Fracture Resistance of Tie Wings of Ceramic Brackets Under Loading

by

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Objectives:

To determine if there a significant difference in fracture strength of tie wings of 1. Polycrystalline ceramic brackets, 2. Monocrystalline ceramic brackets, made by different manufactures.

Materials and Methods:

Sample: The mesial incisal tie wing of 9 brands of commonly used polycrystalline and 5 brands of mono crystalline brackets were tested for fracture strength. Each brand's sample consisted of 15 maxillary right central incisors brackets and 15 maxillary right lateral incisor brackets (.022 slot MBT).

Method: The brackets were bonded onto a ceramic slab. An Instron Universal testing machine was used to apply a vertical force on the mesial incisal wing of each bracket. The force at the point of tie wing fracture was recorded as the fracture strength.

Results:

Polycrystalline brackets: Ormco Symmetri (301.03 N ± 36.56), 3M Clarity (203.55 N ± 36.56) and Forestadent Glam (196.06 N ± 68.84) were the strongest, with no significant difference between them. Dentsply Ovation C was the next strongest (175.87 N ± 48.25).

Henry Schein NeoLucent Plus (119.74 N ± 21.06), Ortho Tech Ref Ceramic (107.53 N ± 51.07), TP Clear Vu (106.17 N ± 27.43), AO Cosmetic (88.52 ± 50.67) and RMO Signature III (84.99 ± 42.30) were the least strong, with no significant differences between them.

Monocrystalline brackets: AO Radiance Plus (262.42 N ± 110.42), Ormco Inspire ICE (240.48 N ± 78.51) Henry Schein NeoCrystal Plus (221.80 N ± 42.07), Ortho Tech PURE (210.66 N ± 42.07) were the strongest, with no significant differences between them, while Dentsply Ovation S (55.80 N ± 13.04) was the weakest.

Conclusions:

There are significant differences in the fracture strength of various brands, both amongst polycrystalline and monocrystalline brackets.

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PREFACE

I would like to thank my thesis committee consisting of Dr. Varun Kalra, Dr. John Burnheimer, Dr. Alejandro Almarza, and Dr, Nilesh Shah for their generous support and guidance. With special gratitude to my major advisor Dr. Varun Kalra, thank you for believing in me and allowing me the opportunity to pursue my thesis. Your knowledge and dedication to the residents are much appreciated!

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1.0 INTRODUCTION

With a trend towards orthodontic treatment with visually less noticeable appliances, the use of ceramic brackets has gained in popularity. Although the number of brands of ceramic brackets offered by manufacturers has increased significantly, a major drawback of ceramic brackets i.e. fracture of tie wings during treatment still persists.

All ceramic brackets are made of aluminum oxide (AL_2O_3) (Swartz 1988, Viazis et al 1993, Karamouzos et al 1997). There are two types of ceramic brackets available, polycrystalline and monocrystalline. Polycrystalline brackets are made by blending aluminum oxide with a binder and molding the mixture into the desired bracket shape. Temperatures above 1800º C are used to burn out the binder and fuse the alumina particles which are about 0.3 micron in size into ceramic grains of 20-30 microns. The fused product is then machined with diamond cutting tools to achieve the final slot dimensions and other details. The machined bracket is then heat-treated to remove surface imperfections and relieve stresses generated by the cutting process (Swartz 1988). The advantage of molding polycrystalline brackets is that they are easier to make and less expensive. The disadvantages of the molding process are the presence of imperfection at grain boundaries and the possible inclusion of minute amounts of impurities, both of which can lead to crack propagation and fracture (Swartz 1988). In addition, because of the refraction of light at the grain boundaries polycrystalline brackets are not as clear as monocrystalline brackets.

Monocrystalline brackets are made by a different process altogether, and as the name implies, they are made from a single man-made sapphire crystal. The process involves heating a molten mass of aluminum oxide at 2100º C and then cooling it in a controlled fashion to produce a single large crystal. These large crystals in the shape of rods are then milled with demanding cutting techniques into the precise bracket shape and dimensions. The machined bracket is then heat-treated to remove surface imperfections and relieve stresses generated by the cutting process (Swartz 1988). The advantage of monocrystalline brackets is the lack of inclusion of impurities and also greater optical clarity due to lack of grain boundaries. The disadvantage is increased difficulty and cost of manufacture. Also, the visual appeal of translucent polycrystalline brackets or clear, glass-like appearance of monocrystalline brackets may be a matter of personal choice.

Ceramic brackets have a definite advantage over metal brackets in terms of decreased visibility. However, one of the distinct disadvantages of ceramic brackets is their brittle nature. The fracture toughness of a material is the total loading energy needed to cause its failure. The fracture toughness values for ceramics is 20 to 40 times less than that for stainless steel (Scott 1988, Swartz 1988, Viazis et al 1993). When stress is applied on a metal, grain boundaries shift, which redistributes and relieves the stress. This shifting of atomic bonds and redistribution of stresses does not occur in ceramics; therefore, they are more brittle and fracture more easily (Scott 1988, Karamouzos et al 1997, Johnson et al 2005). Porosity, inclusion of impurities, cracks, presence of localized stresses and scratches, inadequate heat treatment, improper design and material can all lead to decreased fracture resistance of ceramic brackets. Therefore, to compare fracture resistance of ceramic brackets, individual brands of ceramic brackets produced by different manufacturers, not materials need to be compared (Holt et al 1991).

Previous studies on fracture resistance of ceramic brackets have tested failure due to forces or moments generated by tipping, torsion, shear or impact (Lindauer et al 1994, Holt et al 1991, Rhodes et al 1992, Aknin et al 1996, Johnson et al 2005, Flores et al 1990, Sanchez et al 2008, Matasa et al 1999). A study in 2002 (Wilbur) tested the fracture resistance of tie wings of ceramic brackets by a force applied directly on the wing. However, in the 18 years since then there have been many improvements and refinements in manufacturing processes as well as bracket design. Moreover, several new brands have been introduced, in fact only 1of the 9 brands that were tested in that study exists. Since fracture of tie wings during use continues to be a prevalent problem, it was decided to conduct a study to compare the fracture resistance of tie wings of ceramic brackets under the loading of various brands produced by different manufacturers.

1.1 PROPERTIES OF CERAMIC BRACKETS

While all ceramic brackets are composed of aluminum oxide, two types of ceramic brackets exist: monocrystalline and polycrystalline aluminum oxide. The main visual difference between monocrystalline and polycrystalline ceramic bracket is the translucency. The physical properties of ceramic orthodontic brackets are dependent on the material and manufacture process.

