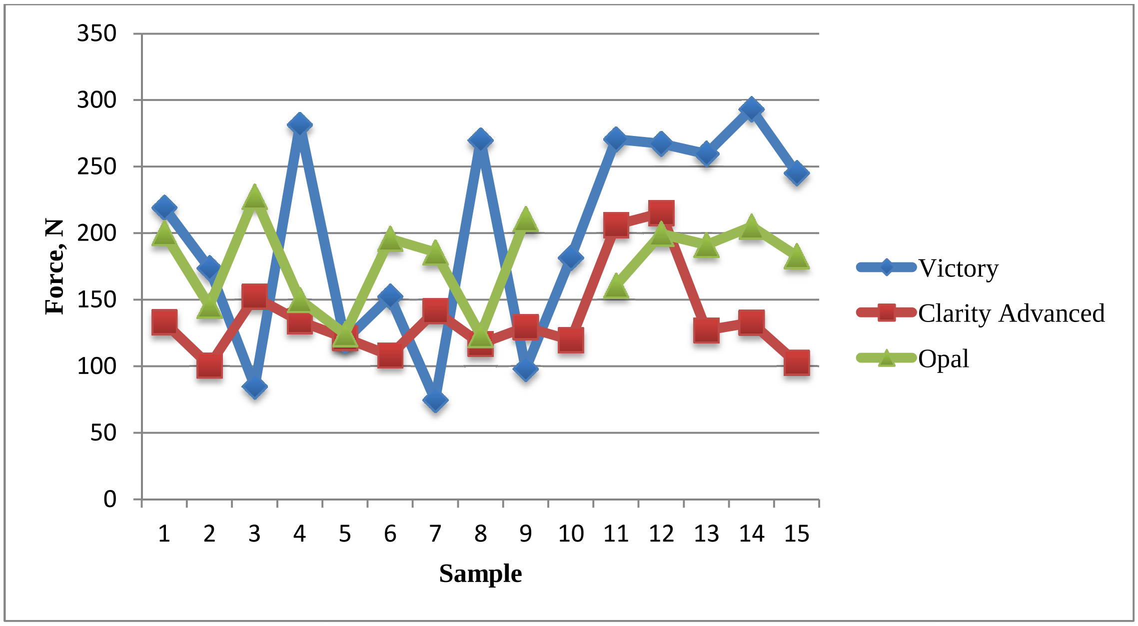

Figure 7: Maximum force level at debond

Table 1: Shear bond strength values (kgf)

| | Victory Series | Clarity Advanced | Avex CX |
|---|---|---|---|
| Max kgf | 22.37 | 13.58 | 20.42 |
| | 17.73 | 10.26 | 14.84 |
| | 8.66 | 15.53 | 23.21 |
| | 28.72 | 13.66 | 15.29 |
| | 12.17 | 12.37 | 12.66 |
| | 15.55 | 11.04 | 19.99 |
| | 7.62 | 14.44 | 18.95 |
| | 27.53 | 11.93 | 12.6 |
| | 10 | 13.2 | 21.5 |
| | 18.52 | 12.21 | Enamel Fracture |
| | 27.61 | 21.03 | 16.39 |
| | 27.27 | 21.96 | 20.36 |
| | 26.5 | 12.96 | 19.51 |
| | 29.92 | 13.55 | 20.91 |
| | 25.02 | 10.47 | 18.65 |
| Average | 20.35 | 13.88 | 18.23 |
| St. Dev. | 7.94 | 3.41 | 3.32 |

Table 2: Shear bond strength values converted to Newtons (N)

| **N** | **Victory** | **Clarity Advanced** | **Opal** |
|---|---|---|---|
| 1 | 219.2 | 133.1 | 200.1 |
| 2 | 173.8 | 100.5 | 145.4 |
| 3 | 84.9 | 152.2 | 227.5 |
| 4 | 281.5 | 133.9 | 149.8 |
| 5 | 119.3 | 121.2 | 124.1 |
| 6 | 152.4 | 108.2 | 195.9 |
| 7 | 74.7 | 141.5 | 185.7 |
| 8 | 269.8 | 116.9 | 123.5 |
| 9 | 98 | 129.4 | 210.7 |
| 10 | 181.5 | 119.7 | Enamel fx |
| 11 | 270.6 | 206.1 | 160.6 |
| 12 | 267.2 | 215.2 | 199.5 |
| 13 | 259.7 | 127.0 | 191.2 |
| 14 | 293.2 | 132.8 | 204.9 |
| 15 | 245.2 | 102.6 | 182.8 |
| | | | |
| Avg | **199.4** | **136.0** | **178.7** |
| St. Dev. | **77.9** | **33.4** | **32.6** |

