DEFORMATION OF REINFORCED POLYCARBONATE ORTHODONTIC BRACKETS STRESSED BY A LABIOLINGUAL MOMENT

BY

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A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

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Winnipeg, Manitoba

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ACKNOWLEDGEMENTS

I would like to thank a number of people who contributed to the completion of this thesis.

I am appreciative of the time and effort put forth by my committee members, Dr. P. Williams (supervisor), Dr. W. Wiltshire (internal examiner) and Dr. K. McLachlan (external examiner).

The dental materials used in this investigation were generously donated by Ormco Corporation (Glendora, CA), GAC International Inc. (Central Islip, N.Y.) and 3M Unitek (Monrovia, CA).

Statistical analysis was performed by Mary Cheang from the Medical Biostatistics consulting unit.

To my classmates, Dr. Ken Danyluk and Dr. Zvi Kantorwitz, I would like to thank them for their friendship and camaraderie.

ABSTRACT

The utilization of a rectangular archwire in a similar dimension rectangular bracket slot helps to control tooth inclination in edgewise mechanics. The bracket which is attached to the crown of the tooth must be able to transmit the stress from the archwire to the periodontal attachment apparatus in order to produce desired tooth movement. Orthodontic brackets made from polycarbonate material have been reported to deform when subjected to a torsional moment. A metal slot has been introduced by some manufacturers to reinforce the polycarbonate bracket and reduce plastic deformation of the bracket. Although there is some evidence in the literature that the metal slot is able to reduce the plastic deformation in the polycarbonate bracket to acceptable levels, the evidence is inconclusive. This thesis reports the results of a study designed to determine whether reinforced polycarbonate brackets experience clinically acceptable amounts of deformation over a period of time under sustained stress. A novel *in vitro* apparatus was designed to eliminate some of the errors present in previous studies. The apparatus simulated labiolingual crown torque by twisting a stainless steel archwire of 0.018 x 0.025 inch dimension in an orthodontic bracket with a 0.018 x 0.025 inch bracket slot. A moment of 2500 g-mm was applied for 28 days with measurements taken at initial moment application, 1 hour, 2 hours, 24 hours and then at regular 7 day intervals to determine the amount of deformation which occurred. Forty orthodontic brackets, consisting of ten polycrystalline ceramic, ten stainless steel and twenty metal slot reinforced polycarbonate brackets were tested. The results of this study showed that there was a significant difference in the amount of elastic, plastic and creep deformation which occurred in the metal slot reinforced polycarbonate brackets when compared to stainless steel and ceramic brackets ($p<0.05$). The combination of elastic, plastic and creep deformation which occurred in the polycarbonate brackets is likely to affect the ability of the bracket to transmit the desired torque.

1. INTRODUCTION

1.0 Forces, Moments and Tooth Movement

A tooth with an intact periodontium has only the crown exposed to the oral environment. The root of the tooth is surrounded by the alveolar housing and is supported and connected to the alveolar housing by the periodontal ligament. When an orthodontic force is applied to a tooth it must be applied to the crown of the tooth. The centre of resistance of a single rooted tooth is estimated to be located a distance from the alveolar crest equal to one third of the distance from the alveolar crest to the apex of the root (Burstone, 1994). Because the point of force application is located at a distance from the centre of resistance, forces and moments are required for control of root movement.

One approach in fixed orthodontic therapy to control root movement is via the use of a rectangular archwire placed into a similar-dimension rectangular orthodontic attachment or bracket that has been bonded to the crown of a tooth. This type of root control is found when using continuous straight wire therapy. The archwire can produce forces which are transmitted through the bracket to the tooth. The active element or archwire must produce the necessary forces and the bracket must be able to transmit these forces so that the appropriate stress is applied to the periodontal attachment apparatus of the tooth. If there is any deformation in the bracket during force application, the stress applied to the tooth will be less than the predicted magnitude.

When a lingually directed force is applied to the crown of a maxillary incisor, as occurs during the retraction of the incisor teeth, a moment is generated which tends to move the crown of the tooth lingually while moving the root apex in a labial direction. In order to maintain the axial inclination of the incisor while it is being retracted, it is necessary to produce a counter-moment which is equal in magnitude and opposite in direction to the moment created by the lingual force applied at the crown. This counter-moment can be produced through a couple created by the rectangular archwire in the rectangular bracket slot. Significant stress is applied to the bracket as the twisting of the rectangular archwire is resisted in the bracket slot. It is necessary, therefore, that the bracket be able to withstand this stress without deforming. It is also imperative that the torsional stiffness of the archwire allow for the creation of a moment which is equal in magnitude to that created by the lingually directed force. If the torsional stiffness of the archwire is too low then the moment created by the lingually directed force will exceed the ability of the archwire to produce a counter moment of sufficient magnitude which will result in lingual tipping of the crown.

1.1 Aesthetic Brackets. Polycarbonates and Ceramics

Birnie (1990), reported that many patients are concerned with the appearance of fixed orthodontic appliances. Two currently available materials which have been introduced to provide an aesthetic alternative to stainless steel brackets are polycarbonate, a polymer material and alumina, a ceramic material. A ceramic bracket made from zirconia has also been produced (Kittipibul and Godfrey, 1995). Ceramic brackets provide good aesthetics, resist staining, are hard and strong (Birnie, 1990). They do, however, have problems in that there have been reports of bracket breakage, tooth enamel wear and fracturing of enamel at the time of bracket debonding (Birnie, 1990). Conversely, pure polycarbonate brackets will not damage the enamel structure like the ceramic brackets but the polycarbonate brackets lack the strength, stiffness and resistance to creep deformation to transmit a moment (Birnie, 1990). Bracket manufacturers have attempted to strengthen the polycarbonate bracket by adding ceramic fillers and a metal slot in the bracket. Further research is required to determine if these additions to the polycarbonate bracket enhance their ability to perform at a clinically acceptable level.

The aim of the work reported here was to determine if the metal slot reinforced polycarbonate bracket is capable of maintaining a significant labiolingual moment over time and to compare its performance to that of stainless steel brackets and ceramic brackets exposed to the same labiolingual moment.

2. REVIEW OF THE LITERATURE

2.0 Edgewise Treatment

2.0.0 Edgewise System

The edgewise orthodontic system was introduced by Edward H. Angle in 1928. This appliance system allowed a rectangular archwire to be placed into a rectangular bracket slot attachment in an edgewise manner. The original dimension of the bracket slot was 0.022 inches in height and 0.028 inches in depth. The rectangular archwires used were drawn from a bar of metal to a dimension of 0.022 inches in height and 0.028 inches in depth, a similar dimension as the bracket slot. This arrangement allowed for control of tooth movement in three planes of space thus allowing for the crown and root position to be precisely adjusted (Angle, 1928).

2.0.1 Attachments

The original edgewise mechanism as proposed by Angle (Angle, 1928) involved banding with plain brazed bands and anchor clamp bands to each tooth that required an attachment. The edgewise bracket was brazed to the band material at the centre of its labial surface. The band was fitted to the tooth and then luted. Orthodontic bands had many disadvantages. They caused discomfort to the patient during placement. Fitting of the orthodontic bands was time consuming for the operator and complicated treatment by impinging on arch length and a subsequent need for closure of band spaces after removal (Newman, 1969). The replacement of orthodontic bands by bonded brackets eliminated these disadvantages. In addition, orthodontic brackets were more aesthetic, created less gingival irritation and facilitated plaque removal thus decreasing the chances of enamel decalcification (Reynolds, 1975). The advent of tooth-coloured brackets was an advancement in aesthetics which remains popular today.

2.1 Forces and Moments

2.1.0 Definition of Force

Any discussion of tooth movement should include the affects of both forces and moments. A force can be represented by a vector because a force has magnitude, a line of action and a sense. A force will cause an object to translate in the direction of force application and the object will not rotate as long as the line of action of the force passes through the centre of resistance of the object.

2.1.1 Definition of Moment

The tendency for rotation around a point is measured as a moment. A moment can be created in two ways, either as the moment of a couple or the moment of a force (Smith and Burstone, 1984).

2.1.2 Moment of a Force

The moment of a force is created when the line of action of the force does not pass through the centre of resistance of an object. The moment is equal to the magnitude of the force multiplied by the perpendicular distance from the line of action of the force to the centre of resistance (Figure I). When both a force and a moment act upon an object, the movement of the object will be a combination of translation and rotation.

2.1.3 Moment of a Couple

The moment of a couple, however, is a "free vector" which means that the couple may be applied to an object anywhere on the object and the same tendency for rotation will occur. The moment of a couple is created when two forces of equal magnitude are applied to an object such that the forces have parallel but non-collinear lines of action and opposite senses (Figure II). The moment of a couple is equal to

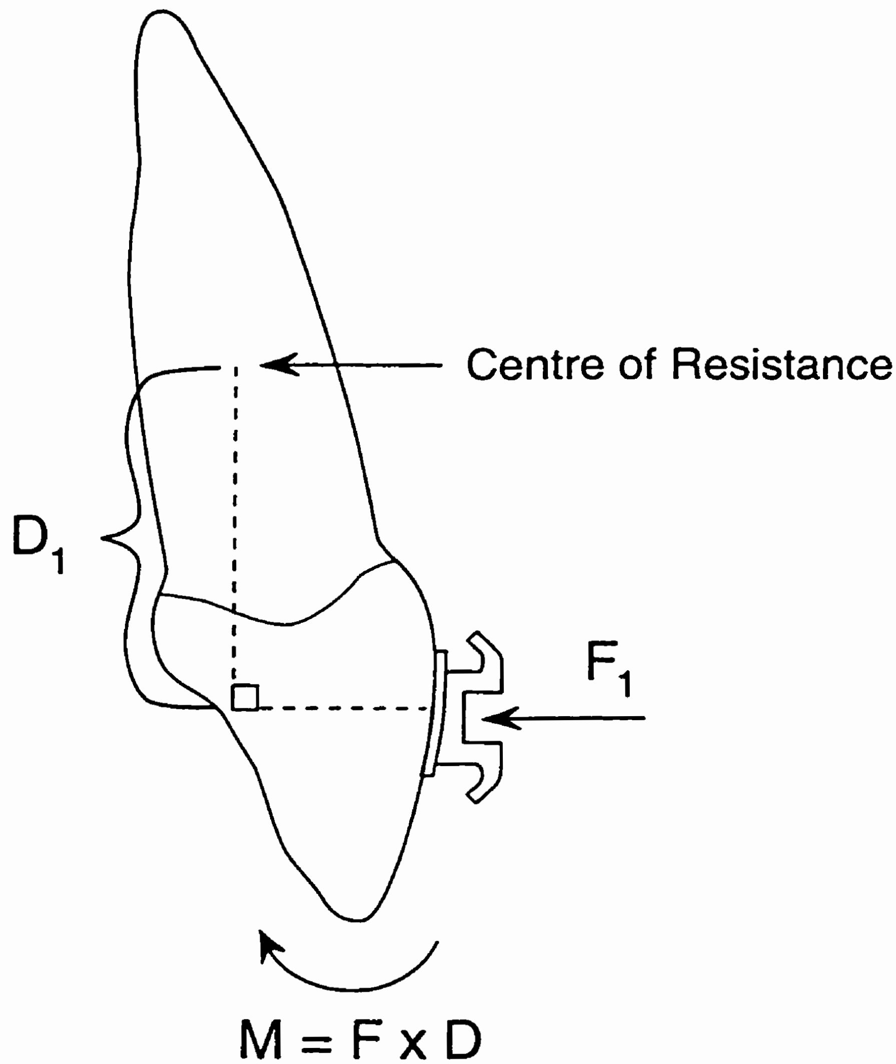

Figure I

Moment of a Force. A force (F_1) is applied at the bracket with a line of action in a lingual direction. This force would tend to move the tooth in a lingual direction as well as rotate it in a clockwise manner. This tendency to rotate the tooth is due to the moment produced by the line of action of the force not passing through the centre of resistance of the tooth. The magnitude of the moment is equal to the magnitude of the force (F_1) multiplied by the perpendicular distance from the force to the centre of resistance (D_1).

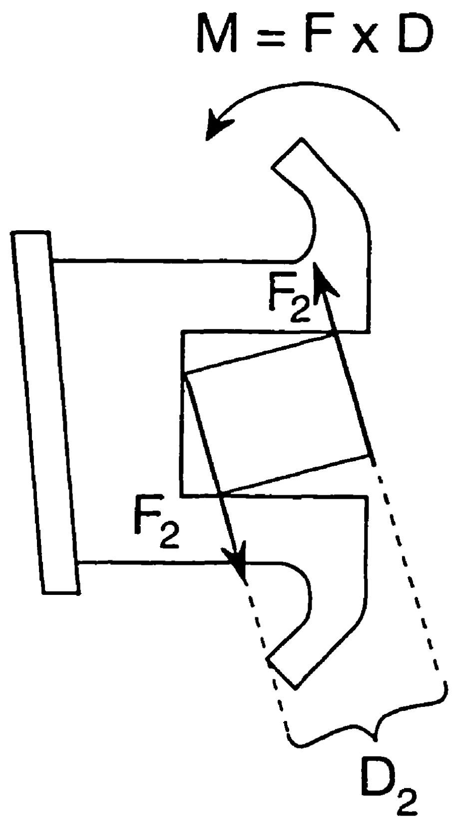

Figure II
Moment of a Couple. The moment of a couple is created when two forces of equal magnitude are applied to an object such that the forces have parallel but noncolinear lines of action and opposite senses. This can occur when a square or rectangle archwire is twisted in a rectangular bracket slot such that the bracket slot resists the twisting of the archwire. The magnitude of the moment created is equal to the magnitude of one of the forces (F_2) multiplied by the perpendicular distance between the two forces (D_2).
Comparison of Figure I and Figure II reveals that the distance D_1 is much greater than the distance D_2. Therefore to produce moments of equal magnitude the forces (F_2) creating the couple must be of proportionally greater magnitude than the force of F_1.

the magnitude of one of the forces multiplied by the perpendicular distance between the two forces (Smith and Burstone,1984). A couple will produce pure rotation of an object, without any translation.

2.1.4 Third Order Mechanics

Third-order tooth movement in orthodontics describes the labiolingual inclination of the teeth. Labiolingual torque is commonly referred to as the moment which affects the inclination of the teeth. A couple can be created when a rectangular archwire is twisted in a similar dimension rectangular bracket slot such that the rotation of the archwire is resisted by the bracket slot (Figure II). This couple will produce a tendency for the tooth to rotate. It is this principle of edgewise mechanics which allows third order control of root position. Since the orthodontic attachment on the crown of a tooth is located some distance from the centre of resistance of the tooth, a force applied at the attachment will create a moment. In order to control root movement, both the force and the moment applied to the tooth must be controlled. If a tooth is to be translated without changing its inclination, the moment created by the force must be counter-balanced by the moment of the couple (created by the rectangular archwire in the rectangular bracket slot) which will be equal in magnitude and opposite in direction. The distance between the forces which are creating the couple in the bracket slot is much smaller than the distance from the centre of resistance to the line of action of the force which is applied at the bracket. This is illustrated when comparing Figure I and Figure II where D_1 in Figure I is of much greater magnitude than D_2 in Figure II (Figure I and Figure II). Because of this, the magnitude of the forces acting in the bracket slot creating a couple must be proportionally larger than the force applied at the bracket in order to create moments of equal magnitude (Isaacson et al., 1993).

2.2 Forces Required to Move Teeth

2.2.0 Physiologic Values

In 1932, Schwarz reported that for simple tipping of a tooth through the biologic process of direct resorption the stress applied to the tooth should be less than that of the capillary blood pressure which is in the range of 20 - 26 grams per cm^2 of surface area. Reitan's (1957) histological experiments on human premolars illustrated that a torquing movement which applied approximately 130 grams of force at the root apex was able to produce the desired physiologic changes without any areas of hyalinization. Direct bone resorption was noted on the pressure side of the tooth and even layers of osteoid were produced on the tension side.

2.2.1 Optimum Moment Values

Many researchers have suggested values for the optimum moment required to produce root torque. Nikolai (1985) suggested that the optimum torque requirement for an average maxillary incisal segment was in the range of 3000 to 3500 g-mm. This was a theoretical calculation based upon normal blood pressure and the projected areas on the root believed to experience the compressive stress. Holt (1991) reported a value of approximately 2400 g-mm as the optimum moment to torque a maxillary central incisor. This value was calculated by multiplying 18.25 mm, which is the average distance from the centre of the crown to the apex of the root on a maxillary central incisor, by 130 grams which, as described earlier, is the force Reitan (1957) found to be physiologically optimal. Wainwright (1973), based on his histological experiment with *Macaque speciosa* monkeys, reported that 2000 g-mm was the optimum moment required to produce lingual root torque.