The polycrystalline bracket formation process is more common and less expensive compared to single-crystal bracket production. After the molded mixture is created by blending aluminum oxide particles with a blender, the mixture is heated to a temperature above 1800 Celsius to fuse the grain particles by the injection-molding or extrusion technique. The fused part then undergoes a machining process with diamond cutting tools to achieve the final bracket design. Finally, the machined bracket finishes with heat treatment to remove any surface imperfection and impurities as well as relieving stress that may have been created during the cutting process (Swartz 1988).

The size of aluminum oxide particles mentioned earlier plays a critical role in optical clarity and the strength for polycrystalline ceramics (Soni et al 1995). Before the mixture stage, aluminum oxide particles have an average size of 0.3 microns. When the particles fuse after the blender phase, ceramic grains fuse to size of 20-30 microns. Higher optical translucency can be achieved with larger ceramic particles. However, the strength of the ceramic follows an opposite pattern as higher strength will be achieved when the particles are smaller. Therefore, the last heat treatment step should be carried out with meticulous care to prevent further fusion of particles, which will have a deleterious effect on the strength of the ceramic (Swartz 1988).

For monocrystalline brackets, the manufacturing process begins with producing the single crystal through crystallization that occurs by heating the mass above a temperature of 2100 Celsius followed by a controlled cooling process. Then the single-crystal gets sculpted by diamond cutting or ultrasonic cutting techniques. Like the polycrystalline crystals, monocrystalline ceramics gets finished with heat treatment to remove the microscopic surface. (Swartz 1988)

Compared to the polycrystalline alumina counterpart, single crystals lack two types of microstructural flaws. The first one is called a grain boundary that occurs at the junction of adjacent crystals. Another type of flaw called pore exists where void occurs in the structure of the ceramic due to the absence of an entire grain or grain fragment. When ceramic fractures, the fracture is likely to extend from the largest microstructural flaw present. In polycrystalline alumina, this could be a grain boundary, a pore, or a combination of the two (McColm 1983).

As mentioned, different physical properties of polycrystalline and monocrystalline contribute to how fracture occurs. Although single crystals are harder than polycrystalline ceramics, surface defects greatly decrease the strength of single crystals and only minimally affect polycrystalline ceramics (Flores et al 1990). Even topical fluoride agents can act as corrosive agents that can produce surface damage leading to a decrease in fracture strength of monocrystalline brackets (Sanchez et al 2008). This demonstrates that polycrystalline ceramics have higher fracture toughness because crack propagation occurs more slowly as crack interacts with the grain boundaries. In contrast, single crystals, lacking those grain boundaries, fracture uniformly all at once (Flores et al 1990).

1.2 FRACTURE OF CERAMIC BRACKETS

1.2.1 REASONS FOR FRACTURE

Additional to how ceramics are made, the innate physical properties of ceramics explain how the fracture propagation occurs. The physical property of ceramic is a result of their atomic bonding (Birnie 1990) as ceramic are primarily bond together with an ionic and covalent bond. Ionic bond forms when a metal atom gives up its valence electron to the outer shell of a non-mental atom, resulting in positive and negative ions that attract each other. A covalent bond, the strongest type, occurs when atoms of the same element nor different elements share electrons (Kingery et al 1976). Metallic bonding allows significant distortion without fracture even when significant compositional impurities exist (Karamouzos et al 1997) When stress is placed on a metal, grain boundaries shift, which redistributes and relieves the stress. In the ceramic atomic arrangement, shifting atomic bonds and redistribution of stress does not occur. Therefore, ceramics are much more brittle and have much lower tensile strength than metal (Scott 1988, Karamouzos et al 1997)

To further understand the difference in the fracture between metal and ceramic fracture property, several terms need to be defined. Yield strength is defined as the stress at which permanent deformation occurs in a material. Because of its brittle nature, yield strength is absent in ceramics. Modulus of elasticity is the slope of the stress and strain curve before the permanent deformation phase. Fracture strength is the stress at which the material fractures and does not return to its original shape. Fracture toughness, which measures the materials ability to resist fracture, is one of the main distinguishing factors for ceramics compared to metals (Scott and Tomlinson 1984) Single-crystal has significantly less fracture toughness compared to stainless steel. Also, the amount of deformation or strain has contrasting values. For stainless steel the strain reaches almost 17% to 18% compared to less than 1% for ceramics. Typical values of fracture toughen for single crystals and polycrystalline alumina are reported to be 2.4 - 4.5 MPa$\sqrt{M}$ and 3.0 - 5.3 5 MPa$\sqrt{M}$ respectively. Stainless steel has a much higher fracture toughness value of 80 – 95 MPa$\sqrt{M}$ (Iwasa and Brandt 1986). Another study also illustrated strong ceramic fracture toughness as ceramics had 20-40 times less fracture strength than that of stainless steel, demonstrating that it is much easier to fracture ceramics. (Hertzberg 1983)

Unlike metal, surface cracks and flaws of ceramics greatly reduce their fracture resistance. Because no plastic deformation occurs in ceramic materials, stresses at the tips of the cracks do not get relieved and lead to further crack propagation until a fracture occurs (Kusy 1988) Kusy derived the following equation to calculate the critical crack size that will lead to total fracture:

$$a = \frac{K_{IC}^2}{\pi \cdot \sigma_F^2} = 5.5\mu m$$

In the study, a scanning electron microscope (SEM) was used to analyze cleaved brackets and found that intergranular fracture indicated the interface between the particles is the weakest link. Several potential solutions were suggested in the study to increase the fracture strength such as decreasing the alumina particles to reduce total grain fragment pull-outs and reducing surface roughness by glazing the surface. Because shallow scratch on the surface of ceramic can jeopardize the fracture resistance of ceramics, an inspection of ceramic brackets for cracks at each patient visit should be part of a normal routine. Additionally, clinicians should try to avoid scratching a ceramic bracket surface during the ligation and advise patients to stay away from chewing hard substances (Kusy 1988)

1.2.2 CONTRIBUTIONS OF DESIGNS ON FRACTURE

The dimension and shape of ceramic brackets also play crucial roles in determining the fracture resistance of the brackets. According to Johnson et al, high fracture strength on torsion was noted on semi-twin ceramic brackets compared to real twin brackets. The higher fracture strength from semi-twin brackets was explained by the morphological difference of semi-twin having one combined structure of mesial and distal tie wings rather than two separate units that is seen in real twin ceramic brackets. Also, the study concluded that brackets with thicker dimensions tend to provide higher fracture strength compared to that of thinner ones. From the study done by Rhodes et al, out of the five bracket types tested, the only real twin bracket demonstrated the highest standard deviation and low fracture strength by second order movement. Therefore, the study suggested that fracture strength varies among different types of ceramic orthodontic brackets as the bracket design along with the manufacturing process may vary as well.