Table 3: Statistical description of data in Newtons (N)

| Group | Bond Strength (N) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | Mean | Std. Dev. | Std. Error | Lower Bound | Upper Bound | Min. | Max. | Range |
| Victory | 15 | 199 | 78 | 20 | 156 | 243 | 75 | 293 | 218 |
| Clarity Advanced | 15 | 136 | 33 | 8.6 | 118 | 155 | 101 | 215 | 114 |
| Avex CX | 14 | 178 | 33 | 8.7 | 160 | 198 | 123 | 227 | 104 |
| Total | 44 | 171 | 58 | 8.7 | 154 | 189 | 75 | 293 | 218 |

Table 4: Tukey's post hoc summary, *significantly different groups

| (I) Group | (J) Group | Mean Difference (I-J) | Std. Error | Sig. | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower Bound | Upper Bound |
| Victory Series | Clarity Advanced | 63.37333 | 19.27745 | *0.006 | 16.4973 | 110.2494 |
| | Avex CX | 20.6948 | 19.61867 | 0.547 | -27.011 | 68.4006 |
| Clarity Advanced | Victory Series | -63.37333 | 19.27745 | *0.006 | -110.2494 | -16.4973 |
| | Avex CX | -42.67853 | 19.61867 | 0.088 | -90.3843 | 5.0272 |
| Avex CX | Victory Series | -20.6948 | 19.61867 | 0.547 | -68.4006 | 27.011 |
| | Clarity Advanced | 42.67853 | 19.61867 | 0.088 | -5.0272 | 90.3843 |

The average ARI score for the Victory series was 1.00 ± 0; the Clarity Advanced was 2.07 ± 0.26; the Avex CX was 1.86 ± 0.36, as depicted in Table 6. The Kruskal-Wallis test was used to determine if any groups were significantly different. A post hoc analysis was performed using the Mann-Whitney test, and found the Victory series to be significantly different from both the Clarity Advanced and the Avex CX with a p value of <0.0001, summarized in Table 7. The Clarity Advanced and the Avex CX were not significantly different from each other. A Weibull analysis was completed for the data sets to determine the probability of failure at increasing force levels. A summary of the Weibull test is given in Table 8, followed by a graph depicting the predicted failure probability in Figure 8.

Table 5: Adhesive Remnant Index (ARI) Scores by group

| **Group** | **ARI Scores*** | | | |
|---|---|---|---|---|
| | **0** | **1** | **2** | **3** |
| Victory | 0 | 15 | 0 | 0 |
| Clarity Advanced | 0 | 0 | 14 | 1 |
| Opal | 0 | 2 | 12 | 0 |

Table 6: Average ARI scores of each group and the calculated p-value from ANOVA analysis

| | Mean | p-value |
|---|---|---|
| Group | | <0.0001 |
| Victory | 1.00 ± 0 | |
| Avex CX | 1.86 ± 0.36 | |
| Clarity Advanced | 2.07 ± 0.26 | |

Table 7: Multiple comparison p-values via the Mann-Whitney test

| | p-value |
|---|---|
| Clarity Advanced vs. Avex CX | 0.0829 |
| Avex CX vs. Victory | <0.0001 |
| Clarity Advanced vs. Victory | <0.0001 |

Table 8: Weibull Modulus and characteristic strength results

| Group | Weibull modulus ($\beta$) | Characteristic Strength ($\alpha$; N) | Shear Bond Strength (N) at 10% Probability of Failure | Shear Bond Strength (N) at 90% Probability of Failure |
|---|---|---|---|---|
| Victory | 2.19 | 228 | 82 | 334 |
| Clarity Advanced | 3.99 | 148 | 84 | 182 |
| Opal | 5.24 | 193 | 126 | 226 |