2.3 Effects of Forces and Moments on Bracket Deformation

2.3.0 Areas of Stress Concentration and Bracket Fracture

Studies using a photoelastic stress analysis have examined the location of stress concentrations due to labiolingual torque (Rains et al., 1977; Aird et al., 1988). Aird et al. (1988) found the stress concentrations occurred at the base of the bracket slot with values ranging from 15 g/mm^2 to 16 g/mm^2. These results correlate with the observations of Aird and Durning (1987) who found that the polycarbonate bracket fractures were located at the base of the bracket slot resulting in the destruction of the tie wings of the bracket and the bracket slot. It would also be expected that deformation of the bracket would occur in the location of greatest stress concentration.

2.3.1 Elastic, Plastic and Creep Deformation

For third order control, orthodontic attachments must be able to withstand and transmit the desired moment. Because of the high forces and the stress concentration effects acting at the bracket slot, the couple created by the rectangular archwire may cause elastic, plastic or creep deformation of the bracket slot. Elastic deformation of the bracket would mean that the bracket would be able to return to its initial form once the stress was removed. Plastic and creep deformation on the other hand are permanent deformation which remains after the stress is removed. Plastic deformation occurs almost instantaneously once the stresses are above the materials elastic limit. Creep deformation however is time dependent as well as stress dependent. Creep deformation occurs when the stress causing the permanent deformation is less than the materials elastic limit. Creep requires sufficient stress which acts over a period of time to allow for viscous flow within the material. The deformation of the bracket slot can create an opening of the tie wing area and increases the effective size of the bracket slot. This would allow for greater rotation of the archwire in the bracket slot and reduce the effective torque (McKnight et al., 1994).

2.4 Brittle Fracture, Impact Strength and Creep

Griffith's theory on brittle fracture assumes that brittle materials have many fine elliptical cracks with strong stress concentrations occurring at the tip of these cracks (Hayden et al., 1965). The stress at the crack tip is proportional to the crack length and inversely proportional to the radius of the crack tip (Eisenstadt, 1971). When a stress is applied to the material at such a level that crack propagation will occur, then the crack will propagate and produce brittle failure. Brittle failure will occur if there is an incremental increase in the length of the crack without any net increase in the net energy of the system (Hayden et al., 1965). A material which possesses low impact strength and fractures in a brittle manner absorbs only a small amount of energy before breaking. However, for a material to possess high impact strength, and therefore resist brittle fracture upon impact loading, the material must be somewhat ductile. Ductility contributes to impact strength in a couple of ways. The stress concentration at the crack tip is reduced in a ductile material as the material produces a more rounded crack tip, thereby increasing the radius of the crack tip and reducing the stress (Eisenstadt, 1971). Also, an increased amount of energy is required to fracture a ductile material due to the plastic deformation of the material which consumes energy (Cottrell, 1967). If the polymer is ductile, then there will be a low level of molecular crosslinking which implies that creep may occur. With a ductile polymer, creep can occur if the load is applied for a long enough period of time even if the loads are very low and at temperatures well below the glass transition temperature. Since polycarbonate material is a ductile material with an elongation percentage of 60% to 100% (Billmeyer Jr., 1962), creep deformation should be expected in polycarbonate brackets.

2.5 Plastic Brackets

2.5.0 Development of Bonded Orthodontic Attachments

The first direct bonding of orthodontic brackets occurred in the 1950's (Newman, 1964; Newman, 1992). Newman was reportedly the first to bond plastic orthodontic attachments to teeth for the purpose of orthodontic tooth movement (Newman, 1964; Newman, 1965; Newman, 1969; Newman, 1992). Newman's studies evaluated many different plastic materials (acrylics, nylons, epoxies, polysulfones, polyphenylene oxides, polycarbonates) and found that of all the plastics evaluated, polycarbonates exhibited the best properties for use as orthodontic attachments.

2.5.1 Advantages and Disadvantages of Polycarbonate Brackets

Some of the advantages of polycarbonate brackets noted by Newman (1964, 1969) were good aesthetics, no odour or bad taste and more durable adhesion of the brackets to the teeth compared with steel brackets. Compared to other polymers, the polycarbonates had good abrasion resistance, high impact strength and resistance to creep and deformation under load (Newman, 1969). Several disadvantages of polycarbonate brackets have been noted. The ability of the polycarbonate bracket to transmit torque during orthodontic treatment was found to be inadequate due to its elastic, plastic and creep distortion during treatment (Dooley et al., 1975; Winchester, 1992). This was a major problem and it was proposed that the use of polycarbonate brackets should be limited to situations where minimal labiolingual root torque is required and a short treatment time is anticipated (Birnie, 1990; Winchester, 1992). Another disadvantage of the polycarbonate material is its tendency to absorb water (Newman,1969). In addition to discoloration and softening, water absorption can increase the creep rate.

2.5.2 Properties of Polycarbonate Materials

Polycarbonate is a commercially available polymer which may be produced by the reaction of phosgene with an alkaline solution of bisphenol A in the presence of an inert solvent such as methylene chloride or by an ester exchange between Bisphenol A and a diphenyl carbonate. Polycarbonates have creep characteristics which are generally better than most of the other thermoplastics. Polycarbonates reportedly have high impact and tensile strength, high elastic modulus and excellent dimensional stability when compared to other polymers (Bikales, 1971). However, compared to other materials which are used in the construction of orthodontic brackets, the polycarbonates have a very low elastic modulus. The elastic modulus of polycarbonate is 2.4 GPa compared to the elastic modulus of stainless steel and alumina which are in the range of 188 GPa and 418 GPa respectively. Polycarbonate is a viscoelastic-plastic which at room temperature has elastic properties at stresses below 27.6 N/mm, viscoelastic properties between stresses of 27.6 N/mm and 62.0 N/mm, and a yield point of approximately 62 N/mm (Brinson, 1972).

When stress is applied to a linear viscoelastic solid there is a resulting strain produced in the solid. The total strain can be separated into elastic deformation and Newtonian flow (Ward, 1971). When the stress is removed the elastic deformation recovers leaving only the deformation caused by the Newtonian flow. Polymers which exhibit a large amount of elastic deformation do so because of a kinked molecular conformation. The elastic properties occur because the polymer is able to exhibit an unkinking and rekinking of the molecular arrangement. In order for this unkinking and rekinking to occur, the polymer must be above its glass temperature T_g. Below the T_g the material behaves elastically through the stretching of bonds (Hayden et al., 1965). Below the T_g the bonds are unable to slide past one another or unkink which leads to brittle failure if the stress is too high (Van Vlack, 1985; Hayden et al., 1965).

Many polymers can be thought of as supercooled liquids which exist between their melting temperature T_m and their glass temperature T_g and , therefore, are subject to viscous flow. The rate of viscous flow may be slow, resulting in creep deformation if the polymer receives a long-term load (Van Vlack, 1985). Below the T_g of a polymer and in the "glassy" phase, the polymer is hard and brittle (Van Vlack, 1985). In the glassy phase, elastic strain occurs by the stretching of bonds within and between molecular chains (Hayden et al., 1965). Creep can occur in a polymer even when the temperature is below its T_g temperature. Below 100° Celsius, polycarbonates exhibit low creep under load (Kroschwitz, 1987). If the side-chains or co-polymers which are part of the polymer are at or above their T_g, the polymer may exhibit creep behaviour under stress (Billmeyer Jr., 1962).

2.6 Alternative Brackets

2.6.0 Ceramic Brackets

Ceramic brackets are composed of aluminium oxide (alumina) (Swartz, 1988). Ceramics are primarily bound together by ionic and covalent bonds. Due to this atomic structure, when stress is applied at a certain level the ceramic crystal lattice will fracture rather than plastically deform. Monocrystalline brackets are made from a single crystal of alumina. Polycrystalline brackets which are made from thousands of fused particles of polycrystalline aluminium oxide contain grain boundaries as a result of the different crystal orientations. These grain boundaries and particle fusion interfaces are sites of imperfections which can act as stress concentration areas that encourage crack propagation and lead to a fracture strength which is lower than the monocrystalline bracket. The production of the bracket from a single crystal of aluminium oxide eliminates the imperfections found in the polycrystalline brackets (Swartz, 1988).

2.6.1 Effect of Scratches on Ceramic Brackets

Aknin et al. (1996) reported that the monocrystalline bracket had greater strength than the polycrystalline bracket when a third order moment was applied with an archwire. All ceramic brackets tested had fracture strengths well above moments that they would be subjected to in a clinical setting. However, Flores et al. (1990) found that scratching of the ceramic brackets significantly affected the monocrystalline brackets, but minimally affected the polycrystalline brackets. This result was explained by the Griffith fracture model and the surface finish of the two ceramic brackets types. Since there are many more natural surface imperfections (grain boundaries, particle fusion interfaces) in the polycrystalline ceramic brackets as compared to the monocrystalline ceramic brackets, a scratch on the polycrystalline bracket will have less of a weakening effect than will a scratch on the monocrystalline ceramic bracket. Since polycrystalline brackets are already "prescratched", a typical polycrystalline bracket must have a lower strength than unscratched monocrystalline bracket, whereas a scratched monocrystalline bracket would be similar to a typical polycrystalline bracket.

2.6.2 Areas of Stress Concentration

Studies have been performed on ceramic brackets to determine the sites of stress concentrations and fracture strength of the brittle ceramic material. Ghosh et al. (1995), using a finite element model to show stress concentrations in ceramic bracket designs, reported that moments which produce lingual root movement created a stress concentration at the line angle where the gingival wall of the bracket slot meets the labial surface of the bracket and at the line angle where the incisal wall of the bracket slot meets the base of the bracket slot. These stress concentration areas for the ceramic bracket are similar to those seen in the plastic bracket (Aird et al., 1988).

2.6.3 Fracture of Ceramic Brackets

Fracture resistance of ceramic brackets due to archwire torsion was examined by Holt et al. (1991). Their results showed that the ceramic brackets fractured when subjected to moments in the range of 3700 g-mm to 6100 g-mm. These moments differed by almost a factor of two from the range of acceptable clinical values which is reported to be in the range of 2000 - 3500 g-mm (Reitan, 1957; Wainwright, 1973; Nikolai, 1985). Lindauer et al. (1994) found that second order moments necessary to fracture ceramic brackets were in the range of 15 905 g-mm to 35 291 g-mm for central incisor brackets. A moment of the couple created in the second order is produced by the equal and opposite forces acting at the mesial and distal tie wings of the orthodontic bracket (Figure III). The magnitude of the moment is equal to the magnitude of one of the forces acting at the tie wing of the bracket multiplied by the perpendicular distance between the two forces. The distance between the forces creating a couple in third order mechanics (Figure II) is significantly smaller than the distance between the forces in second order mechanics. Due to the differences in distance between the forces producing the second order and third order couples, the stress levels at fracture which are acting on the bracket tie wings is similar in both methods of moment application (Lindauer et al., 1994).

2.6.4 Deformation of Stainless Steel Brackets

In contrast to ionic and covalent bonds which are the predominant bonds in ceramics and which do not allow for plastic deformation, the predominant bonding in metals are metallic bonds which facilitate plastic deformation (Flores et al., 1990). Flores et al. (1994) used an archwire and torquing key to apply labiolingual torque to orthodontic brackets which were made from different types of stainless steel. They found that the moment required to reach the yield strength of the stainless steel brackets was in the range of 3500 g-mm to 9300 g-mm. The yield strength of a

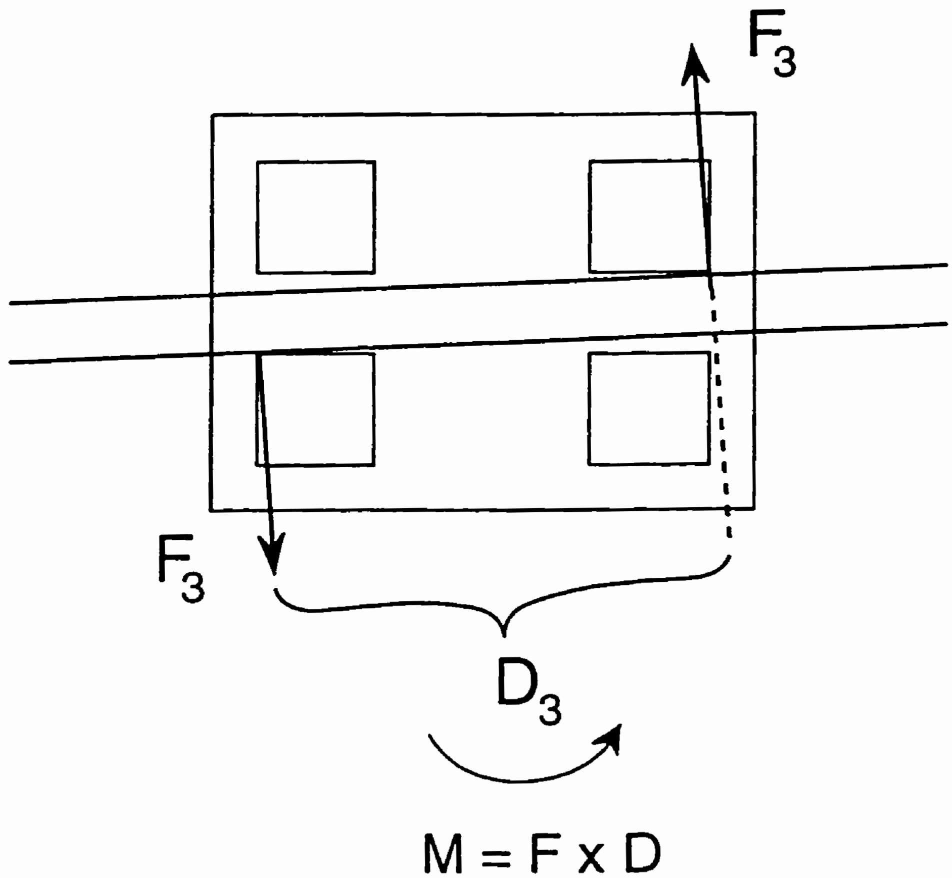

Figure III
Moment of a couple created in the second order. An example of this type of moment is one which will tend to rotate the tooth in a counter-clockwise direction as the right superior bracket wing and left inferior bracket wing resist the movement of the archwire. The magnitude is equal to the magnitude of one of the forces (F_3) multiplied by the perpendicular distance (D_3) between the two forces.
Comparison of Figure II and Figure III shows that the distance D_2 which is the distance between the two forces (F_2) acting within the bracket slot is smaller than the distance D_3 which is the distance between the two forces (F_3) acting between the bracket wings.

material is the stress which approximates the stress at which plastic flow begins and a permanent change in shape of the material occurs (Flores et al., 1994). Their result illustrates that stainless steel brackets may permanently deform if subjected to a large third order moment which exceeds the reported optimum moment values.

2.7 Deformation of Polycarbonate Brackets

2.7.0 Non-reinforced Polycarbonate Brackets and Torque

Few studies have reported on the deformation of polycarbonate brackets when subjected to torque. Dobrin et al. (1975) studied non-reinforced polycarbonate edgewise brackets which were loaded with a full dimension, rectangular, stainless steel archwire of 0.018 x 0.025 inch dimension to simulate lingual root torque. Weights were used to cause the archwire to twist and produce a moment. Each weight was applied for one minute. Bracket deformation was determined by measuring the angle of rotation of the orthodontic wire after loading and unloading of the weight. It was found that a significant amount of deformation (7.75 to 13.5 degrees) occurred when a clinically significant moment was applied. Dobrin et al. (1975) also tested three brackets for periods of 17 to 69 hours under a moment of 2000 g-mm. Creep occurred in these brackets with the total amount of deformation ranging from 16.75 to 29.75 degrees.

2.7.1 Reinforced Polycarbonate Brackets and Torque

Attempts to improve the deformation characteristics of polycarbonate brackets have included the reinforcement of these brackets with ceramic filler and/or stainless steel slot inserts. McKnight et al. (1994) compared stainless steel, ceramic reinforced polycarbonate, and polycrystalline ceramic brackets. With a full dimension archwire delivering a moment, they reported that the ceramic reinforced polycarbonate brackets experienced the greatest amount of distortion while the polycrystalline ceramic brackets exhibited no detectable distortion. Using one type of stainless steel bracket as a control, Feldner et al. (1994) investigated the deformation of different types of polycarbonate brackets when subjected to forces generated by torsion. They reported that polycarbonate brackets which were not reinforced with metal slots exhibited significant deformation and would be unable to transmit a sufficient moment to the teeth. The metal slot reinforced polycarbonate brackets were found to be comparable to stainless steel brackets with respect to their ability to deliver adequate torque upon initial application of the moment. These researchers suggested that there was a need to determine if the ability of polycarbonate bracket to transmit torque will continue throughout treatment or if sufficient creep will occur in the bracket to diminish the ability of the bracket to transmit the necessary torque.