Ghosh et al evaluated the relationship between the ceramic bracket dimension and stress distribution using finite element analysis. After three-dimensional models of six brackets types were obtained using a vernier caliper accurate to 0.001 inch, the computer analysis provided stress distribution of the brackets when loaded with torsion and tipping necessary for fracture on a full-size stainless-steel archwire (0.0215-inch x 0.028-inch). The study found that the stress distribution was not uniform where there was a sudden change in the cross-section of the structure. Stresses were localized at corners and areas of abrupt change in the bracket shape. For torsional data, the maximum stress level was demonstrated to be almost half in brackets with beveled or rounded archwire slots compared to brackets with square base slot design. Also, lower stress values were reported when increased thickness of material was noted between the base of the arch wire slot and the tying slot.

1.2.3 FRACTURE DURING ROTATIONAL MOVEMENT

Second order movement occurs when the mesiodistal tipping force is applied on the tie wings of the bracket from the archwire to generate rotational movement of teeth. When excess force is applied to the tie wings, combined with the brittle nature of the ceramics and the localized stress concentration will lead to fracture of ceramic orthodontic brackets. Rhodes et al investigated the fracture resistance of ceramic brackets when second order tipping forces were applied on archwire through a specially designed apparatus. Four polycrystalline and one single-crystalline maxillary right central incisor twin brackets were tested and reported significant differences. The mean fracture force ranged between 301.3 to 648.7 g. High variability of fracture force, indicated by the high standard deviation, was explained by possible different manufacturing processes for the different brands. Gunn and Powers also studied the effect of mesial and distal tipping force on ceramic brackets and found the bracket fracture force ranged from 2400 to 3400 g, which was far different from the study values from Rhodes et al. This drastic difference can most possibly be explained by the failure to consider the distance components of total applied moment (Lindauer et al 1994). When the inter-bracket distance is smaller, brackets can tolerate higher second order forces which were noted in the study from Gunn and Powers. In the study from Lindauer et al, which accounted for the distance component, the mean second order tipping moment at fracture ranged between 15,905 to 35,291g-mm. The only monocrystalline bracket in Lindauer et al's study, Starfire TMB, fractured at lowest load level which was contrary to its initial expectation of higher fracture resistance due to its material property. This could be explained by the true twin bracket design, shown to have weaker fracture tolerance by Rhode et al, or by the surface impurities introduced previous or during the study. Lindauer et al also demonstrated that central incisor brackets have higher fracture resistance than that of lateral incisor brackets. The difference of the mesiodistal width of the bracket was the possible explanation for this finding. Overall, the study concluded that the second order forces produced clinically are much lower than the high fracture moment recorded from the study and are unlikely to cause a fracture.

1.2.4 FRACTURE DURING TORQUE

Although Lindauer et al suggested that clinical fractures from second order movements on ceramic brackets are improbable, the study mentioned the third order torqueing moments are more likely to cause ceramic bracket breakage in a clinical setting. Because the torque force act across the depth of the bracket, the couples of their moment are greater at the bracket wings.

In the study done by Holt et al, lingual root torque was applied to six types of 0.022-inch slot ceramic brackets on a full size 0.0215x 0.028-inch archwire. While five bracket types were semi-twin polycrystalline, Starfire TMB, the only monocrystalline bracket, was a real-twin bracket. From the torsional force, mean ceramic brackets fracture values ranged from 3,706 to 6,177 g-mm, which were higher than average torque required for physiological tooth movement ranging from 3000 to 3500 g-mm (Nikolai 1985). Although the only monocrystalline bracket, Starfire TMB, had the highest fracture strength, it had the most variation with a range of 3,301 to 9,682 g-mm.

Aknin et al also tested lingual torsional force on 0.022 slot maxillary brackets. Six polycrystalline brackets were semi-twin design. Starfire TMB, a single-crystal alumina, was a real-twin bracket. From the torsional force, mean polycrystalline ceramic brackets fracture occurred at values ranging 5,755 to 9,315 g-mm. The only monocrystalline bracket, Starfiire TMB, did not fracture in this study as the wire came out of the slot of the bracket. For the polycrystalline brackets that fractured, the predominant fracture site was noted to be the incisal tie wing.

From both studies from Holt et al and Aknin et al, torque values needed for fracture polycrystalline brackets were higher than the force needed for physiological tooth movement. The minimum fracture values from both studies, which are 3,706 g-mm and 5,755 g-mm, are higher than the highest value recommended to move teeth at 3500 g-mm. Therefore, one may assume torsional force applied clinically will not result in ceramic bracket fracture. However, clinicians tend to add more torque than needed due to the discrepancy between the wire and the bracket slot. Also, excessive torque rather than incremental adjustments may be added for faster and less chair time. According to Nikolai, torquing force over 5,000 g-mm can be produced when a 30-degree discrepancy between wire and slot exists. Therefore, orthodontists may be advised to add third order bends gradually in multiple visits to obtain the necessary torque in ceramic brackets and avoid adding high torque force on archwire that may result in a ceramic fracture.

1.2.5 FRACTURE DURING TENSILE FORCE

Johnson et al tested the fracture of seven ceramic brackets loaded with tensile forces on the tie wings. 0.014-inch steel wires were looped under the distoincisal tie wings of ten central incisor brackets for each brand. A tensile force was loaded with utilizing the Instron machine. While all six polycrystalline brands fractured with the tensile force, the only monocrystalline, Inspire, did not fracture as the steel ligature tie broke before any tie wings could fracture. Reported mean fracture strength for the six polycrystalline brands ranged from 84.28 MPa to 147.71 MPa.

Significant differences between those six polycrystalline brands were noted as well. Furthermore, semi-twin polycrystalline brands had significantly higher fracture strength than the real-twin polycrystalline brands. This was explained by the fact that the semi-twin design allows for a more stabilized structure as the mesial and distal wings are combined into a single unit rather than independent elements. In addition, brands with thinner tie wing dimensions labiogingivally demonstrated weaker fracture strength from the tensile load.

1.2.6 FRACTURE DURING RANDOM IMPACT

A random impact such as sports-related injury and biting objects can lead to fracture of ceramic brackets especially in the anterior teeth. Matasa tested the impact resistance of ten ceramic brackets by dropping a steel ball at a height of 50 inches to the center of the facial surfaces of the recycled brackets and analyzed the fracture using ophthalmic lens standards. From the nine polycrystalline brackets, eight were semi-twin design and one was a single tie wing design. The only monocrystalline bracket was a real twin design. Polycrystalline brackets with the semi-twin design were found to be superior in the fracture resistance as higher incidences of fracture occurred for the real twin and single tie wing design. The most common site of fracture was noted to be the interface between the base and the tie wing. The study concluded that the significant factors affecting the fracture resistance of ceramic brackets include the bracket design, material, and manufacturing process.