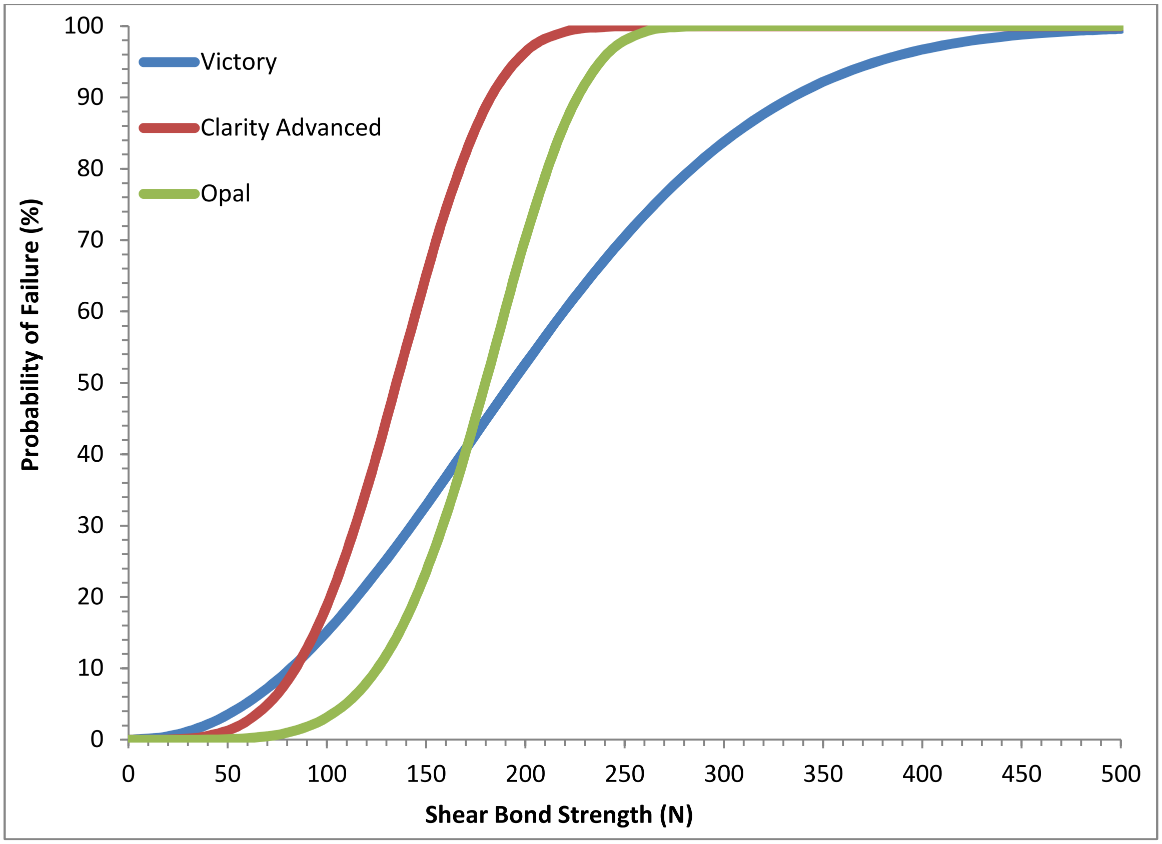

Figure 8: Weibull probability of failure

# CHAPTER 5
# DISCUSSION

Ceramic brackets are now the most commonly used esthetic bracket, after previous attempts with polycarbonate materials proved inadequate for clinical use. The original concern with ceramic brackets was a bond strength that exceeded the strength of the enamel to which they were bonded, creating a risk for damage to teeth during bracket removal. This problem led to iatrogenic enamel fractures during debond (Bordeaux et al., 1994). Continuing research has led to a change in the retention design of many ceramic brackets, moving in the direction of mechanical retention rather than chemical. Some manufacturers still combine mechanical and chemical, but the chemical treatment with a silane coupler is usually performed only on part of the bracket.

Manufacturers have also modified the debond technique and some companies, such as 3M Unitek and American Orthodontics, have designed pliers specifically for ceramic bracket removal. The testing that was performed on the brackets in this study was a shear bond test, the industry standard for bond strength testing, though it does not mimic the clinical debond technique recommended by the manufacturer (Finnema et al., 2010). The 3M Unitek plier advised for use with the Clarity Advanced bracket has two beaks that reach around the mesial and distal tie wings of the bracket with a vertical piece of metal that fits between the wings. Upon squeezing the plier and thus the bracket in a mesial-distal direction, the bracket fails in the midline and the two halves of the bracket peel off the tooth. This unique failure design was noted during the shear debond test, as many of the brackets failed in the middle, leaving the other half of the bracket attached to the tooth. While this does not accurately reproduce what happens clinically, it can still give us an idea of the strength of the bond.

Opal Orthodontics recommends first removing all adhesive flash with a high speed handpiece, then using a Weingart plier to gently squeeze the Avex CX bracket in a mesial distal direction, while rocking gently until the bracket releases. It was noted all of the brackets that were debonded in the Avex CX group were debonded intact, without fracture. The unique retention grooves that were cut in the base of the bracket were often filled with adhesive resin, while the adhesive that was sandwiched between the tooth and the flat surfaces of the base often remained on the tooth.