Alkire et al. (1997) tested four different polycarbonate brackets, one stainless steel and one ceramic bracket type with an *in vitro* torque apparatus to investigate the amount of torsional creep in polycarbonate brackets. The test apparatus used a cantilever beam type of arrangement to provide the torsional moment. The cantilever was made from 0.0215 x 0.028 inch stainless steel archwire bent to form an equilateral triangle with the base placed into the bracket slot of 0.022 x 0.028 inch dimension. The archwire was ligated into the bracket slot with wire ligatures and a 100 g weight was suspended from the archwire a distance of 20 mm away from the bracket slot in an effort to produce a 2000 g-mm moment. The apparatus was stored in a water bath at a temperature of 34-37° Celsius for 28 days, and measurements of the angular change in the cantilever were recorded. The reason for storing the apparatus in a water bath is that polycarbonate brackets have been reported to absorb water which may increase their creep characteristics (Winchester, 1992).

Alkire et al. (1997) found no clinically significant difference in creep between the stainless steel, ceramic and metal slot reinforced polycarbonate brackets when loaded for 28 days in an aqueous environment. The above mentioned test apparatus was not, however, without its limitations. Since the cantilever, which created the torsional moment, was perpendicular to the bracket slot before activation there was a decrease in the distance between the weight and the bracket upon loading as a result of the deformation occurring in the bracket and the cantilever archwire which moved inferiorly and towards the bracket upon loading. This effectively reduced the moment applied to the bracket as the perpendicular distance from the line of force to the bracket decreased. The moment was further reduced due to buoyancy of the weight in the water bath. The investigators reported that buoyancy decreased the effective weight by 11.5 g which decreased the moment from 2000 g-mm to 1770 g-mm. The authors reported that although the moment had the greatest effect on the bracket, there were also shear and other forces which occurred during the testing. The use of ligatures to engage the archwire into the bracket slot also introduced a variable into the apparatus.

To date there have been no studies which have utilized a creep test that minimizes extraneous forces to determine the deformation of metal slot reinforced polycarbonate brackets when subjected to a moment. If research can show that there is no clinically relevant deformation of metal slot reinforced polycarbonate brackets when clinically useful moments are applied, then orthodontic treatment with these aesthetic alternative brackets will be viable for most orthodontic patients regardless of the treatment time required.

The aim, therefore, of the this *in vitro* study, was to determine if the metal slot reinforced polycarbonate brackets are sufficiently stiff and creep resistant to maintain the desired labiolingual moment and to compare their performance to that of stainless steel brackets and ceramic brackets exposed to the same labiolingual moment.

3. METHODS AND MATERIALS:

3.0 Test Apparatus Design

A test apparatus was designed to measure the creep in orthodontic brackets subjected to simulated lingual root torque. The final design was selected after evaluating multiple preliminary designs. The apparatus permitted an orthodontic archwire (torquing archwire) to be twisted from both sides of the orthodontic bracket being tested (test bracket), in a manner that simulated lingual root torque (Figure IV). The dimension of both the archwire (Nubryte Gold ®, GAC International, Inc., Central Islip, N.Y.) and the bracket slot were reported by the manufacturer to be 0.018 x 0.025 inch dimension. The archwire was supported by the bracket and support pins which were located on either side of the superior aspect of the test apparatus. The test bracket was bonded to the superior aspect of the test apparatus (Figure VI). A protractor was positioned on the superior aspect of the test apparatus opposite the test bracket (Figure V, Figure VI and Figure VII). A plastic pointer which was used to measure the deformation of the bracket during the test was attached to the archwire between the bracket and the protractor. A torquing beam was positioned between the protractor and one of the support pins while another torquing beam was positioned between the bracket and the other support pin. The positioning of the support pins and the torquing beams resulted in the torquing beams being located equidistant from the test bracket which was bonded to the test apparatus (Figure VII). The torquing beams were attached to the archwire via a ceramic orthodontic bracket (Lumina ®, Ormco Corp., Glendora, CA) which was bonded in the middle of each torquing beam (Figure IV and Figure V). The torquing beams were free to rotate. Weights with a mass of 12.5 grams were hung from positioning grooves located at the front of each torquing beam and produced a twisting movement of the archwire (Figure IV and Figure V). The distance from the ceramic bracket in

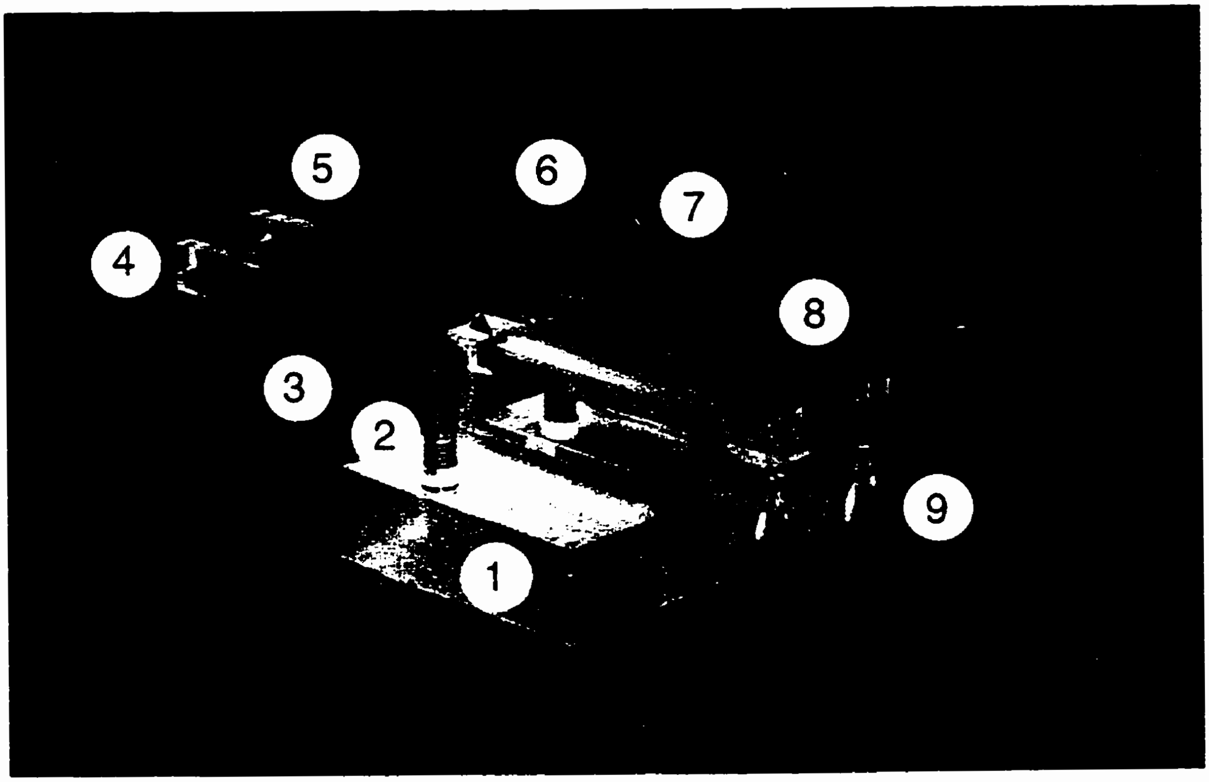

Figure IV
Three-quarter view of the test apparatus with the 2500 g-mm moment applied. Components of the apparatus include: 1. Apparatus base. 2. Support pins. 3. Archwire of 0.018 x 0.025 inch dimension. 4. Ceramic bracket attached to the torquing beam. 5. Test bracket. 6. Plastic pointer. 7. Protractor. 8. Torquing beams. 9. Load of 12.5 grams applied to each torquing beam.

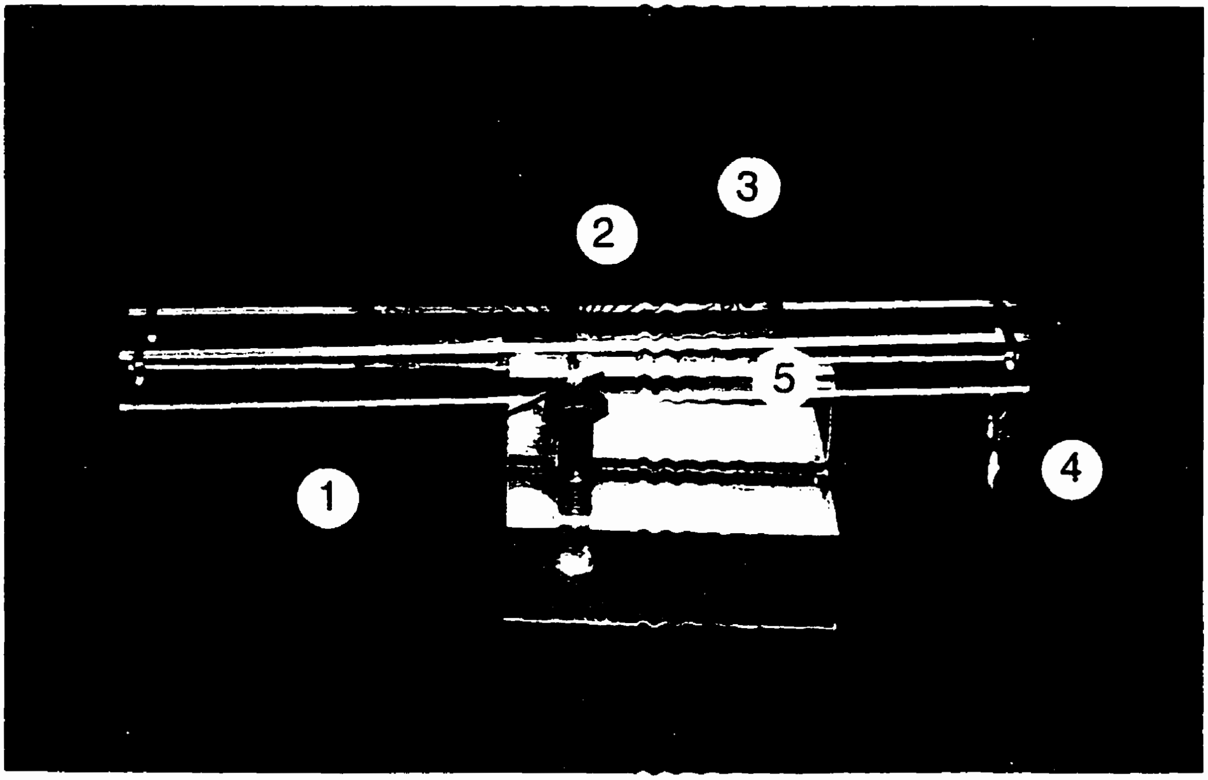

Figure V

Side view of the test apparatus with the 2500 g-mm moment applied. Angular readings were taken from the protractor and plastic pointer which was sharpened at the superior end. The distance from the ceramic bracket, which was attached to the torquing beam, to the groove in the torquing beam where the weights were attached equals 100 mm. Note the test bracket is obscured in this view.
Labelled componets include: 1. Ceramic bracket attached to the torquing beam. 2. Plastic pointer. 3. Protractor. 4. Weights. 5. Moment arm of 100 mm.

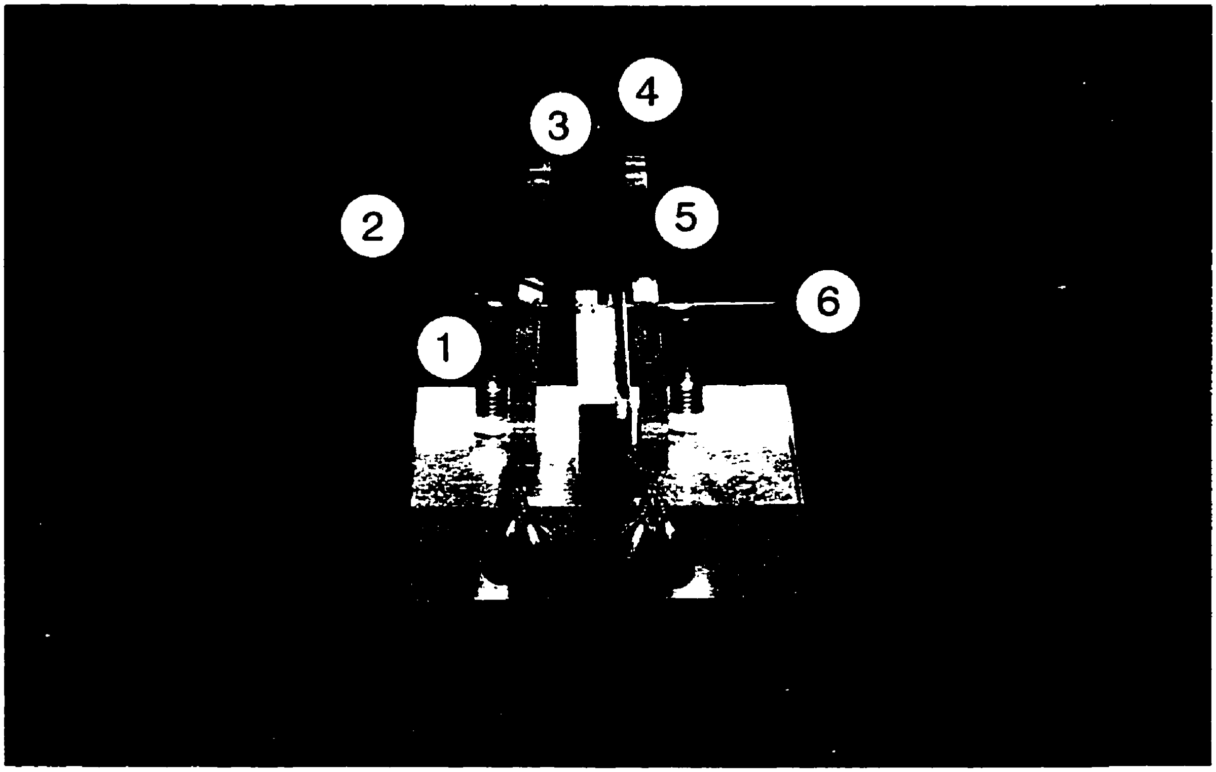

Figure VI

Frontal view of the test apparatus with the 2500 g-mm moment applied. The archwire rests on the support pins and the test bracket. The plastic pointer is luted to the archwire and positioned between the test bracket and the protractor. Both torquing beams are free to rotate which in turn rotates the archwire. Note the torquing beam brackets are obscured in this view.
Labelled components include: 1. Support pin. 2. Test bracket 3. Plastic pointer. 4. Protractor. 5. Torquing beam. 6. Archwire.

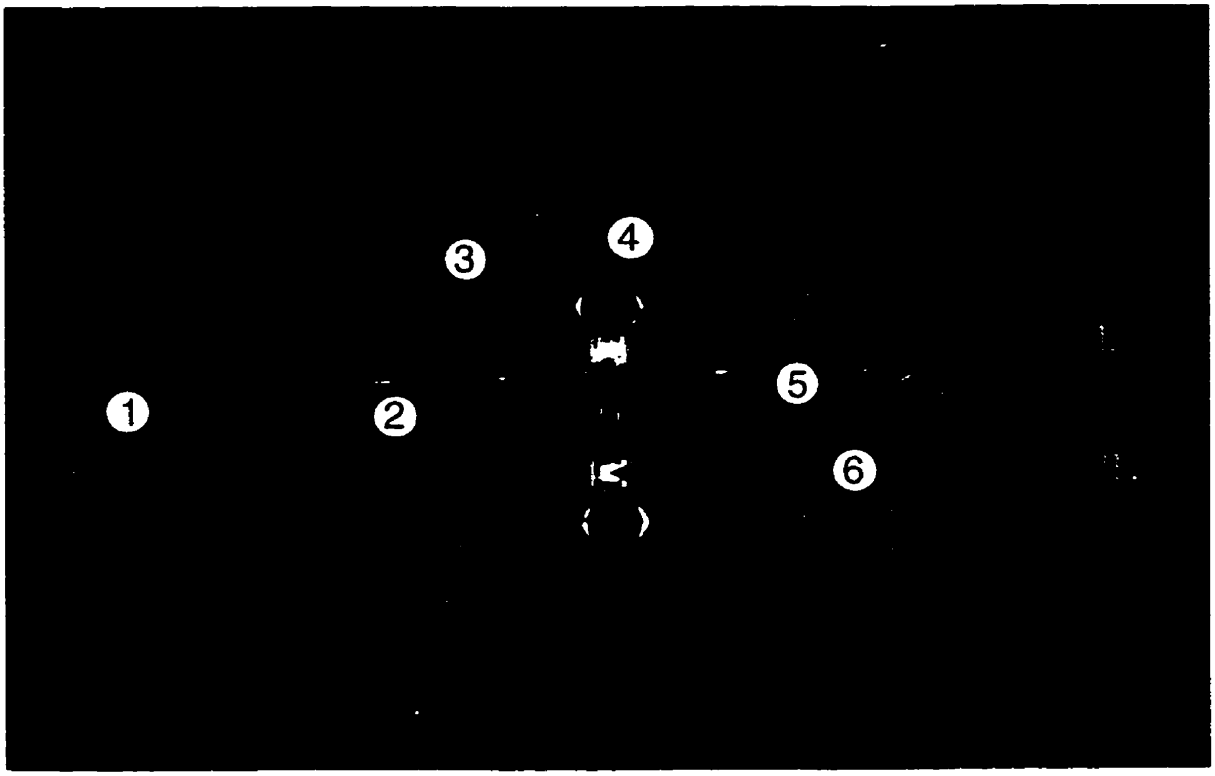

Figure VII

Superior view of the test apparatus. The archwire rests on the support pins and the test bracket. The torquing beams rest on the archwire and are attached to the archwire with ceramic brackets which are luted to the torquing beams. The torquing beams are located equidistant from the test bracket.
Labelled components include: 1. Torquing beam. 2. Test bracket. 3. Plastic pointer. 4. Archwire. 5. Protractor. 6. Moment arm.

the middle of the torquing beam to the positioning groove was 100 mm. The moment created was equal to the force created from the weights hung from both torquing beams (12.5 grams + 12.5 grams) multiplied by the length of the moment arm (100 mm) resulting in a moment of 2500 g-mm. When the torquing beam was in a horizontal position the distance from the positioning groove to the archwire was equal to 100 mm. Due to the design of the apparatus the moment created decreased as the torquing beams deviated from the horizontal position and thereby decreased the effective length of the moment arm. The maximum decrease in the effective length of the moment arm was recorded to be 1.0 ± 1.0 mm. This would result in a maximum decrease in the effective moment arm by 2.0 mm which would be produced by a deviation of the torquing beams from the horizontal position by approximately 11.5° producing a range of moments from 2450 g-mm to 2500 g-mm.