Wilbur’s study also tested the impact resistance of nine ceramic bracket brands but used a different method. Instron machine was used to load labial force on mesioincisal and distogingival tie wings of right maxillary central and lateral incisor brackets. The nine brands include 3 M Clarity, American 20/40, RMO Signature II, 3M Transcend, Ortho Organizer Illusion, RMO Luxi, Ormco Inspire, GAC Allure, and Masel Ecllipse. Significant differences in mean fracture strength were noted for various brands. 3M Clarity bracket had the strongest fracture strength of 253 N with a standard deviation of 86 N. The weakest brand was Masel Eclipse with a fracture strength of 94 N and a standard deviation of 38 N. This study did not support the claim from Matasa et al that brackets with semi-twin designs have higher fracture resistances than brackets with real-twin design. The strongest and the weakest brackets were both real twin design from Wilbur's study. Wilbur also found that significant differences exist in mesioincisal and distogingival tie wings. In general, mesioincisal tie wings were more prone to fracture than distogingival tie wings, which was demonstrated in six out of nine brands.

2.0 STATEMENT OF PURPOSE

Ceramic orthodontic brackets are more esthetic than metal brackets and increasingly preferred by patients. However, a major drawback of ceramic brackets is that due to their brittle nature they fracture more readily during use. The part of the bracket that fractures most often is the tie wing. Fracture of tie wings results in the replacement of the entire bracket which is time-consuming and inconvenient for the patient as well as the doctor. It can also lead to increased treatment time in braces and possible injury from swallowing or inhaling the broken fragments. There is no published data on the comparison of fracture strength of the tie wings of ceramic brackets currently available from various manufacturers.

The purpose of this study is to compare the fracture strength of currently available ceramic brackets during the loading of tie wings from various manufacturers. The results will help the practitioner choose a ceramic bracket that is strong and less likely to fracture during use.

The specific research questions that are addressed by this study are:

1. Is there a significant difference in fracture strength of polycrystalline ceramic made by different manufacturers?
2. Is there a significant difference in fracture strength of monocrystalline ceramic made by different manufacturers?

3.0 MATERIALS AND METHODS

As seen in Figures 1 and 2, fourteen different brands of brackets were tested. Nine brands were polycrystalline brackets, while five brands were monocrystalline brackets. A total of four hundred and twenty ceramic orthodontic brackets was tested in the study. Thirty brackets from fourteen manufacturers were tested. Each brand's sample was composed of fifteen maxillary right central incisors brackets and fifteen maxillary right lateral incisor brackets (.022 slot MBT). All mesioincsial wings were tested.

3.1 SPECIMEN PREPARATION

The brackets were bonded to ceramic slabs (3''x12'' ceramic tile) with 3M Transbond XT adhesive. Before bonding, the ceramic tile was treated with the Reliance Porcelain Bonding System according to the manufacturer's recommended protocol. After treating the ceramic tile with Reliance Porc-Etch phosphoric acid etchant for three minutes, the surface was thoroughly rinsed with water and dried with an air syringe. A generous coat of Reliance Porcelain conditioner (silane coupling agent) was then applied to the ceramic tile for one minute. A coat of 3M Transbond enamel primer was then applied to the ceramic tile surface and cured for ten seconds with an orthodontic curing light. 3M Transbond XT bonding adhesive was then applied to the base of the orthodontic bracket and the brackets were positioned and cured on the ceramic tile.

3.2 TESTING APPARATUS AND PROCEDURE

An Instron Universal testing machine (Instron Corp., Canton, Mass.) was used to apply a vertical force on the mesial incisal wings of each bracket. A testing point was fit onto the output of an Instron machine (Figure 3). This testing point applied a vertical force to the middle of the facial surface of the mesial incisal tie wing of the orthodontic brackets. The end of the testing point tapers to a circular point which appears to be approximately .8 mm in diameter. The brackets were oriented so that the testing point contacted the tie wing halfway across its mesiodistal width as well and the length of the bracket. After the bracket was oriented in the correct position under the testing point, the testing point descended at a rate of .10’’/min. This speed was selected to be as fast as possible and still allow the force value to be read accurately from the Instron machine’s digital display. The Instron machine provided a digital read-out of the force as it increased until the tie wing fractured. The force at the point of tie wing fracture was recorded as the fracture strength. During the evaluation of this apparatus in a pilot study, some deformation of the testing point was noted after testing several dozen brackets. To control for this, the testing point was changed every fifteen brackets. No significant deformation was noted when the testing point was changed every fifteen brackets

For statistical analysis, Kruskal-Wallis tests were used to examine the relationship between force and company. Dunn’s test, with Bonferroni adjustment, was used to examine pairwise comparisons of force between companies.

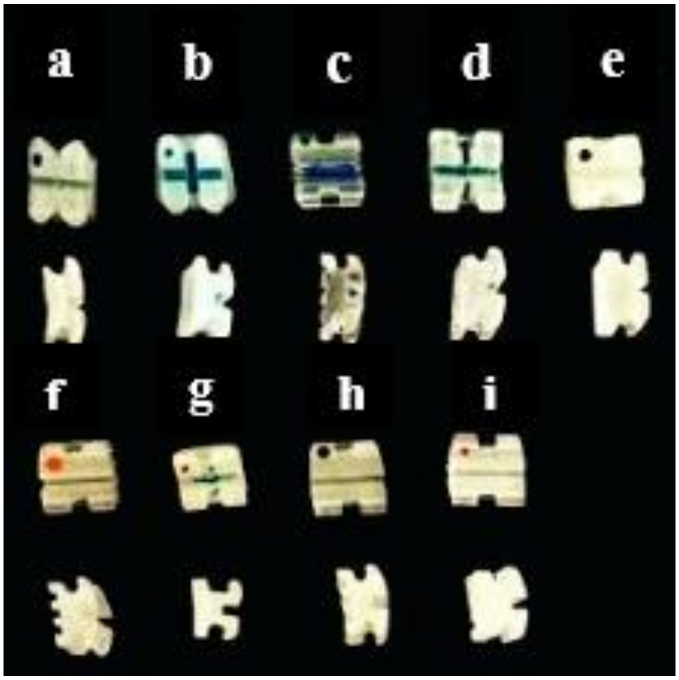

Figure 1 Facial and distal views of polycrystalline ceramic brackets.