There is a notably large standard deviation within the Victory Series group, which has not been reported in other studies. The large variation in bond strength could be the result of inconsistent blade placement prior to debond. The blade was placed at the bracket tooth interface, and because the metal brackets have a much thinner base than the ceramic brackets, it is conceivable that blade placement may not have been as consistent with the metal brackets. If the blade deviated from this interface, it may have caused the base to deform more easily. Another possible contributing factor to this variability is a difference in bonding protocol. The protocol followed for this study involved coating the base of the bracket with primer before adding the adhesive resin. This is not the standard protocol used with metal brackets, which are usually bonded after applying the adhesive resin directly to the bracket pad. It is also of interest that the metal brackets all had an adhesive remnant index (ARI) score of 1, which means that a majority of the adhesive remained on the bracket. This is different than what is viewed clinically, when the entire imprint of the base of the bracket can often be seen in the adhesive resin that remains on the tooth. This score would also suggest that the weakest part of the bond was between the adhesive resin and the tooth. Previous studies including the Victory series and original Clarity bracket in a shear bond test showed average ARI scores of 3, which is different than the findings of the current study, possibly due to differences in etching time, adhesive, or crosshead speed used during debond (Soderquist et al., 2006). The slow crosshead speed used in this study may not be indicative of the faster loads applied clinically, which is a consideration for further research (Viazis et al., 1990). Both ceramic brackets had average ARI scores closer to 2, which made them statistically different from the Victory Series metal bracket. A score of 2 also means that more of the adhesive resin was left on the tooth than the bracket, suggesting the weakest point of the bond was between the bracket and the adhesive. Previous chemically bonded ceramic brackets had a very strong bond between the adhesive resin and the bracket, forcing the failure to occur at the tooth surface (Viazis et al., 1990). This testing shows that mechanically retained brackets significantly decrease the risk of enamel damage by creating a weaker bond between the adhesive and the bracket.

The study reports the shear bond strength in Newtons, a unit of force. Most studies report the shear bond strength in MPa, which takes into account the surface area of the base of the bracket (Finnema et al., 2010). Because of the unknown value of the surface area and the inability of the clinician to change this parameter of the bracket, the force alone, which is the concern of the clinician, has been reported. Another concern was the micromechanical nature of the base of the bracket, and the ability to accurately calculate the surface area of the base of each bracket used. A rough calculation of the average forces recorded for each sample using bracket sizes reported in other studies resulted in MPa values ranging from 13.6 MPa to 19.9 MPa . These estimates show the shear bond strength of all brackets in this study meet the minimum values of clinical acceptability, previously determined to be 6-8 MPa, when estimating the bracket base to be 10 $mm^2$ (Habibi et al., 2007). The average shear bond strength of both ceramic groups is less than that of the Victory series stainless steel group used as a control, which suggests that mechanically retained ceramic brackets do not have an unacceptably high shear bond strength.

Another indication of safer ceramic brackets is the lower average shear bond strength calculated for both types of ceramic bracket. The Avex CX bracket had a lower bond strength than the Victory Series metal bracket and a higher bond strength than the Clarity Advanced. The smaller difference in bond strength between the Avex CX bracket and the Victory Series was statistically insignificant. While the difference between the Avex CX bracket and the Victory Series metal bracket is not statistically significant, the average bond strength of the Avex CX is lower than that of the Victory Series. While the average bond strength of the ceramic brackets was lower than metal, one enamel fracture was still noted in the Avex CX ceramic bracket group. The force had reached a level of 164 N before the enamel fractured. This force level is far less than the maximum values recorded for each group, which indicates that the tooth may have had a pre-existing flaw in the enamel that was not detected at the time of bonding. Due to the variability of possible causes of failure, this sample was not included in the calculations.

The Weibull analysis was performed to evaluate the reliability of each group. Higher Weibull modulus values are more favorable, and the results showed the Opal Avex CX group performed better than the others. The higher values of the Opal group can be seen in the graph presented in the results section. Mean values provide an overview of bracket performance, but clinicians may also be interested in the percentage of brackets that have a lower bond strength outside the mean, as these would be more likely to exhibit bond failures. Opal also performed better with a lower percentage of brackets exhibiting a low bond strength, without displaying an excessively high bond strength, which would also be undesirable.

# CHAPTER 6
# CONCLUSION

This study demonstrated the shear debond characteristics of newer generations of ceramic brackets have improved in safety compared to previously chemically bonded brackets. Not only has the shear debond force decreased to a level less than a commonly used metal bracket, but a cohesive bond failure was consistently demonstrated with more resin remaining on the tooth, suggesting the weaker point of the bond was located between the bracket and the adhesive resin. This study may increase the confidence of the clinician in using mechanically retained ceramic brackets, but the direct correlation is limited by the unique methods of debond employed by the clinician and recommended by the manufacturer. Further research on the clinical debond characteristics is needed to support the in vitro findings of this study. It is evident that limitations of the material toughness and the unique design of the bracket play a significant role in the debond process.

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