The test apparatus and torquing beams were constructed from industrial acrylic (Cyrolite Acrylic, F.F. Cyro Industries Ltd. Toronto, ON). The support pins were 6.35 mm (1/4 inch) hexagonal steel screws. A detailed description of the apparatus is presented in Appendix I.

3.1 Rational for Apparatus Design

In order to approximate the clinical situation the apparatus was designed to simulate lingual root torque by twisting an archwire in the bracket slot. Attempts were made to eliminate extraneous forces, as would occur in a cantilever beam design, so that the bracket would experience only the forces from the couple created by the twisting of the archwire in the bracket slot. It was decided that two torquing beams would be used as this would apply a more equal stress to both sides of the bracket. The ceramic brackets bonded to the middle of the torquing beams were used to attach the torquing beams to the archwire. Ceramic brackets were used in this capacity as they allowed the torquing beams to be placed on and off the archwire with relative ease so that they could be used for each test. The ceramic brackets represented a readily available attachment device which had the necessary dimensions for the use at hand. The lack of ductility and creep of the material made these brackets suitable for the purpose of attaching the torquing beam to the archwire. The torquing beams were located equidistant from the test bracket which was bonded to the superior aspect of the test apparatus in an attempt to produce an equal amount of twist in the archwire from either side of the bracket. The torquing beams were also placed as close as possible to the superior aspect of the test apparatus, while remaining equidistant from the test bracket, to decrease the amount of twisting of the archwire and maintain the torquing beams close to a horizontal position relative to the base of the apparatus. By maintaining the torquing beams in the horizontal position the desired moment was maintained. The protractor permitted angular measurement with accuracy of 0.5 degrees to be made which was deemed to be adequate. A plastic pointer was used instead of metal since soldering a metal pointer to the archwire may have affected the archwire properties and therefore affected the test results. The design of the apparatus also allowed the archwire to be place in the bracket without the need for ligation which could have affected the twisting of the archwire in the bracket slot and added support to the tie wings. Ligation would have added another variable to the test which would have been difficult to standardize.

3.2 Bracket and Bonding Agent Materials

A total of 60 brackets, ten polycrystalline ceramic brackets (Lumina ®, Batch # 5L2, Ormco Corp., Glendora, CA), twenty stainless steel brackets (Omni Arch ®, Group # 5681, GAC International, Inc., Central Islip, N.Y.), thirty polycarbonate brackets reinforced with metal slots (14 Spirit MB ®, Batch # 6F21, Ormco Corp., Glendora, CA. and 16 Elan ®, Group # 6415, GAC International, Inc., Central Islip, N.Y.) were tested at the 2500 g-mm moment. Because of a high debonding incidence of the stainless steel and polycarbonate brackets, this number of brackets was needed in order to obtain four groups of ten brackets each which remained bonded to the test apparatus for the full 28 day test period. The four bracket types used can be seen in Figure VIII. All brackets used in the experiment were maxillary left central incisor brackets with a manufacturer reported slot size of 0.018 inches x 0.025 inches. The Omni Arch and Elan brackets had 12° of torque built into the bracket slot whereas the Lumina and Spirit MB brackets had 14° of torque built into the bracket slot.

The Lumina brackets are composed of polycrystalline alumina. The base of the bracket is coated with spheres to create a bonding surface which provides 100% mechanical bonding. The spheres which are hollow and are made of zirconia are 37 microns to 44 microns in size. The Omni Arch brackets are made from stainless steel and use a mesh base to facilitate mechanical bonding. The Spirit brackets are made from polycarbonate with ceramic filler particles and a metal slot insert. The base of the bracket has multiple mushroom-like projections which provide mechanical bonding. The Elan brackets are also made from polycarbonate material with a ceramic filler and metal slot insert. The Elan bracket, however, utilizes plastic primer (Elan bracket adhesive starter's kit, GAC International, Inc., Central Islip, N.Y.) to produce a chemical bond. A thin layer of the plastic primer is applied to the bracket followed by an unfilled bonding resin which is then light cured for 10 seconds.

The bonding resin used to lute the brackets was Transbond XT ® (Lot # 013096, 3M Unitek, Monrovia, CA). Trans-Bond is a light cured resin adhesive which includes an unfilled bonding resin primer and a filled resin adhesive.

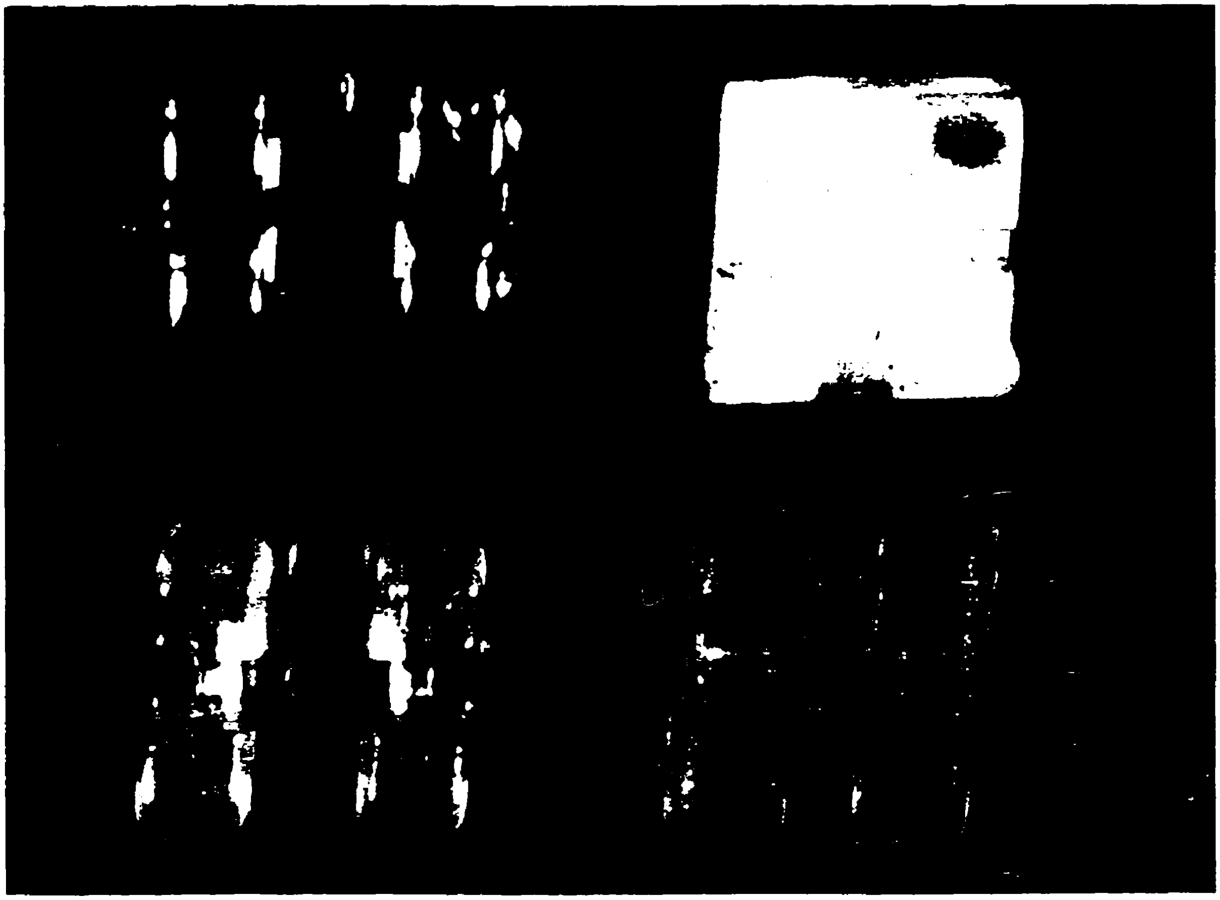

Figure VIII

The four test brackets used in the experiment were twin brackets with a slot size of 0.018 x 0.025 inches. The brackets from the top left in a clockwise manner are: Omni Arch (stainless steel), Lumina (polycrystalline ceramic), Spirit (polycarbonate), Elan (polycarbonate).

3.3 Pilot Studies

Before the design of the apparatus was finalized several pilot studies were performed to delineate certain design variables.

3.3.0 First Pilot Study

The first pilot study determined whether there was a difference between using one torquing beam which would generate the desired moment from only one side of the test bracket or using two torquing beams on either side of the test bracket to produce the desired moment. A moment of 2000 g-mm was generated by both methods. There was no significant difference in the amount of permanent deformation which occurred over the 17 day test period (unpaired, two tailed t-test, $t = 0.25$, $df = 2$, non-significant $p>0.05$).

Although a single beam apparatus would be simpler to build, the final design used two torquing beams, one on either side of the test bracket, in order to more equally distribute the stresses across the bracket slot.

3.3.1 Second Pilot Study

A second pilot study was performed to evaluate the suitability of using a moment which represented the moment of greatest magnitude reported in the literature. Since a review of the literature revealed that the range of acceptable moments for third order torque is 2000 g-mm to 3500 g-mm (Reitan, 1957; Wainwright, 1973; Nikolai, 1985; Holt et al., 1991), a moment of 3500 g-mm was selected for this pilot study.

Ten ceramic brackets were bonded to the test apparatus as described previously. A moment of 3500 g-mm was applied to the test bracket. There were no debonds of the ceramic brackets from the test apparatus over the 28 day test period (Table I).

Lumina (Ceramic Brackets)
Raw data, using a 3500 g-mm moment measured at various intervals

First Measurement

	0.5 g	0.5 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	78.0	74.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	73.0	78.5
App. #2	74.5	74.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	74.0	74.0
App. #3	75.0	76.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	76.0	75.5
App. #4	73.5	70.5	78.0	78.0	78.0	78.0	78.5	78.0	78.5	78.0	73.0	75.0
App. #5	76.0	75.5	79.0	79.0	79.0	79.0	79.5	79.5	79.5	79.5	76.0	76.0
App. #6	75.0	75.0	79.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5	75.5	75.0
App. #7	75.5	76.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5	77.0	75.5
App. #8	75.5	71.0	76.0	76.0	76.0	76.0	76.0	76.0	76.0	76.0	71.0	75.0
App. #9	73.5	75.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	75.5	73.5
App. #10	76.0	76.5	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	76.5	76.0

Second measurement

	0.5 g	0.5 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	78.0	74.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	73.5	78.5
App. #2	74.5	74.5	78.0	78.0	78.0	78.0	78.0	78.0	78.0	78.0	74.0	74.0
App. #3	75.0	76.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	76.0	75.5
App. #4	74.0	70.5	77.5	78.0	78.0	78.0	78.0	78.0	78.0	78.0	73.0	75.0
App. #5	76.0	75.5	79.0	79.0	79.0	79.0	79.5	79.5	79.5	79.5	76.0	76.0
App. #6	75.0	75.0	79.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5	75.5	75.0
App. #7	75.5	76.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5	79.5	77.0	76.0
App. #8	75.5	71.0	76.0	76.0	76.0	76.0	76.0	76.0	76.0	76.0	71.0	75.5
App. #9	73.5	75.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	79.0	75.5	73.5
App. #10	76.0	76.5	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	76.0	76.0

<u>Table I</u>

INW = Initial reading using the non-working arch wire with the 0.5 gram weights
IW = Initial reading using the working arch wire with the 0.5 gram weights
Init = Initial reading using the working arch wire with the 35 gram weights
D = Day
FW = Final reading using the working arch wire and the 0.5 gram weights
FNW = Final reading using the non-working arch wire and the 0.5 gram weights
App. = Apparatus

When the Spirit brackets were bonded to the test apparatus and subjected to the 3500 g-mm moment, all ten of the brackets debonded within a 24 hour period. Due to this problem, a third pilot study was conducted to determine a suitable moment.

3.3.2 Third Pilot Study

The third pilot study was conducted to select the moment to be used for testing the brackets. Since no ceramic brackets debonded when subjected to a moment of 3500 g-mm only Omni Arch and Spirit test brackets were used. The third pilot study evaluated moments of 2000 g-mm, 2500 g-mm, 3000 g-mm and 3500 g-mm. All the stainless steel brackets subjected to the 3500 g-mm moment debonded within hours of the moment application and the Spirit brackets all debonded within 3 days. At 3000 g-mm the stainless steel and Spirit brackets all debonded within 3 days. With a 2500 g-mm moment there was no debonding of the Spirit brackets after 3 days whereas the stainless steel brackets tested had one bracket which did not debond and one which debonded after 2 days. There were no debonds of either the Spirit or the stainless steel brackets when a moment of 2000 g-mm was used.

Based on the results of the pilot study a moment of 2500 g-mm was selected because it appeared to represent the upper limit of moment application while maintaining bracket adhesion to the test apparatus.

3.4 Test Procedure

The brackets to be tested (test brackets) were bonded to the superior aspect of the test apparatus on the side opposite to the protractor slot. The brackets were aligned so that the bracket slot was perpendicular to the length of the test apparatus and so that a rectangular stainless steel archwire (torquing archwire) when placed in the bracket slot, also rested on the flat surface of the support pins (Figure VI and Figure VII). The gingival aspect of the bracket was closest to the front of the test apparatus. The test brackets were bonded to the acrylic by placing a thin layer of acrylic solvent bonding liquid (WELD-ON 3, IPS Corp. Gardena, CA.) on the acrylic in the area where the test bracket was to be bonded. The action of the solvent is to break apart temporarily the polymerized chains which are held together with secondary bonding forces between the polarized molecules in the acrylic. Once these chains are separated the bonding resin may flow in between the polymerized chains. The bonding resin could be a resin that is dissolved in the solvent, or it could be the solvent itself. As the secondary bonding forces join the polymer chains back together, following the evaporation of the solvent, the resin which has penetrated between the chains of the polymer is "bonded" into the polymer by both mechanical interlocking and secondary bonding forces. If excess solvent was placed on the acrylic it was allowed to evaporate until there was only a thin layer remaining. Before the solvent totally evaporated unfilled bonding resin primer was placed on the solvent and light cured for 10 seconds. The filled resin adhesive was then applied to the base of the test bracket and the bracket positioned on the test apparatus in the manner described above. The bracket was manually seated onto the acrylic. The excess resin that extruded from beneath the bracket base was removed from the sides of the bracket before light curing. All brackets were light cured from all four sides for a period of 10 seconds per side and then for an additional 10 seconds through the base of the apparatus. All test brackets, except the Elan brackets, utilized mechanical bonding of the adhesive to the base of the bracket. The Elan brackets which required solvent bonding and a plastic primer supplied by the manufacturer (Elan Light Cure PCM Adhesive, Resin "P") were bonded according to the manufacturer's instructions. A thin layer of the primer was applied to the bracket base followed by the unfilled resin which was light cured for a period of 10 seconds.

The archwire was placed in the test bracket such that the plastic pointer which was fixed to it was located between the test bracket and the protractor slot while the archwire rested evenly in the bracket slot and on the support pins (Figure VI and Figure VII). The protractor was then fitted into place and secured with dental utility wax. Care was taken to ensure that no wax was placed in the area of the archwire. A hole in the base of the protractor enabled the protractor to be placed on top of the archwire so that the archwire and plastic pointer were located at the focal point of the protractor (Figure IV and Figure V). To reduce the parallax error the archwire was then moved, if needed, so that the plastic pointer was as close to the protractor as possible without being in contact.