(a) Ormco Symmetri, (b) 3M Clairty, (c) Forestadent Glam, (d) Dentsply Ovation C, (e) Henry Schein NeoLucent, (f) Ortho Tech Ref Ceramic, (g) TP ClearVu, (h) AO Cosmetic, (i) RMO Signature III,

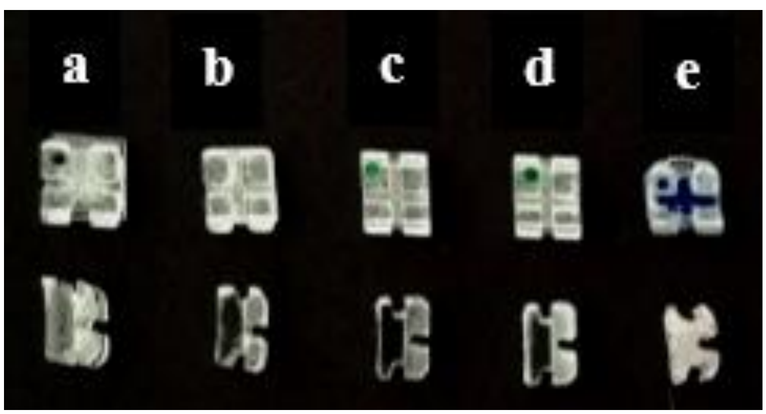

Figure 2 Facial and distal views of monocrystalline ceramic brackets.

(a) AO Radiance, (b) Ormco Inspire ICE, (c) Henry Schein NeoCrystal, (d) Ortho Tech PURE, (e) Dentsply Ovation S

Figure 3 Ceramic tile placed on the testing apparatus of the Instron machine with the testing point

4.0 RESULTS

4.1 POLYCRYSTALLINE BRACKETS

4.1.1 COMBINED STRENGTH OF CENTRAL AND LATERAL INCISOR BRACKETS

Table 1 shows the mean strength required to fracture the polycrystalline ceramic brackets according to brands with standard deviation and sample size for central incisor, lateral incisor, and combined incisors. According to Table 2, among the polycrystalline group comprising both the central and lateral incisors, Ormco Symmetri brackets exhibited the highest mean fracture strength of 310.30 N. RMO Signature III exhibited the lowest fracture strength of 84.99 N. The Ormco Symmetri brackets had the highest standard deviation of 90.46, while the Henry Schein NeoLucent Plus brackets showed the least variability of 21.06.

Table 3 demonstrates the statistical differences among the polycrystalline brands. Ormco Symmetri brackets with the highest overall mean fracture strength were statistically different from the mean fracture strengths of six brands—Dentsply Ovation C, Henry Schein NeoLucent Plus, Ortho Tech Ref Ceramic, TP ClearVu, AO Cosmetic, and RMO Signature III. 3M Clairty and Forestadent Glam did not have statistically different mean fracture strength values from that of Ormco Symmetri.

3M Clarity brackets exhibited a mean fracture strength of 203.55 N with a standard deviation of 36.56. While 3M Clarity brackets were statistically different from Henry Schein NeoLucent Plus, Ortho Tech Ref Ceramic, TP ClearVu, AO Cosmetic, and RMO Signature III, there were no significant differences with Ormco Symmetri, Forestadent Glam, and Dentsply Ovation C.

With a mean fracture strength of 196.06 N and a standard deviation of 68.84, Forestadent Glam brackets were statistically different from Henry Schein NeoLucent Plus, Ortho Tech Ref Ceramic, TP ClearVu, AO Cosmetic, and RMO Signature III. There were no significant differences with Ormco Symmetri, 3M Clarity, and Dentsply Ovation C.

Dentsply Ovation C brackets exhibited a mean fracture strength of 175.87 N with a standard deviation of 48.25. While Dentsply Ovation C brackets were statistically different from Ormco Symmetri, Ortho Tech Ref Ceramic, TP ClearVu, AO Cosmetic, and RMO Signature III, there were no significant differences with 3M Clarity, Forestadent Glam, and Henry Schein NeoLucent Plus.

With a mean fracture strength of 119.74 N and the smallest standard deviation of 21.06, Henry Schein NeoLucent Plus brackets were statistically different from Ormco Symmetri, 3M Clarity, Forestadent Glam, and Dentsply Ovation C. There were no significant differences with Ortho Tech Ref Ceramic, TP ClearVu, AO Cosmetic, and RMO Signature III.

Ortho Tech Ref Ceramic brackets exhibited a mean fracture strength of 107.53 N and a standard deviation of 51.07. Ortho Tech Ref Ceramic brackets were statistically different from Ormco Symmetri, 3M Clarity, Forestadent Glam, and Dentsply Ovation C. There were no significant differences with Henry Schein NeoLucent Plus, TP ClearVu, AO Cosmetic, and RMO Signature III.

With a mean fracture strength of 106.17 N and a standard deviation of 27.43, TP ClearVu brackets were statistically different from Ormco Symmetri, 3M Clarity, Forestadent Glam, and

Dentsply Ovation C. No significant differences were found with Henry Schein NeoLucent Plus, Ortho Tech Ref Ceramic, AO Cosmetic, and RMO Signature III.

AO Cosmetic brackets demonstrated a mean fracture strength of 88.52 N and a standard deviation of 50.67. Statistical significances were found with Ormco Symmetri, 3M Clarity, Forestadent Glam, and Dentsply Ovation C. No significant differences were found with Henry Schein NeoLucent Plus, Ortho Tech Ref Ceramic, TP ClearVu, and RMO Signature III.

With the smallest mean fracture strength of 84.99 N and a standard deviation of 42.30, RMO Signature III brackets were statistically different from Ormco Symmetri, 3M Clarity, Forestadent Glam, and Dentsply Ovation C. No significant differences were found with Henry Schein NeoLucent Plus, Ortho Tech Ref Ceramic, TP ClearVu, and AO Cosmetic.

4.1.2 STRENGTH OF CENTRAL INCISOR BRACKETS

Table 4 shows the mean strength required to fracture the polycrystalline ceramic brackets according to brands with standard deviation and sample size for central incisor. Table 5 gives the statistical difference comparison among the polycrystalline brands comprising central incisor brackets. Among the polycrystalline group comprising central incisors, Ormco Symmetri brackets exhibited the highest mean fracture strength of 310. 41 N. TP ClearVu exhibited the lowest fracture strength of 89.59 N. Similar to the combined central and lateral data, the highest standard deviation was noted from Ormco Symmetri brackets with a value of 106.22, while the Henry Schein NeoLucent Plus brackets showed the least variability of 20.29.

4.1.3 STRENGTH OF LATERAL INCISOR BRACKETS

Table 6 shows the mean fracture strength required to fracture the polycrystalline ceramic brackets according to brands with standard deviation and sample size for lateral incisor brackets. Table 7 gives the statistical difference comparison among the polycrystalline brands comprising lateral incisor brackets. Among the polycrystalline group comprising lateral incisors, Ormco Symmetri brackets exhibited the highest mean fracture strength of 292.19 N. AO Cosmetic exhibited the lowest fracture strength of 56.34 N. Ormco Symmetri brackets exhibited the highest standard deviation with a value of 74.09, while the AO Cosmetic brackets showed the least variability of 14.48.

Table 1 Mean fracture strength and standard deviation of polycrystalline brackets in Newtons according to manufacturer/brand and tooth designation

Manufacturer/brand	Mean Fracture Strength ± SD	Number of Brackets
Ormco Symetri		
Central Incisor	310.41 ± 106.22	15
Lateral Incisor	292.19 ± 74.09	15
Central and Lateral Incisor	301.30 ± 90.46	30
3M Clarity		
Central Incisor	180.62 ± 28.97	15
Lateral Incisor	226.47 ± 28.35	15
Central and Lateral Incisor	203.55 ± 36.56	30
Forestadent Glam		
Central Incisor	242.85 ± 58.06	15
Lateral Incisor	149.28 ± 41.90	15
Central and Lateral Incisor	196.06 ± 68.84	30
Dentsply Ovation C		
Central Incisor	198.36 ± 54.77	15
Lateral Incisor	153.38 ± 27.17	15
Central and Lateral Incisor	175.87 ± 48.25	30
Henry Schein NeoLucent Plus		
Central Incisor	124.83 ± 20.29	15

Lateral Incisor	114.65 ± 21.25	15
Central and Lateral Incisor	119.74 ± 21.06	30
Ortho Technology Ref Ceramic		
Central Incisor	141.41 ± 50.92	15
Lateral Incisor	73.66 ± 18.73	15
Central and Lateral Incisor	107.53 ± 51.07	30
TP ClearVu		
Central Incisor	89.59 ± 20.64	15
Lateral Incisor	122.75 ± 23.29	15
Central and Lateral Incisor	106.17 ± 27.43	30
AO Cosmetic		
Central Incisor	120.71 ± 53.76	15
Lateral Incisor	56.34 ± 14.48	15
Central and Lateral Incisor	88.52 ± 50.67	30
RMO Signature III		
Central Incisor	94.91 ± 37.19	15
Lateral Incisor	75.06 ± 45.95	15
Central and Lateral Incisor	84.99 ± 42.30	30

Table 2 Mean fracture strength of polycrstyalline brackets in Newtons

(average of central and lateral incisor brackets, n=30)

	Manufacturer	Mean Fracture Strength	Standard Deviation
1st	Ormco Symmetri	301.30	± 90.46
2nd	3M Clarity	203.55	± 36.56
3rd	Forestadent Glam	196.06	± 68.84
4th	Dentsply Ovation C	175.87	± 48.25
5th	Henry Schein NeoLucent Plus	119.74	± 21.06
6th	Ortho Tech Ref Ceramic	107.53	± 51.07
7th	TP ClearVu	106.17	± 27.43
8th	AO Cosmetic	88.52	± 50.67
9th	RMO Signature III	84.99	± 42.30

Table 3 Dunn's pairwise comparison of mean fracture strength among polycrystalline manufacturer/brand (Central and lateral incisor brackets, n=30)

Brand	3M Clarity	Forestadent Glam	Dentsply Ovation C	Henry Schein NeoLucent	Ortho Tech Ref Ceramic	TP ClearVu	AO Cosmetic	RMO Signature III
Ormco Symmetri	NS	NS	*	*	*	*	*	*
3M Clarity		NS	NS	*	*	*	*	*
Forestadent Glam			NS	*	*	*	*	*
Dentsply Ovation C				NS	*	*	*	*
HS NeoLucent Plus					NS	NS	NS	NS
Ortho Tech Ref Ceramic						NS	NS	NS
TP ClearVu							NS	NS
AO Cosmetic								NS

*= $p \leq 0.025$

Table 4 Mean fracture strength of polycrstyalline brackets in Newtons

(Central incisor brackets. n=15)

	Manufacturer	Mean Fracture Strength (N)	Standard Deviation
1st	Ormco Symetri	310.41	± 106.22
2nd	Forestadent Glam	242.85	± 58.06
3rd	Dentsply Ovation C	198.36	± 54.77
4th	3M Clarity	180.62	± 28.97
5th	Ortho Tech Ref Ceramic	141.41	± 50.92
6th	Henry Schein NeoLucent Plus	124.83	± 20.29
7th	AO Cosmetic	120.71	± 53.76
8th	RMO Signature III	94.91	± 37.19
9th	TP ClearVu	89.59	± 20.64

Table 5 Dunn's pairwise comparison of central incisor brackets among polycrystalline manufacturer/brand

(Central incisor brackets. n=15)

Brand	Forestadent Glam	Dentsply Ovation C	3M Clarity	Ortho Tech Ref Ceramic	Henry Schein NeoLucent	AO Cosmetic	RMO Signature III	TP ClearVu
Ormco Symmetri	NS	NS	NS	*	*	*	*	*
Forestadent Glam		NS	NS	*	*	*	*	*
Dentsply Ovation C			NS	NS	NS	NS	*	*
3M Clarity				NS	NS	NS	*	*
Ortho Tech Ref Ceramic					NS	NS	NS	NS
HS NeoLucent Plus						NS	NS	NS
AO Cosmetic							NS	NS
RMO Signature III								NS

*= p ≤ 0.025

Table 6 Mean fracture strength of polycrystalline brackets in Newtons

(Lateral incisor brackets, n=15)

	Manufacturer	Mean Fracture Strength (N)	Standard Deviation
1st	Ormco Symmetri	292.19	± 74.09
2nd	3M Clarity	226.47	± 28.35
3rd	Dentsply Ovation C	153.38	± 27.17
4th	Forestadent Glam	149.28	± 41.90
5th	TP ClearVu	122.75	± 23.29
6th	Henry Schein NeoLucent Plus	114.65	± 21.25
7th	RMO Signature III	75.06	± 45.95
8th	Ortho Tech Ref Ceramic	73.66	± 18.73
9th	AO Cosmetic	56.34	± 14.48

Table 7 Dunn's pairwise comparison of lateral incisor brackets among polycrystalline manufacturer/brands (Lateral incisor brackets, n=15)

Brand	3M Clarity	Dentsply Ovation C	Forestadent Glam	TP ClearVu	Henry Schein NeoLucent	RMO Signature III	Ortho Tech Ref Ceramic	AO Cosmetic
Ormco Symmetri	NS	NS	NS	*	*	*	*	*
3M Clarity		NS	NS	*	*	*	*	*
Dentsply Ovation C			NS	NS	NS	*	*	*
Forestadent Glam				NS	NS	*	*	*
TP ClearVu					NS	NS	NS	*
HS NeoLucent Plus						NS	NS	NS
RMO Signature III							NS	NS
Ortho Tech Ref Ceramic								NS