The torquing beam brackets engaged the archwire so that they were equidistant, 13.5 ± 1 mm, from the test bracket. A 0.25 ± 0.01 gram weight (pre-load) was placed in the positioning groove at the front of both torquing beams. This weight caused rotation of both the torquing beams and the archwire in the test bracket so that any archwire bracket slot dimensional discrepancy remaining between the archwire and the test bracket was eliminated. A zero point reading was recorded from the protractor. To reduce parallax error during the reading, the investigator utilized one eye only and centred that eye perpendicular to the protractor and in line with the 90° angle indicator of the protractor. Since the first archwire which represented the non-working archwire, was not stressed or permanently deformed by the heavier weights which were used to simulate the lingual root torque, it was used as a reference archwire to measure the permanent deformation of the brackets after the application of the working load. Upon completion of the zero point reading the 0.25 ± 0.01 gram weights were removed from the torquing beams, the torquing beams were removed from the archwire, and the non-working archwire was removed while leaving the protractor in place.

A new archwire with pointer, the working archwire, was placed into the test bracket, the torquing beams were placed on the archwire and the 0.25 ± 0.01 gram weights were placed in the positioning grooves at the front of the torquing beams. A zero-point recording for the working archwire was made from the protractor. The 0.25 gram weights were removed and the two 12.5 ● 0.01 gram weights (working load) were hung from the positioning grooves at the front of each torquing beam. Immediately, the deflection at the initial working load was read and recorded from the protractor. Further readings were recorded at 1 hour after initial load, 2 hours after initial load, 24 hours after initial load, day 7, day 14, day 21, and day 28 to determine the plastic deformation caused by creep.

At day 28 the 12.5 ± 0.01 gram weights were removed and the 0.25 ± 0.01 gram weights were placed back in the positioning grooves. A recording was made which represented the final reading for the working archwire. The pre-load weights were removed, the torquing beams removed from the archwire as well as the working archwire without disturbing the protractor. The non-working archwire was then placed into the test bracket and the torquing beams placed back on the archwire. The 0.25 ● 0.01 gram weights were placed into the positioning grooves on the torquing beams and a reading was recorded from the protractor. This reading which represented the final reading from the non-working archwire was subtracted from the initial reading of the non-working archwire to give the value of the brackets permanent deformation over the 28 day period.

All recordings were performed a second time, 15 minutes after the initial recordings as a means of determining intra-examiner reliability.

Following the completion of each trial, the torquing beams, archwire, protractor and test bracket were all removed from the test apparatus and a new test bracket luted to the test apparatus to begin another test. A new, unused working archwire was used for each test so that each bracket tested would begin with an unstrained archwire.

An additional investigation was used to determine initial plastic deformation. Initial plastic deformation of the test bracket was measured with the same test apparatus and procedure as previously described with the exception that the torquing beams were only loaded with the 12.5 ± 0.01 gram weights for a period 1 minute. Twenty additional, new brackets (five from each group) were used for this test. The difference between the zero point measurement for the non-working archwire and the final reading for the non-working archwire represented the initial plastic deformation of the test bracket.

3.5 Error Study

The use of a non-working archwire to evaluate the deformation caused by creep in the test brackets was necessary in order to avoid the possible contribution of any permanent deformation of the working archwire that may have occured when it was stressed under a constant load. In order to be confident that inter-changing the working and non-working archwires had no effect on the angular measurement, an error study was conducted. Nine brackets were tested, three Omni-Arch, three Spirit and three Elan. The brackets were bonded and the archwire/pointer and protractor were positioned as previously described. Two readings were taken. For the first reading the torquing beams were placed on the archwire as close to the test bracket as possible. The 0.25 ± 0.01 gram weights were placed in the positioning grooves and an angular measurement recorded. The torquing beams and the archwire were removed without disturbing the protractor. The archwire was then placed back into the test bracket slot. For the second reading the torquing beams were placed on the archwire as far as possible away from the test bracket without touching the support pins. A second angular measurement was then recorded. If the two measurements were the same, then variations in the location of the non-working archwire would not effect the measurement accuracy and the use of the non-working archwire to evaluate the total plastic deformation is justified.

3.6 Method of Data Analysis

3.6.0 Intra-examiner Reliability

Intra-examiner reliability was evaluated to determine if repeat measurements were consistent. All measurements were recorded a second time approximately 15 minutes after the initial measurements. Intra-class correlation coefficients were used to statistically evaluate if the first and second measurements were the same and therefore determine the reliability of the measurements.

3.6.1 Total Deformation Upon Initial Moment Application

The total amount of deformation (plastic and elastic) upon initial moment application of 2500g-mm was calculated by subtracting the initial angular deflection created by the preload from that caused by the initial application of the working load. The former value was the zero point for the working archwire. All four test groups were compared using ANOVA and Tukey's multiple comparison test.

3.6.2 Plastic Deformation Upon Initial Moment Application

The procedure for determining the plastic deformation of the test brackets upon initial application of the 2500 g-mm moment was described in Section 3.4. The four different bracket groups were compared with ANOVA and Tukey's multiple comparison test.

3.6.3 Plastic and Creep Deformation

The amount of plastic deformation including that contributed by creep was determined by subtracting the final non-working archwire reading with the 0.25 gram weights from the zero point reading of the non-working archwire. ANOVA and Tukey's multiple comparison test was used to determine if there were differences between the groups. To determine the contribution made by creep, the initial plastic deformation produced by the application of the 2500 g-mm moment was subtracted from the total amount of permanent deformation found in the bracket after the 28 day test period.

3.6.4 Pattern of Deformation

A repeated measures ANOVA was used to determine if there was a pattern with respect to when the deformation of the brackets took place.

3.6.5 Archwire Plastic Deformation

The difference between the change in the working archwire compared to the change in the non-working archwire was evaluated using a paired t-test to determine if there was plastic deformation which occurred in the working archwire over the 28 day experimental period.

3.7 Bracket Debonds during Experiment

Using a stereo microscope with magnification up to 12.5 times, representative debonded brackets and test apparati were examined and photomicrographs were taken to record the pattern of the debonded surfaces.

4. RESULTS

4.0 Elastic / Plastic Deformation Upon Initial Moment Application

The amount of deformation recorded included the elastic and plastic deformation occurring in the archwire as well as the test bracket. The mean deformation in degrees upon initial loading for the Lumina (ceramic) bracket was 3.45°, for the Omni Arch (stainless steel) 5.95°, for the Spirit (polycarbonate) 7.95° and for the Elan (polycarbonate) 8.05°. The mean deformation and standard deviations are shown in Table II and in Figure IX. The unpaired, two way analysis of variance and Tukey's multiple comparison test revealed that there was a significant difference between the ceramic, stainless steel and polycarbonate brackets ($p < 0.05$), but no significant difference between the two types of polycarbonate brackets ($p > 0.05$) which exhibited the greatest amount of deformation.

4.1 Plastic Deformation Upon Initial Moment Application

The mean plastic deformation occurring upon initial application of the 2500 g-mm moment for the Lumina and Omni Arch test brackets was 0.1° and 0.5°. Mean plastic deformation for the Spirit and Elan brackets was 1.3° and 1.4° respectively. Table III and Figure X illustrate the mean amount of the plastic deformation found in the test brackets upon the initial moment application of 2500 g-mm. The mean amount of plastic deformation did not include any contribution by the archwire as readings were taken using the non-working archwire. An unpaired, two way analysis of variance and a Tukey's multiple comparison test illustrated that there was no statistically significant difference between the ceramic and stainless steel brackets nor was there a statistically significant difference between the Spirit and Elan brackets ($p > 0.05$). However, the ceramic and stainless steel brackets had significantly less plastic deformation than the Spirit and Elan brackets ($p < 0.05$).

Elastic / Plastic Deformation
Moment of 2500 g-mm

	Degree (°)	Standard Deviation	p< 0.05
Lumina (Ceramic)	3.45	0.60	A
Omni Arch (Stainless Steel)	5.95	0.80	B
Spirit (Polycarbonate)	7.95	1.09	C
Elan (Polycarbonate)	8.05	0.90	C

Table II
The mean elastic and plastic deformation upon initial application of the 2500 g-mm moment is calculated as the change in degrees from the "zero point" reading with the 0.5 gram load to the angular reading upon initial application of the 25 gram load. The deformation in the test bracket and the working archwire are included. The letter at the right side of the table indicates whether statistical differences exist between the different bracket types ($p<0.05$). Different letters indicate significant differences between the groups.

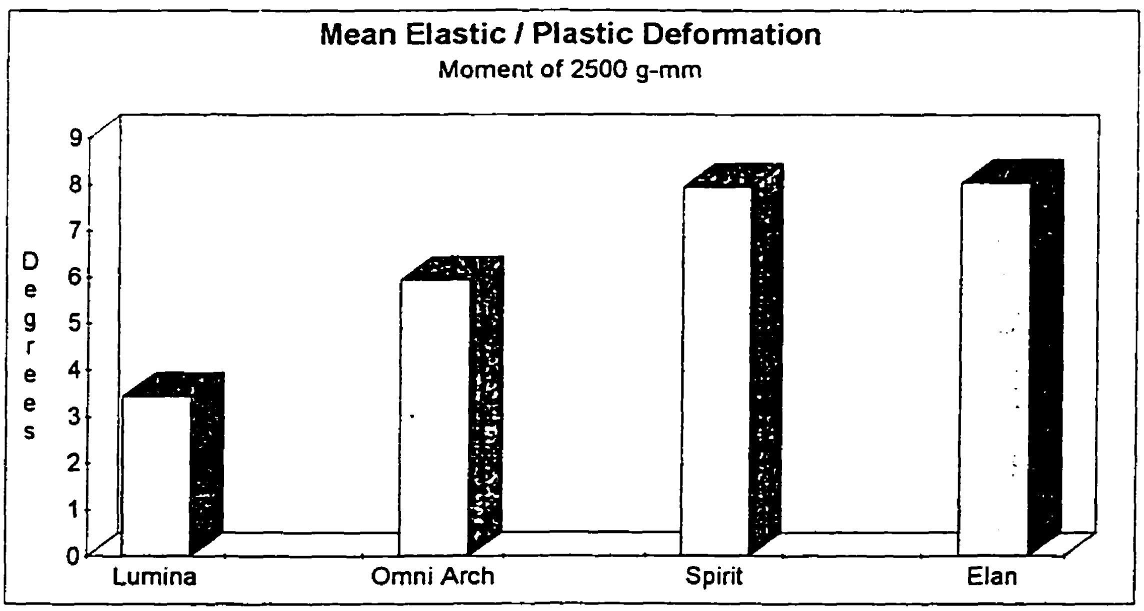

Figure IX
Graphic representation of Table II comparing the mean elastic / plastic deformation which occurred upon initial application of the 2500 g-mm moment.

Mean Plastic Deformation
Moment of 2500 g-mm

	Degree (°)	Standard Deviation	p< 0.05
Lumina (Ceramic)	0.10	0.22	A
Omni Arch (Stainless Steel)	0.50	0.35	A
Spirit (Polycarbonate)	1.30	0.45	B
Elan (Polycarbonate)	1.40	0.55	B

Table III
The mean amount of plastic deformation was similar between the ceramic and metal brackets ($p>0.05$). There was a significant amount of plastic deformation found in the polycarbonate brackets ($p<0.05$). The letter at the right side of the table indicates whether statistical differences exist between the different bracket types ($p<0.05$).

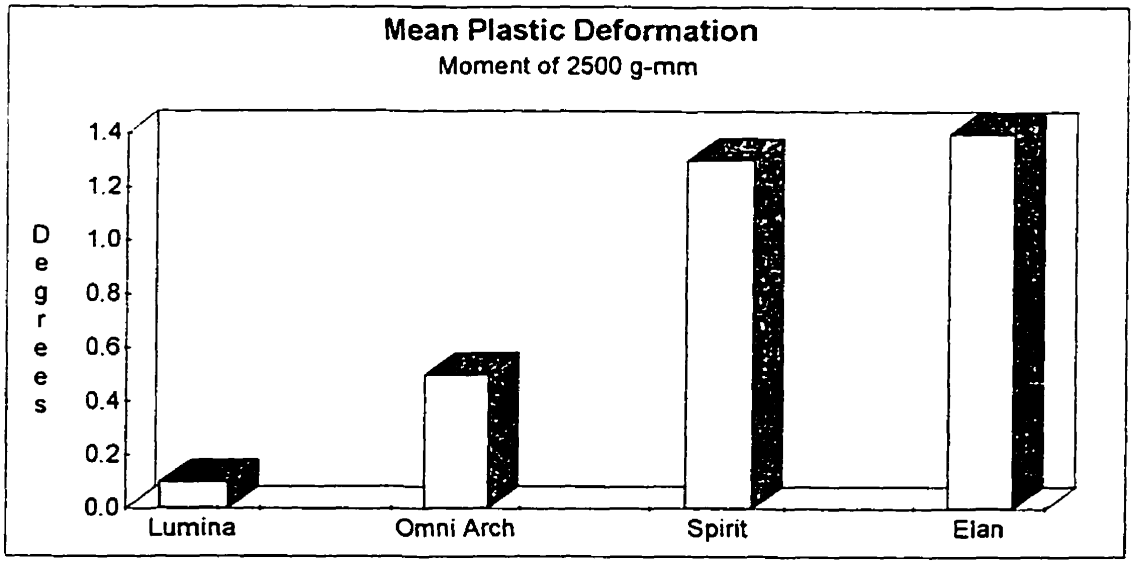

Figure X
Graphic representation of Table III comparing the mean amount of plastic deformation for each bracket type upon initial application of 2500 g-mm moment.

4.2 Plastic Deformation Including Creep

The mean amount of plastic deformation including creep which occurred over the 28 day test period for the Lumina and Omni Arch brackets was 0.05° and 0.3° respectively. These values (0.05° and 0.3°) represent a decrease over the mean amount of plastic deformation upon initial moment application for both the Lumina and Omni Arch brackets. However, the measurements for plastic deformation upon initial moment application and plastic deformation including creep over the 28 day test period for both the Lumina and the Omni Arch brackets were within the measurement error of 0.5°. Therefore, the differences found in the recordings were likely representative of measurement error. The Spirit and Elan brackets had a mean plastic deformation over the 28 day test period of 2.00° and 2.05° respectively. This represented a mean increase in the amount of plastic deformation of 0.7° and 0.65° respectively for the Spirit and Elan brackets compared to the initial amount of mean plastic deformation which occurred with the initial application of the 2500 g-mm moment. Table IV and Figure XI illustrate the mean plastic deformation over the 28 day test period which occurred in each bracket type. An unpaired, two way analysis of variance and a Tukey's multiple comparison test was used to compare the mean amount of plastic deformation over the 28 day test period for each of the bracket types. The statistical analysis found that the ceramic and stainless steel brackets were not significantly different ($p > 0.05$) and the Spirit and Elan brackets were also statistically similar ($p > 0.05$). However, the ceramic and stainless steel brackets exhibited significantly less deformation over the 28 day period compared to the Spirit and Elan brackets ($p < 0.05$).

4.3 Mean Pattern of Deformation

The mean pattern of deformation included the creep deformation of the test bracket and the working archwire. The Lumina brackets demonstrated no significant

Mean Plastic Deformation Over 28 Day Period

	Degree (°)	Standard Deviation	p< 0.05
Lumina (Ceramic)	0.05	0.28	A
Omni Arch (Stainless Steel)	0.30	0.26	A
Spirit (Polycarbonate)	2.00	0.91	B
Elan (Polycarbonate)	2.05	0.69	B

Table IV
The mean amount of plastic deformation (initial plastic deformation plus creep) was calculated using the non-working archwire to eliminate possible influences created by plastic deformation of the working archwire. There was essentially no plastic deformation in the ceramic and stainless steel brackets ($p>0.05$), but the polycarbonate brackets exhibited significant plastic deformation ($p<0.05$). The letter at the right side of the table indicates whether statistical differences existed between the different bracket types ($p<0.05$).