*= $p \leq 0.025$

4.2 MONOCRYSTALLINE BRACKETS

4.2.1 COMBINED STRENGTH OF CENTRAL AND LATERAL INCISOR BRACKETS

Table 8 shows the mean strength required to fracture the monocrystalline ceramic brackets according to brands with standard deviation and sample size for central incisor, lateral incisor, and combined incisors. According to Table 9, consisted of monocrystalline brands of both the central and lateral incisors, AO Radiance Plus brackets demonstrated the highest mean fracture strength of 262.42 N. Dentsply Ovation S bracket had the lowest mean fracture strength of 55.80 N. Highest variability was noted from AO Radiance Plus with a standard deviation of 110.42, while the smallest standard deviation of 13.04 came from Dentsply Ovation S. Table 10 demonstrates the statistical differences among the monocrystalline brands. Dentsply Ovation S brackets were statically weaker than all four other monocrystalline brands. The differences in the mean fracture strength among the other four monocrystalline brackets, AO Radiance Plus, Ormco Inspire ICE, Henry Schein NeoCrystal Plus, and Ortho Tech PURE, were statically insignificant as the differences were relatively small with values ranging from 210.66 N to 262.42 N.

4.2.2 STRENGTH OF CENTRAL INCISOR BRACKETS

According to Table 11, consisted of monocrystalline brands of central incisor brackets, AO Radiance Plus brackets demonstrated the highest mean fracture strength of 334.96 N. Dentsply Ovation S bracket had the lowest mean fracture strength of 59.53 N. Highest variability was noted from AO Radiance Plus with a standard deviation of 82.38, while the smallest standard deviation of 14.59 came from Dentsply Ovation S. Table 12 demonstrates the statistical differences among the monocrystalline brands for central incisor brackets. While Dentsply Ovation S brackets were statically different and weaker than all four other monocrystalline brands. AO Radiance Plus brackets were significantly different and stronger than all other monocrystalline brands.

4.2.3 STRENGTH OF LATERAL INCISOR BRACKETS

According to Table 13, consisted of monocrystalline brands of lateral incisor brackets, Henry Schein NeoCrystal Plus brackets demonstrated the highest mean fracture strength of 244.51 N. Dentsply Ovation S bracket had the lowest mean fracture strength of 52.07 N. Highest variability was noted from AO Radiance Plus with a standard deviation of 84.81, while the smallest standard deviation of 10.45 was observed from Dentsply Ovation S. Table 14 demonstrates the statistical differences among the monocrystalline brands for lateral incisor brackets. Dentsply Ovation S brackets were statically different and weaker than all four other monocrystalline brands.

Table 8 Mean fracture strength and standard deviation of monocrystalline brackets in Newtons according to manufacturer/brand and tooth designation

Manufacturer/brand	Mean fracture strength ± SD	Number of brackets
AO Radiance Plus		
Central Incisor	334.96 ± 82.38	15
Lateral Incisor	189.87 ± 84.81	15
Central and Lateral Incisor	262.42 ± 110.42	30
Ormco Inspire ICE		
Central Incisor	239.90 ± 78.21	15
Lateral Incisor	241.06 ± 81.53	15
Central and Lateral Incisor	240.48 ± 78.51	30
Henry Schein NeoCrystal Plus		
Central Incisor	199.07 ± 31.05	15
Lateral Incisor	244.51 ± 39.95	15
Central and Lateral Incisor	221.80 ± 42.07	30
Ortho Technology PURE		
Central Incisor	215.25 ± 54.38	15
Lateral Incisor	206.06 ± 55.24	15
Central and Lateral Incisor	210.66 ± 54.06	30
Dentsply Ovation S		
Central Incisor	59.53 ± 14.59	15
Lateral Incisor	52.07 ± 10.45	15
Central and Lateral Incisor	55.80 ± 13.04	30

Table 9 Mean fracture strength of monocrystalline brackets in Newtons

(average of central and lateral incisor brackets, n=30)

	Manufacturer	Mean Fracture Strength (N)	Standard Deviation
1st	AO Radiance Plus	262.42	± 110.42
2nd	Ormco Inspire ICE	240.48	± 78.51
3rd	Henry Schein NeoCrystal Plus	221.80	± 42.07
4th	Ortho Tech PURE	210.66	± 54.06
5th	Dentsply Ovation S	55.80	± 13.04

Table 10 Dunn's pairwise comparison of mean fracture strength among monocrystalline manufacturer/brand

(Central and lateral incisor brackets, n=30)

Brand	Ormco Inspire ICE	Henry Schein NeoCrystal	Ortho Tech PURE	Dentsply Ovation S
AO Radiance Plus	NS	NS	NS	*
Ormco Inspire ICE		NS	NS	*
Henry Schein NeoCrystal Plus			NS	*
Ortho Tech PURE				*

*= $p \leq 0.025$

Table 11 Mean fracture strength of monocrystalline brackets in Newtons (Central incisor brackets, n=15)

	Manufacturer	Mean Fracture Strength (N)	Standard Deviation
1st	AO Radiance Plus	334.96	± 82.38
2nd	Ormco Inspire ICE	239.90	± 78.21
3rd	Ortho Tech PURE	215.25	± 54.38
4th	Henry Schein NeoCrystal Plus	199.07	± 31.05
5th	Dentsply Ovation S	59.53	± 14.59

Table 12 Dunn's pairwise comparison of mean fracture strength among monocrystalline manufacturer/brand (Central incisor brackets. n=15)

Brand	Ormco Inspire ICE	Ortho Tech PURE	Henry Schein NeoCrystal	Dentsply Ovation S
AO Radiance Plus	*	*	*	*
Ormco Inspire ICE		NS	NS	*
Ortho Tech PURE			NS	*
Henry Schein NeoCrystal Plus				*

*= $p \leq 0.025$

Table 13 Mean fracture strength of monocrystalline brackets in Newtons (Lateral incisors brackets, n=15)

	Manufacturer	Mean Fracture Strength (N)	Standard Deviation
1st	Henry Schein NeoCrystal Plus	244.51	± 39.95
2nd	Ormco Inspire ICE	241.06	± 81.53
3rd	Ortho Tech PURE	206.06	± 55.24
4th	AO Radiance Plus	189.87	± 84.81
5th	Dentsply Ovation S	52.07	± 10.45

Table 14 Dunn's pairwise comparison of mean fracture strength among monocrystalline manufacturer/brand (Lateral incisor brackets, n=15)

Brand	Ormco Inspire ICE	Ortho Tech PURE	AO Radiance	Dentsply Ovation S
Henry Schein NeoCrystal Plus	NS	NS	NS	*
Ormco Inspire ICE		NS	NS	*
Ortho Tech PURE			NS	*
AO Radiance Plus				*

*= $p \leq 0.025$

5.0 DISCUSSION

Despite continued improvements in ceramic brackets, one of the major drawbacks of ceramic brackets is their brittle nature which can lead to fractures during clinical use. Especially the tie wings are the parts of the bracket most prone to fracture. The aim of the study was to investigate the fracture resistance of various commercially available polycrystalline and monocrystalline ceramic brackets during the loading of tie wings.

Upper incisor brackets were chosen for this study because Viazis et al found that the upper central incisor and upper lateral incisor accounted for 77 % of the bracket failure from the upper anterior brackets tested. Another reason for selecting the maxillary anterior brackets was the nature of their location. In most cases, maxillary anterior teeth are the most labial part of the dentitions, which also make them more prone to accidental trauma (Altun and Guven 2008). The mesioincisal tie wing was chosen since Wlibur's study noted weaker fracture strength for the mesioincisal tie wings compared to the distogignival tie wings for six out of nine total brands tested. Also, from the findings of Holt et al and Aknin et al, incisal half of the bracket was found to be more prone to fracture than the gingival half from the torsional force.

In this study, the results of the fracture strength of polycrystalline ceramic brackets can be broadly separated into three groups. The first group comprising of Ormco Symmetri (301.03 N ± 36.56), 3M Clarity (203.55 N ± 36.56), and Forestadent Glam (196.06 N ± 68.84), were the strongest and did not have significant differences from each other. Dentsply Ovation C (175.87 N ± 48.25) brackets represent the second group. The last group consisting of Henry Schein NeoLucent (119.74 N ± 21.06), Ortho Tech Ref Ceramic (107.53 N ± 51.07), TP ClearVu (106.17

N ± 27.43), AO Cosmetic (88.52 ± 50.67) and RMO Signature III (84.99 ± 42.30), were the least strong, with no significant differences between them.

The only brand of the polycrystalline ceramic bracket that was common between this study and that of Wilber's study was the 3M Clarity. In this study, the fracture strength of 3M Clarity was 203.55 N, which did not differ greatly from the fracture strength of 253 N found in Wilbur 's study. The slightly higher strength in Wilbur's study can be explained by the fact that they reported an average of the combined strength of mesioincisal and distogingival tie wings. In Wilbur's study, distogingival tie wings were generally found to have higher fracture strength than mesioincisal tie wings. This could account for the slightly higher fracture strength of 3M Clarity reported in Wilbur's study.

The strength of the polycrystalline ceramic brackets in this study had a wide range from 84.99 N to 301.30 N. There was also a wide variation in the fracture strength within the brands themselves. Ormco Symmetri, which had the highest fracture strength of 301.30 N also had the highest standard deviation of ± 90.46. Wilbur also noted a broad range between 94 N and 253 N in the fracture strength among the nine ceramic bracket brands tested. Similarly, Wilbur also noted a wide variation in fracture strength within the brands themselves; for example, 3M Clarity brackets had a standard deviation of 86. Rhodes et al examined the relationship of the second order movement and ceramic bracket fracture and found a highly variable standard deviation for fracture forces. Rhodes et al attributed this to the differences in the manufacturing processes, materials used, and the different bracket designs. Flores et al also reported large standard deviation values from investigating the effect of torsional force on ceramic bracket fracture and explained that broad scatter values are more likely to be observed from higher strength ceramic materials

The reason for a wide difference in strength between brands as well as within brands is likely due to the differences in the manufacturing process and the design of the brackets. Porosity, inclusion of impurities, cracks, presence of localized stresses and scratches, inadequate heat treatment, and improper design and material can all lead to decreased fracture resistance of ceramic brackets (Holt et al 1991). Viazis et al found that the two primary causes of ceramic fracture which accounted for 90% in the study were internal defects and machining interference. Various brands have different manufacturing processes in areas such as heat treatment, nature of the finishing surface, and the size of grain fragments used to process the ceramic brackets (Holt et al 1991). In this study, the two highest fracture strength from the polycrystalline group were observed from Ormco Symmetri and 3M Clarity with values of 301.30 N and 203.55 N respectively. According to Ormco, Ormco Symmetri has increased strength from its predecessors by using its advanced polycrystalline alumina ceramic manufacturing technology. 3M Clarity attributed its high fracture strength to utilizing small size grain and its fine-grained polycrystalline ceramic injection molding technique.

In addition to varying manufacturing processes, various designs and shapes may seem to attribute to the fracture strength differences of ceramic bracket brands. Ghosh et al found that higher fracture strengths under both torsional and tipping forces were observed from brackets with smooth and round designs. According to Ormco's manufacturer claim, Ormco Symmetri, the highest fracture strength bracket from the polycrystalline group, claim to have a smooth surface with rounded contours.

The fracture strength of monocrystalline brackets in this study can be stratified into two groups. The first group consists of AO Radiance Plus (262.42 N ± 110.42), Ormco Inspire ICE (240.48 N ± 78.51), Henry Schein NeoCrystal Plus (221.80 N ± 42.07), Ortho Tech PURE (210.66

N ± 42.07), which were the strongest with no significant differences between them. The second group consists of Dentsply Ovation S (55.80 N ± 13.04) brackets which were significantly weaker than all other monocrystalline brands. Similar to polycrystalline brackets, the variability in fracture strength between and within brands is likely due to differences in manufacturing process and design. AO Radiance Plus with the highest fracture resistance observed in this study reported a unique proprietary heat polish process to help smooth away microvoids and flaws. AO Radiance Plus also claims to have durable tie wings with thicker tie wings compared to other competitors' brackets.

In summary, fracture resistance of ceramic brackets varied by manufacture including large variability within brands. So, it is possible that even with the brands with overall strong fracture resistance some brackets could have low fracture resistance. Clinicians need to understand and consider this variability of ceramic brackets when utilizing them in clinical practice.

The new information generated by this study should allow the practitioner to make an informed decision regarding the fracture resistance of tie wings of various ceramic brackets and their likelihood of breakage during treatment.

6.0 CONCLUSION

The purpose of this study was to compare the fracture strength of tie wings of currently available ceramic brackets from various manufacturers. Both, polycrystalline and monocrystalline brackets were tested.

Broadly, the following conclusions can be drawn based on the results of this study:

1. Polycrystalline brackets:

a) Ormco Symmetri, 3M Clarity and Forestadent Glam are the strongest

b) Dentsply Ovation C is the next strongest

c) Henry Schein Neo Lucent Plus, Ortho Tech Ref Ceramic, TP Clear VU and AO Cosmetic brackets are the least strong

2. Monocrystalline brackets:

a) AO Radiance Plus, Ormco ICE, Henry Schein Neo Crystal Plus and Orth Tech PURE are the strongest

b) Dentsply Ovation S is the weakest

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