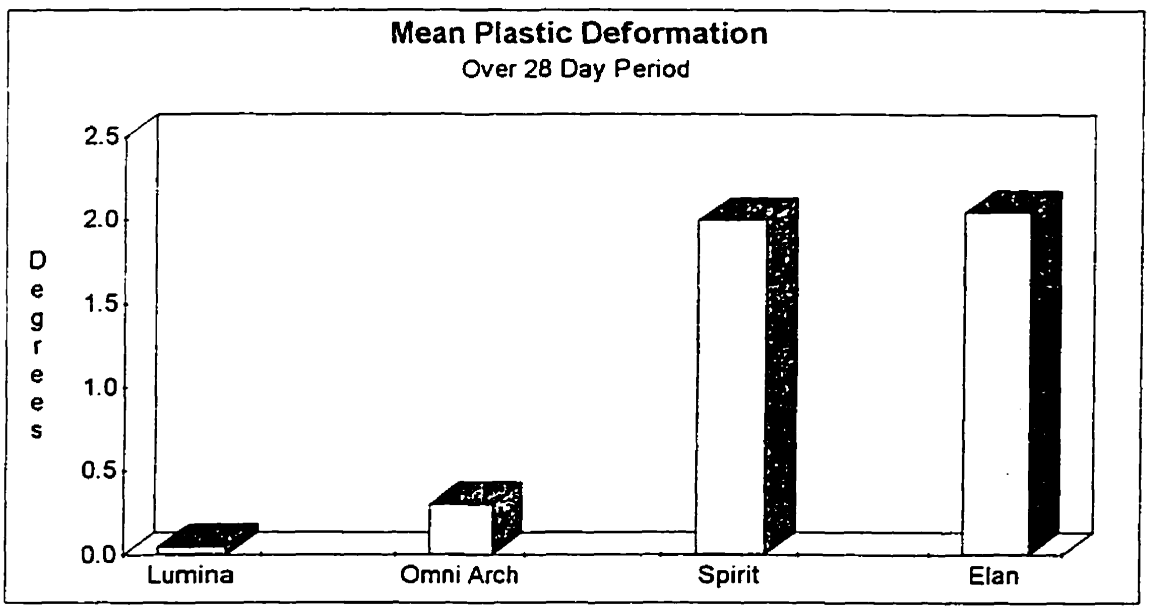

Figure XI
Graphic representation of Table IV comparing the mean plastic deformation of the different bracket types.

deformation during the entire test period of 28 days. The Omni Arch bracket exhibited significant deformation ($p < 0.05$) relative to the initial reading at day 7 with no further significant deformation occurring over the remainder of the test period ($p > 0.05$). The Spirit bracket had significant deformation ($p < 0.05$) relative to the initial reading at 2 hours. There was a continued significant increase in the amount of deformation ($p < 0.05$) for the Spirit brackets at 24 hours, day 7 and day 21. The Elan brackets exhibited significant deformation ($p < 0.05$) relative to the initial reading at 2 hours. Continued deformation occurred with the Elan brackets with significant deformation ($p < 0.05$) occurring at day 7 and day 21. There appeared to be a gradual and continual increase in the plastic deformation for both the Spirit and Elan brackets over the 28 day test period. Table V illustrates the pattern of deformation.

4.4 Archwire Plastic Deformation

A paired t-test showed that the working archwire readings had a significantly greater amount of angular change compared to the non-working archwire ($p < 0.05$) with a mean difference of $0.375° \pm 0.732°$. This would suggest that there was plastic deformation of the working archwire during the experimental period.

4.5 Bracket Debonds During Experiment

The stainless steel brackets exhibited the greatest variability with respect to debonding with 10 out of 20 of the tested brackets debonding prior to the end of the 28 day experimental period. The time periods when the debonds occurred was as follows: one before hour 1, three before hour 24, four before day 7 and two before day 21 (Table VI).

Lumina Brackets

Initial	A
1 Hour	A
2 Hour	A
24 Hour	A
Day 7	A
Day 14	A
Day 21	A
Day 28	A

Omni Arch Brackets

Initial	A
1 Hour	A
2 Hour	A
24 Hour	AB
Day 7	BC
Day 14	BC
Day 21	C
Day 28	C

Spirit Brackets

Initial	A
1 Hour	AB
2 Hour	B
24 Hour	C
Day 7	D
Day 14	DE
Day 21	EF
Day 28	F

Elan Brackets

Initial	A
1 Hour	AB
2 Hour	BC
24 Hour	CD
Day 7	DE
Day 14	EF
Day 21	F
Day 28	F

<u>Table V</u>

Repeated Measures ANOVA

The pattern of the average deformation (elastic and plastic) which was recorded during the specified time periods is shown. The Omni Arch, Spirit and Elan brackets appeared to exhibit some deformation over time. The pattern of increasing deformation was more evident in the polycarbonate brackets (Spirit and Elan) than it was in the stainless steel (Omni Arch) brackets. The Lumina brackets did not exhibit any pattern of deformation.

The Elan brackets totalled 6 debonds out of the 16 which were tested. The time periods for which debonds occurred for the Elan brackets was as follows: one before day 7, two before day 14, two before day 21, one before day 28 (Table VI).

Spirit brackets had a total of 4 debonds out of the 14 tested at 2500 g-mm. Debonds occurred at: three before day 7 and one before day 21 (Table VI).

The ceramic brackets exhibited no debonds at the 2500 g-mm moment.

Test Bracket Debonds
Moment of 2500 g-mm

Bracket Type	Brackets Tested	1 Hour	24 Hour	Day 7	Day 14	Day 21	Day 28	Total
Lumina	10	0	0	0	0	0	0	0
Omni Arch	20	1	3	4	0	2	0	10
Spirit	14	0	0	3	0	1	0	4
Elan	16	0	0	1	2	2	1	6

Number of Debonds

Table VI
The number of brackets for each bracket type which debonded at each measurement interval

Debonding of the test brackets prematurely during the experiment while utilizing a 2500 g-mm moment occurred in a complex manner. The majority of the bonding resin remained on the test apparatus with isolated areas of resin tags remaining attached to the bracket (Figure XII, Figure XIII and Figure XIV). There was also evidence of the mushroom-like retentive elements of the Spirit MB brackets fracturing and remaining with the bonding resin on the apparatus (Figure XIII).

4.6 Intra-examiner Reliability

There was an excellent reliability between the first and second measurements which were taken for each time interval for each bracket type. An intra-class correlation coefficient of 1.0 would represent 100% agreement between the first and

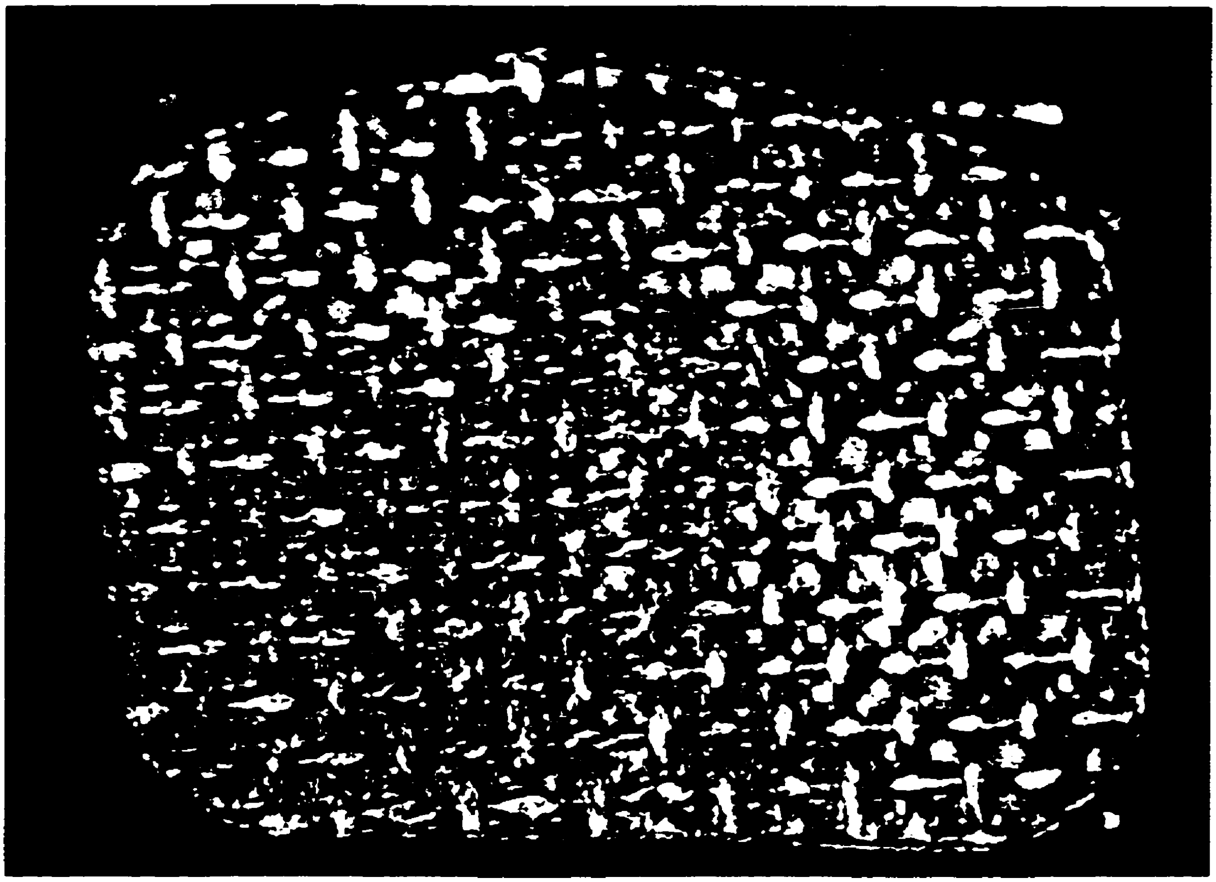

Figure XII

Photomicrograph of a debonded Omni Arch bracket (5x magnification). Evidence of a few resin tags in the wire mesh at the gingival (top of photo) and mesial (right of photo) aspects of the bracket base.

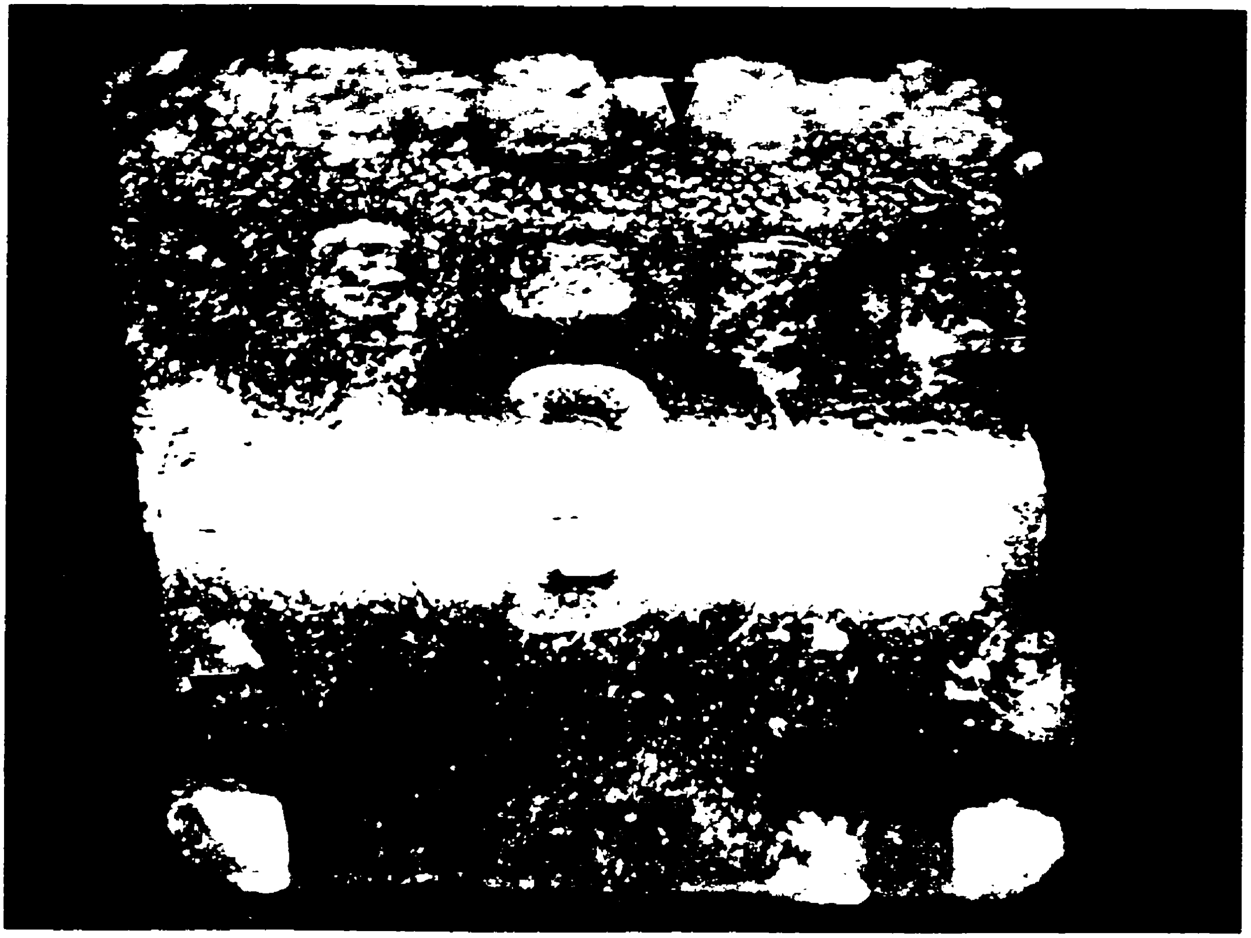

Figure XIII

Photomicrograph of a debonded Spirit bracket (5x magnification). The mechanically retentive base can be seen with evidence of a few resin tags on the gingival half of the bracket base (top of photo) and some fractures of the retentive elements in the incisal half of the bracket base (bottom of photo).

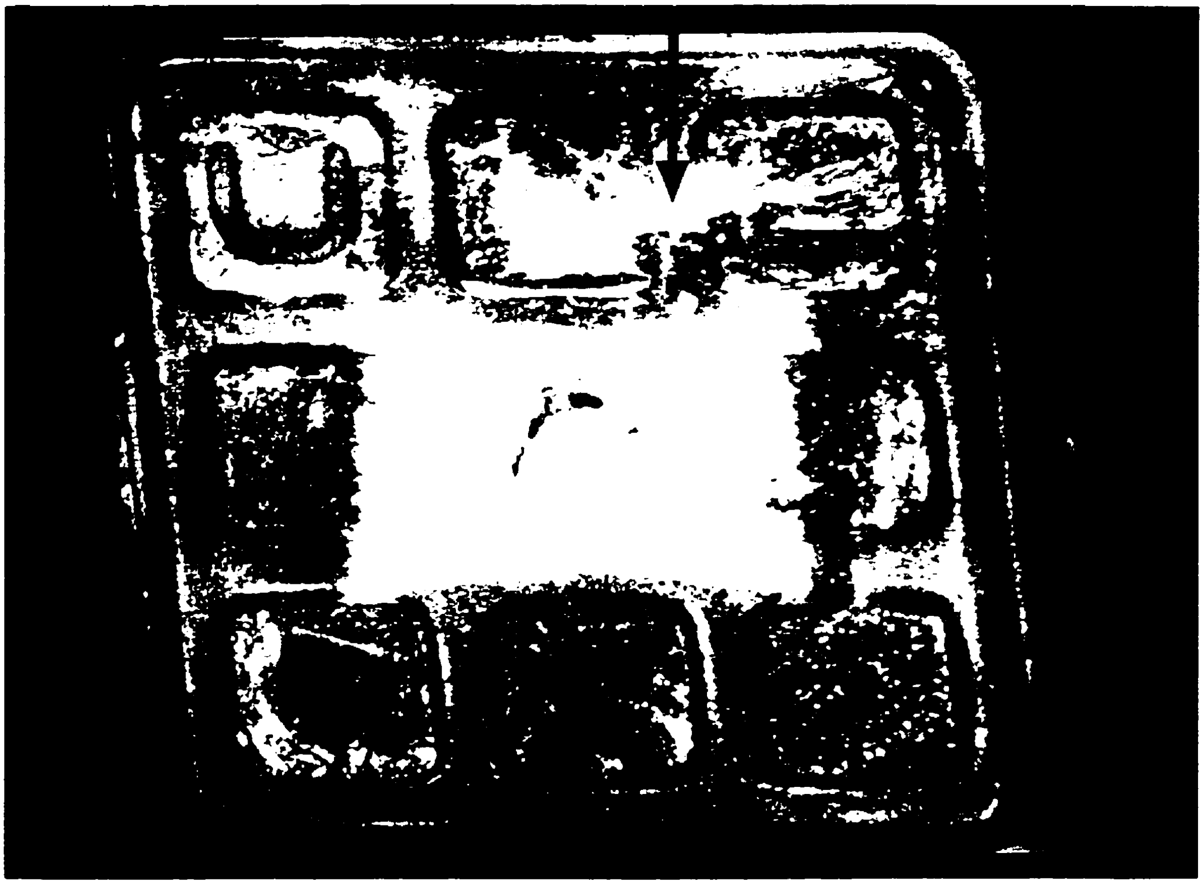

Figure XIV

Photomicrograph of a debonded Elan bracket (5x magnification).
Evidence of a resin remnant in the recessed area of the gingival aspect of the bracket base (top of photo).

second measurements. The intra-class correlation coefficient for the initial non-working archwire was 0.99743 95% CI (0.99561, 0.99849) which represents very good reliability, as 0.99743 closely approaches 1.0, at the 95% confidence level with a range of 0.99561 to 0.99849. The final non-working archwire had an even more impressive intra-class correlation coefficient of 0.99943 95% CI (0.99903, 0.99967). The first and second measurements for all recordings of the four different bracket types is shown in Tables VII, VIII, IX, X.

4.7 Error Study

Within the precision limits of the measuring apparatus, no difference in the angulation of the plastic pointer regardless of the position of the torquing beams was detected. There were no statistical analyses performed for the error study due to the fact that the measurements with the torquing beams as far apart as possible compared to the measurements with the torquing beams as close together as possible were identical. This finding indicated that the non-working archwires could be used to evaluate the creep occurring in the test brackets (Table XI).

Lumina (Ceramic Brackets)
Raw data, using a 2500 g-mm moment measured at various time intervals

First Measurement

	0.5 g	0.5 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	80.0	79.5	82.5	82.0	82.5	82.5	82.5	82.5	82.5	82.5	80.0	80.0
App. #2	77.5	78.5	81.5	81.5	81.5	81.5	81.5	81.5	81.5	81.5	79.0	77.5
App. #3	78.5	82.0	85.5	86.0	86.0	86.0	86.0	86.5	86.5	86.5	83.0	78.5
App. #4	74.5	80.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	80.5	74.5
App. #5	74.5	79.5	84.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	80.5	74.5
App. #6	77.5	83.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	83.5	77.5
App. #7	79.0	83.0	87.0	87.0	87.0	87.0	87.0	87.0	87.0	87.0	85.0	78.5
App. #8	83.0	81.0	84.5	84.0	84.0	84.0	84.0	84.0	84.0	84.0	80.5	83.5
App. #9	73.5	79.5	82.0	82.0	82.0	82.0	82.0	82.0	82.0	82.0	80.0	74.0
App. #10	79.0	78.0	81.5	82.0	82.0	82.0	82.0	82.0	82.0	82.0	79.0	79.0
Mean Deformation per Interval				0.00	0.05	0.00	0.00	0.05	0.00	0.00		

Second measurement

	0.5 g	0.5 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	80.0	79.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5	80.0	80.0
App. #2	78.0	79.0	81.5	81.5	81.5	81.5	81.5	81.5	81.5	81.5	79.0	77.5
App. #3	78.5	82.0	86.0	86.0	86.0	86.0	86.5	86.5	86.5	86.5	83.0	78.5
App. #4	74.5	80.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	80.5	74.5
App. #5	74.5	79.5	84.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	80.5	74.5
App. #6	77.5	83.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	86.5	83.5	77.5
App. #7	78.5	83.0	87.0	87.0	87.0	87.0	87.0	87.0	87.5	87.5	85.0	78.5
App. #8	83.5	81.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	80.5	83.5
App. #9	73.5	79.5	82.0	82.0	82.0	82.0	82.0	82.0	82.0	82.0	80.0	74.0
App. #10	79.0	78.0	81.5	82.0	82.0	82.0	82.0	82.0	82.0	82.0	79.0	79.0

Table VII

The mean deformation per interval is the average amount of deformation which occurred between each specific time interval.
INW = Initial reading using the non-working arch wire with the 0.5 gram weights
IW = Initial reading using the working arch wire with the 0.5 gram weights
Init = Initial reading using the working arch wire with the 25 gram weights
D = Day
FW = Final reading using the working arch wire and the 0.5 gram weights
FNW = Final reading using the non-working arch wire and the 0.5 gram weights
App. = Apparatus

Omni Arch (Stainless Steel Brackets)
Raw data using a 2500 g-mm moment measured at various time intervals

First Measurement

	0.5 g	0.5 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	73.0	81.0	85.5	85.5	85.5	86.0	86.0	86.0	86.0	86.0	81.5	73.5
App. #2	73.0	79.0	84.5	84.5	84.5	84.5	85.0	85.0	85.0	85.0	79.5	73.5
App. #3	74.0	78.0	83.5	83.5	83.5	83.5	83.5	84.0	84.0	84.0	79.0	74.0
App. #4	71.5	73.5	80.0	80.0	80.0	80.5	80.5	80.5	80.5	81.0	73.5	71.5
App. #5	72.0	73.5	79.5	79.5	79.5	79.5	79.5	79.5	80.0	80.0	73.5	72.0
App. #6	72.5	76.0	81.5	81.5	81.5	81.5	81.5	81.5	81.5	81.5	76.5	72.5
App. #7	75.0	78.5	84.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	79.0	75.5
App. #8	73.5	72.0	79.0	78.5	78.5	78.5	79.0	79.0	79.0	79.0	72.5	74.0
App. #9	70.0	77.5	84.0	84.0	84.5	84.5	85.0	85.0	85.0	85.0	79.5	70.5
App. #10	81.5	80.0	87.0	87.0	87.0	87.0	87.0	87.0	87.0	87.0	80.0	82.0
Mean Deformation per Interval				-0.05	0.05	0.10	0.15	0.05	0.05	0.05		

Second measurement

	0.5 g	0.5 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	73.0	81.0	85.5	85.5	85.5	86.0	86.0	86.0	86.0	86.0	81.5	73.5
App. #2	73.0	78.5	84.5	84.5	84.5	84.5	85.0	85.0	85.0	85.0	79.5	73.5
App. #3	74.0	78.0	83.5	83.5	84.0	83.5	83.5	83.5	84.0	84.0	79.0	74.0
App. #4	71.5	73.5	80.0	80.0	80.0	80.5	80.5	80.5	80.5	80.5	73.5	71.5
App. #5	72.0	73.0	79.5	79.5	79.5	79.5	79.5	79.5	80.0	80.0	73.5	72.0
App. #6	72.5	76.0	81.5	81.5	81.5	81.5	81.5	81.5	81.5	81.5	76.5	72.5
App. #7	75.0	78.5	84.0	84.0	84.0	84.0	84.0	84.0	84.0	84.0	79.0	75.5
App. #8	73.5	72.0	78.5	78.5	78.5	78.5	79.0	79.0	79.0	79.0	72.5	74.0
App. #9	70.0	77.5	84.0	84.5	84.5	84.5	85.0	85.0	85.0	85.0	79.5	70.5
App. #10	81.5	80.0	87.0	87.0	87.0	87.0	87.0	87.0	87.0	87.0	80.0	82.0

Table VIII

The mean deformation per interval is the average amount of deformation which occurred between each specific time interval.
INW = Initial reading using the non-working arch wire with the 0.5 gram weights
IW = Initial reading using the working arch wire with the 0.5 gram weights
Init = Initial reading using the working arch wire with the 25 gram weights
D = Day
FW = Final reading using the working arch wire and the 0.5 gram weights
FNW = Final reading using the non-working arch wire and the 0.5 gram weights
App. = Apparatus

Spirit (Polycarbonate Brackets)
Raw data using a 2500 g-mm moment measured at various time intervals

First Measurement

	0.5 g	0.5 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	80.0	79.5	87.0	87.0	87.0	87.5	87.5	87.5	87.5	88.0	80.0	81.5
App. #2	75.0	85.5	94.0	94.5	94.5	95.0	95.5	95.5	96.0	96.0	88.0	78.5
App. #3	75.5	82.0	90.5	90.5	90.5	91.5	91.5	91.5	91.5	91.5	84.5	77.5
App. #4	77.0	81.5	91.5	91.5	92.0	92.5	93.0	93.5	93.5	93.5	84.0	79.5
App. #5	76.0	81.5	90.5	90.5	90.5	91.0	91.5	91.5	91.5	91.5	84.5	78.5
App. #6	73.5	77.5	84.0	84.0	84.5	84.5	84.5	84.5	84.5	84.5	79.5	75.0
App. #7	76.5	83.5	91.0	91.0	91.0	91.5	91.5	91.5	91.5	91.5	85.5	78.5
App. #8	80.5	80.5	88.0	88.5	88.5	88.5	89.0	89.5	89.5	90.0	83.0	82.5
App. #9	71.5	77.0	85.0	85.5	85.5	86.0	86.5	86.5	87.0	87.0	79.0	73.5
App. #10	71.0	74.5	81.0	81.0	81.0	81.0	81.5	81.5	82.0	82.0	76.0	72.0
Mean Deformation per Interval				0.15	0.10	0.40	0.30	0.20	0.15	0.10		

Second measurement

	0.5 g	0.5 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	80.0	79.5	87.0	87.0	87.0	87.5	87.5	87.5	87.5	88.0	80.0	81.5
App. #2	75.0	85.5	94.0	94.5	94.5	95.0	95.5	95.5	96.0	96.0	87.5	78.5
App. #3	75.5	82.0	90.5	90.5	90.5	91.5	91.5	91.5	91.5	91.5	84.0	77.5
App. #4	76.5	81.5	91.5	91.5	92.0	92.5	93.0	93.5	93.5	93.5	83.5	79.5
App. #5	76.0	81.5	90.5	90.5	90.5	91.0	91.5	91.5	91.5	91.5	84.5	78.5
App. #6	73.5	78.0	84.0	84.0	84.0	84.5	84.5	84.5	84.5	84.5	79.5	75.0
App. #7	76.5	83.5	91.0	91.0	91.0	91.5	91.5	91.5	91.5	91.5	85.0	78.5
App. #8	80.5	80.5	88.5	88.5	88.5	89.0	89.5	89.5	89.5	90.0	82.5	82.5
App. #9	72.0	77.0	84.5	85.5	85.5	86.0	86.5	86.5	87.0	87.0	79.0	73.5
App. #10	71.0	74.5	81.0	81.0	81.0	81.0	81.5	81.5	82.0	82.0	76.0	72.0

Table IX

The mean deformation per interval is the average amount of deformation which occurred between each specific time interval.
INW = Initial reading using the non-working arch wire with the 0.5 gram weights
IW = Initial reading using the working arch wire with the 0.5 gram weights
Init = Initial reading using the working arch wire with the 25 gram weights
D = Day
FW = Final reading using the working arch wire and the 0.5 gram weights
FNW = Final reading using the non-working arch wire and the 0.5 gram weights
App. = Apparatus

Elan (Polycarbonate Brackets)
Raw data using a 2500 g-mm moment measured at various time intervals

First Measurement

	0.5 g	0.5 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	25 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	75.0	79.0	87.5	87.5	87.5	88.0	88.0	88.0	88.5	88.5	81.5	77.0
App. #2	75.5	81.5	90.0	90.0	90.0	90.5	90.5	90.5	91.0	91.0	84.5	78.5
App. #3	77.5	84.5	91.0	91.5	91.5	91.5	91.5	92.0	92.0	92.0	85.5	78.5
App. #4	75.0	81.5	90.0	90.5	90.5	90.5	91.0	91.0	91.0	91.0	84.5	75.5
App. #5	75.0	85.0	92.5	92.5	93.0	93.0	93.0	93.5	93.5	93.5	87.5	76.5
App. #6	75.5	84.5	93.0	93.0	93.0	93.5	93.5	94.0	94.0	94.0	87.0	78.0
App. #7	76.0	83.0	91.5	91.5	91.5	91.5	92.0	92.0	92.0	92.0	85.5	78.0
App. #8	81.5	82.0	91.0	91.5	91.5	91.5	92.0	92.0	92.5	92.5	85.0	84.0
App. #9	75.5	84.5	91.0	91.0	91.0	91.5	91.5	91.5	91.5	91.5	86.5	77.0
App. #10	74.0	83.0	91.5	92.0	92.0	92.0	92.5	92.5	92.5	92.5	87.0	77.5
Mean Deformation per Interval				0.20	0.05	0.15	0.20	0.15	0.15	0.00		

Second measurement

	0.5 g	0.5 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	35 g	0.5 g	0.5 g
	INW	IW	Init.	1 hr.	2 hr.	24 hr.	D 7	D 14	D 21	D 28	FW	FNW
App. #1	75.0	79.0	87.5	87.5	87.5	88.0	88.0	88.5	88.5	88.5	81.5	77.5
App. #2	75.5	81.5	90.0	90.0	90.0	90.5	90.5	90.5	91.0	91.0	84.5	78.5
App. #3	78.0	84.5	91.5	91.5	91.5	91.5	91.5	92.0	92.0	92.0	85.5	78.5
App. #4	74.5	81.5	90.5	90.5	90.5	90.5	91.0	91.0	91.0	91.0	84.5	75.5
App. #5	75.0	85.0	92.5	93.0	93.0	93.0	93.5	93.5	93.5	93.5	87.5	76.5
App. #6	76.0	84.5	93.0	93.0	93.0	93.5	93.5	94.0	94.0	94.0	87.0	78.0
App. #7	76.0	83.0	91.5	91.5	91.5	91.5	92.0	92.0	92.0	92.0	85.5	77.5
App. #8	81.5	82.0	91.0	91.5	91.5	91.5	92.0	92.0	92.5	92.5	85.5	84.0
App. #9	75.5	84.5	91.0	91.0	91.0	91.5	91.5	91.5	91.5	91.5	86.5	77.0
App. #10	74.0	83.0	91.5	92.0	92.0	92.0	92.5	92.5	92.5	92.5	87.0	77.5

Table X

The mean deformation per interval is the average amount of deformation which occurred between each specific time interval.
INW = Initial reading using the non-working arch wire with the 0.5 gram weights
IW = Initial reading using the working arch wire with the 0.5 gram weights
Init = Initial reading using the working arch wire with the 25 gram weights
D = Day
FW = Final reading using the working arch wire and the 0.5 gram weights
FNW = Final reading using the non-working arch wire and the 0.5 gram weights
App. = Apparatus

ERROR STUDY

	Archwire Twist Angle	
	Torquing beams apart	Torquing beams together
Omni Arch Brackets	70.5	70.5
	82.0	82.0
	73.5	73.5
Spirit brackets	78.5	78.5
	80.5	80.5
	82.0	82.0
Elan brackets	85.0	85.0
	84.0	84.0
	75.5	75.5

Table XI
Test for change in archwire twist angle due to changing the distance of the torque arms relative to the test bracket.
A 0.25 gram load was applied to each torquing beam for this test. Within the precision of the apparatus, there was no detectable difference in the angular measurement regardless of the position of the torquing beams relative to the test bracket and each other.

5. DISCUSSION

5.0 Third Order Torque

5.0.0 Bracket Material

Since delivery of the desired torque is dependent upon the bracket slot being able to resist the twisting of the archwire, the ability of the bracket material to resist deformation will also effect the torque being delivered. Elastic and/or plastic deformation which occurs in the bracket may result in bracket slot opening, effectively increasing the dimension of the bracket slot and thereby allowing the archwire to twist in the slot resulting in a decrease of the effective torque (McKnight et al., 1994). Ceramic brackets would be expected to exhibit very little elastic and little or no plastic deformation. Polycarbonate brackets because of their polymer structure would be expected to deform under conditions of adequate stress and time (Van Vlack, 1985) resulting in a loss of torque delivery. The stainless steel brackets should have deformation characteristics somewhere between the ceramic and polycarbonate brackets due to the elastic modulus of stainless steel falling between alumina and polycarbonate and metallic bonding which allows for plastic deformation.

5.0.1 Bracket Slot / Archwire Size Differential

Unless the archwire is a precision fit for the bracket slot there will be some freedom for rotation of the archwire until it engages the bracket slot. This is referred to as torsional play. Creekmore and Kunik (1993) reported that there are manufacturing tolerances in bracket and archwire designs which ensure that an 0.018 x 0.025 inch archwire will be able to be placed into an 0.018 x 0.025 inch bracket slot. These tolerances are such that the 0.018 inch dimension of an archwire is actually 0.0178 inches and the 0.018 dimension of the bracket slot ranges from 0.0182 inches to 0.0192 inches (Creekmore and Kunik, 1993). This discrepancy between the 0.018 x 0.025 inch archwire in a 0.018 x 0.025 inch bracket slot results in approximately 6°

of rotation of the archwire in the bracket slot. Therefore, a central incisor bracket with 12° of torque built into the bracket may only deliver 6° of the prescribed torque when a "full dimension" straight archwire is inserted into the bracket slot. This would necessitate adding twist to the archwire to compensate for the torsional play between the archwire and the bracket slot.

Producing the desired torsional moment is one of the most difficult mechanical tasks in edgewise orthodontic therapy (Meling et al., 1997). With the 0.018 x 0.025 inch archwire in a 0.018 x0.025 inch bracket slot, Meling et al. (1997) reported torsional play ranging from 3.6 degrees to 6.1 degrees, while the working range of the archwire was 2.6 degrees per 1000 g-mm (using an interbracket distance of 4 mm). Using this data calculations show that an archwire which is twisted 5.2 degrees to deliver a 2000 g-mm moment may in fact not exert any moment due to the torsional play which may be as great as 6.1 degrees.

The archwire / bracket slot differential was taken into account in the present study by allowing the archwire to twist in the bracket slot until it was engaged in the direction that the simulated lingual root torque would occur. This was accomplished by placing 0.25 gram weights on the torquing beams. At this "engaged" position a "zero point" reading was made.

5.0.2 Archwire Bevel

The above discussion on archwire / bracket slot differential assumes that the bracket slot and archwire are perfect rectangles. However, Sebanc et al. (1984) reported that measurements of the archwire / bracket slot differential are greater than the theoretical result. Sebanc et al. (1984) attributed the difference between the measured and theoretical value to be due to the bevel on the edges of the archwire. The greater the amount of bevel the greater will be the rotation of the archwire in the bracket slot. Meling et al. (1997) also agreed that edge bevel significantly influences torsional play between the archwire and the bracket slot.

The archwires used in this experiment were stainless steel straight archwire blanks with a manufacturer's reported dimension of 0.018 x 0.025 inches (Nubryte Gold ®, GAC International, Inc., Central Islip, N.Y.). Arch bevel was not considered to be a factor in the experimental results as the archwire was engaged in the bracket before recording began. Also with the use of an 0.018 x 0.025 archwire in a 0.018 x 0.025 bracket slot, the effect of arch bevel is reduced (Sebanc et al., 1984).

5.0.3 Ligation

Bracket slot / archwire size discrepancy can influence the moment delivered by a given amount of twist in an archwire. Several mechanisms that can reduce this discrepancy have been identified. Levin (1985) reported that the ligation of the archwire to a bracket may support the tie wings of the bracket and decrease the deformation of the bracket slot. Dobrin et al. (1975) found that the addition of composite material over the bracket face decreased deformation of polycarbonate brackets. Feldner et al. (1994) found that elastic ligation of a metal slot reinforced polycarbonate bracket increased the magnitude of the moment delivered.

The experimental apparatus in the present study was designed so that ligation of the archwire into the bracket slot was not required. This was desirable because it eliminated the need to standardize the ligation force applied to the archwire and eliminated the possible influence of ligation on the deformation of the brackets tested. It would be expected that archwires would be ligated into the bracket slot in the *in vivo* situation, which may improve torque delivery.

5.1 Range of Moments Delivered by the Test Apparatus

During the 28 days while the torquing beams were loaded with the 12.5 gram weights the moment created from both torquing beams had a range of 2450 g-mm to 2500 g-mm. This range of moments is greater in magnitude than those used in previous studies (1770 g-mm to 2000 g-mm) which attempted to observe plastic deformation including creep (Dobrin, 1975; Feldner et al., 1994; Alkire et al., 1997). The change in the length of the moment arm used by Alkire et al. (1997) would be expected to be greater than the change in the moment arm which occurred in this experiment. The small change in the moment produced due to the position of the torquing beams varying from horizontal is likely inconsequential in the present investigation.

5.2 Deformation of the Apparatus

The contribution made by the possible deformation of the apparatus in the reading for bracket deformation was considered to be negligible. Reasons for this assumption include: 1. the apparatus was massive in size relative to the bracket, 2. the measurement device was connected to the apparatus and would negate the deformation which occurred in the apparatus, 3. the measurement precision used in this experiment (0.5 degrees) was deemed to be unable to detect the small amount of deformation which may have occurred in the apparatus.

5.3 Bracket Debonds

The location of the debonds occurred at the bracket adhesive interface and within the adhesive. This finding justifies bonding the brackets to the acrylic, as bonding to the test apparatus did not limit the magnitude of the moment which could be used. The limiting factor was the adhesive and the retentive element of the bracket both of which are determined by the manufacturer for clinical use. It would therefore be expected that a moment of similar magnitude used *in vivo* would also result in a similar number of debonds as occurred in the *in vitro* situation reported in this experiment. The 50%, 38% and 29% rate of debonds experienced with the Omni Arch, Elan and Spirit brackets respectively following the application of a 2500 g-mm moment would likely be unacceptable clinically. The debonding of the bracket at a moment only slightly above that deemed necessary for tooth movement may in fact be beneficial as the tooth would otherwise experience unacceptably large stresses which may cause pain and/or damage to the root structure.

Alkire et al., (1997) also experienced debonds during their experiment. They did not however, provide information on the location of the debond so direct comparison to their study is not possible. Other *in vitro* studies which utilized torque to deform orthodontic brackets (Dobrin, 1975; Feldner et al., 1994) did not report on any debonding of test brackets during their experiments.

5.4 Plastic Deformation of the Archwire

Plastic deformation of the archwire was evaluated by comparing the change in the non-working archwire and the working archwire. A paired t-test determined that there was slight plastic deformation in the working archwire which had been subjected to the 2500 g-mm moment for the 28 day test period. On average the amount of plastic deformation which occurred in the archwire was approximately 0.4°. This result is similar to Goldberg et al. (1983) who reported a 0.017 x 0.025 inch stainless steel archwire experienced less than 1 degree of permanent deformation when subjected to a 2500 g-mm moment. This amount of deformation in the archwire would be insignificant in a clinical situation, but it may affect *in vitro* experimental results when a high degree of precision measurement is employed.

5.5 Deformation of Brackets

5.5.0 Plastic and Elastic Deformation Upon Initial Moment Application

Although the ceramic brackets exhibited a mean amount of plastic deformation of 0.1° with a standard deviation of 0.22° this value is likely in error since ceramics do not experience any plastic deformation at room temperature (Kingery, 1976). Holt et al. (1991) reported that ceramics exhibit very little elastic or plastic deformation. Lack of appreciable plastic deformation of ceramic brackets is consistent with their structural design. Flores et al. (1990) stated that due to the covalent and ionic bonds which are the principal bonds found in ceramics, there is no plastic deformation in ceramics but instead overload results in brittle fracture.

The stainless steel brackets exhibited 0.5° of plastic deformation, however this was found to be statistically similar to the ceramic brackets ($p > 0.05$) indicating minimal plastic deformation. It must also be kept in mind that the measurement precision of the test apparatus is 0.5°. Considering that the working range of an 0.018 x 0.025 inch stainless steel archwire is 2.6 ° per 1000 g-mm, 0.5° of plastic deformation would decrease the moment from 2500 g-mm to 2310 g-mm which is unlikely to be of any clinical significance. The affect of archwire / bracket slot differential and archwire bevel would have a much greater effect on the delivery of torque in continuous edgewise mechanics than 0.5° of plastic deformation in the bracket. The Spirit and Elan brackets did exhibit a significantly greater amount of plastic deformation when compared to the stainless steel and ceramic brackets ($p < 0.05$). The 1.4° and 1.3° of plastic deformation which occurred in the Spirit and Elan brackets respectively would decrease the moment of 2500 g-mm by approximately 540 g-mm. Although a decrease in the moment by 540 g-mm may be significant clinically, the archwire / bracket slot differential is still a greater factor in torque delivery with continuous edgewise mechanics (Table III and Figure X).

The total amount of deformation upon initial application of the 2500 g-mm moment is listed in Table XII. The measurement taken for the total amount of deformation upon initial application of the 2500 g-mm moment included the deformation which occurred in the bracket as well as the deformation in the archwire. Since ceramics exhibit very little elastic or plastic deformation (Holt et al., 1991), the assumption is made that the 3.45° which was recorded as the total amount of deformation for ceramic brackets upon initial application of the 2500 g-mm moment represented the elastic and plastic deformation which occurred in the archwire. By using this assumption, the 3.45° was subtracted from the total deformation readings recorded for the stainless steel and polycarbonate brackets resulting in an estimation of the elastic / plastic deformation which occurred in each bracket type upon initial application of the 2500 g-mm moment . The above calculation yielded a mean elastic / plastic bracket deformation of 2.5° for the stainless steel brackets, 4.5° for the Spirit brackets and 4.6° for the Elan brackets (Table XII).

Elastic / Plastic Bracket Deformation
Upon Initial Application of 2500 g-mm Moment

	Total Deformation	*Calculated Arch Wire Deformation	Total Bracket Deformation
Lumina (Ceramic)	3.45	3.45	0.0
Omni Arch (Stainless Steel)	5.95	3.45	2.5
Spirit (Polycarbonate)	7.95	3.45	4.5
Elan (Polycarbonate)	8.05	3.45	4.6

Numbers represent angular displacement in degrees

<u>Table XII</u>
The total deformation upon initial application of the 2500 g-mm moment includes the deformation which occurs in the working archwire. *The assumption is made that the amount of deformation which was recorded for the ceramic bracket was in fact the deformation which occurred in the working archwire. By subtracting the deformation which occurred in the archwire, the total amount of deformation (elastic and plastic) of the different brackets can be estimated.

In a maxillary central incisor bracket with a torque prescription of 12°, the 2.5° of deformation seen with the stainless steel bracket would result in a 21% decrease in the expression of the bracket prescription whereas the two polycarbonate brackets would exhibit approximately a 38% decrease in the expression of the bracket prescription. This amount of torque loss would likely be of clinical significance.

Continuing with the above assumption and calculation, an approximation of the amount of elastic deformation which occurred upon initial moment application was calculated by subtracting the initial plastic deformation (Table III) from the above calculated elastic / plastic bracket deformation. This calculation gave an estimated 2° of elastic deformation in the stainless steel brackets and 3.2° of elastic deformation in both the Spirit and Elan brackets (Table XIII). It can be seen that the amount of elastic deformation is greater than the amount of plastic deformation upon initial application of the 2500 g-mm moment (Figure XV). Clinically, elastic deformation may not be a negative factor if the elastic deformation could be recovered by stress relaxation in the bracket.

5.5.1 Plastic Deformation Including Creep

Both the ceramic and stainless steel brackets plastically deformed by less than 0.5° following the 28 day test period indicating little if any permanent deformation. In the polycarbonate brackets there was an increase in the average amount of permanent deformation detected from the initial moment application to the end of the 28 day test period indicating creep had occurred (Figure XVI). The Spirit brackets increased to an average total plastic deformation of 2.05° and the Elan brackets increased to an average total plastic deformation of 2.0°. This result suggested that there was creep which increased the Spirit plastic deformation by 0.65° or 32% and the Elan plastic

Elastic Bracket Deformation
Upon Initial Application of 2500 g-mm Moment

	Total Bracket Deformation	Plastic Deformation	Elastic Deformation
Omni Arch (Stainless Steel)	2.5	0.5	2.0
Spirit (Polycarbonate)	4.5	1.3	3.2
Elan (Polycarbonate)	4.6	1.4	3.2

Table XIII
Using the information from Table III and Table XII a comparison of the amount of plastic and elastic deformation for each bracket type can be made, assuming no elastic or plastic deformation of the ceramic bracket.

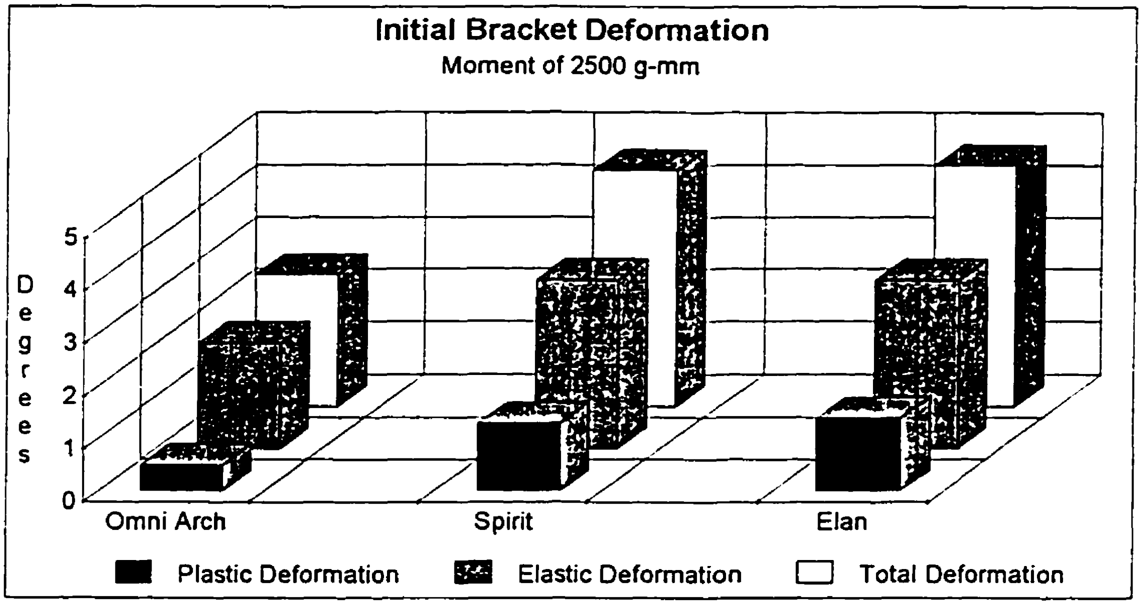

Figure XV
Comparison of the plastic deformation and elastic deformation which occurred in the stainless steel and polycarbonate brackets upon initial application of a 2500 g-mm moment. Data calculation based on the assumption that the ceramic bracket does not elastically or plastically deform.

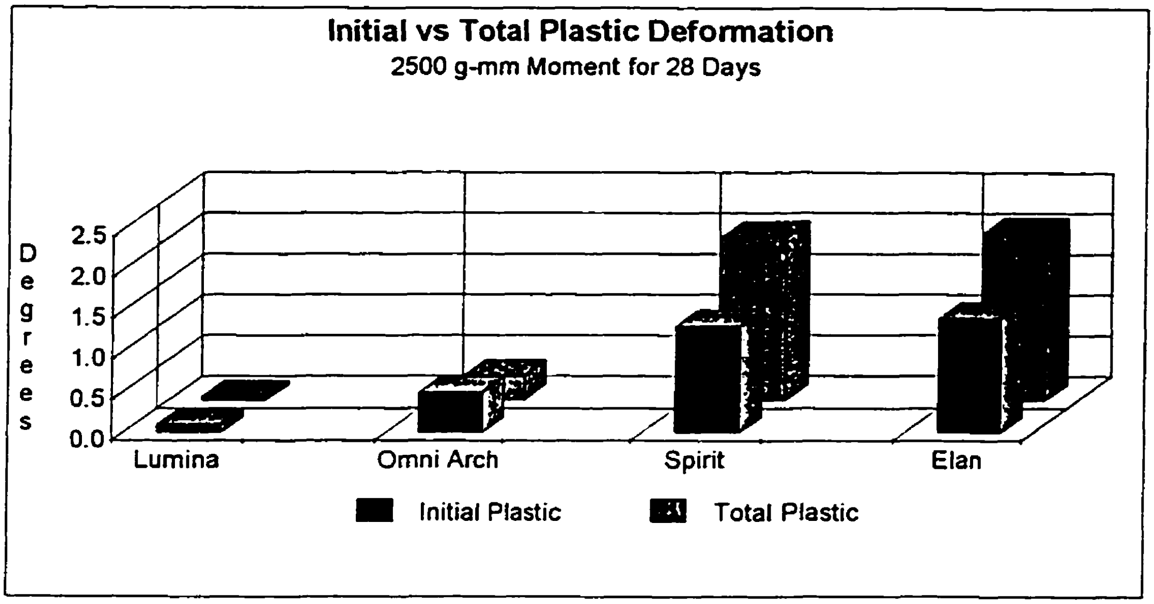

Figure XVI
Graphic comparison of Table III and Table IV. It can be seen that the amount of plastic deformation decreased for the ceramic and metal brackets. This is due to the initial and total plastic deformation readings being within the measurement error of 0.5° and therefore are essentially zero. There was a continued amount of creep in the polycarbonate brackets with creep contributing approximately 35% of the total plastic deformation which was found over the 28 day test period.

Calculation for Creep
in Degrees

	Total Plastic Deformation	Initial Plastic Deformation	Creep Total - Initial
Lumina (Ceramic)	0.05	0.10	0.00
Omni Arch (Stainless Steel)	0.30	0.50	0.00
Spirit (Polycarbonate)	2.00	1.30	0.70
Elan (Polycarbonate)	2.05	1.40	0.65

Table XIV
The calculation for creep in the ceramic and stainless steel brackets indicated a negative value. The amount of plastic deformation recorded is within the measurement error of 0.5° and is therefore recorded as zero. There did appear to be creep occurring in the polycarbonate brackets which contributed 32% - 35% to the total amount of plastic deformation.

deformation by 0.7° or 35% (Table XIV). Although the clinical significance of 0.7° may be minimal, if the trend towards continual creep over an extended treatment time of 2 years were to continue then it is likely that the amount of deformation which occurs due to creep would effect the clinical performance of the polycarbonate brackets.

During the 28 day experimental period there was a greater amount of plastic deformation which occurred immediately upon application of the 2500 g-mm moment compared to the amount of creep which occurred thereafter (Figure XVII). There appeared to be a continual increase in creep deformation in both the Spirit and Elan brackets over the 28 day period, with little, if any creep occurring in the Lumina and Omni Arch brackets (Table XIV and Figure XVII). The trend for continual creep of the polycarbonate brackets (Spirit and Elan) found in the present investigation was not in agreement with Alkire et al. (1997) who found a decrease in creep rate with time, with the majority of the creep occurring within the first two days of their experiment. A possible explanation for the decrease in the creep rate found by Alkire et al. (1997) may be due to the design of their test apparatus which would experience a greater decrease in the effective moment as deformation of the bracket and/or moment arm occurred in their experiment. Also the moment used in the Alkire et al. (1997) experiment was less than the moment used in this investigation.

5.5.2 Total Bracket Deformation and Effect on Torque Delivered

The total amount of bracket deformation after 28 days can be calculated from the information in Table XIII, which illustrates the total amount of bracket deformation upon initial load application, and Table XIV, which shows the amount of creep which occurred over the 28 day period. This information revealed a total bracket deformation (elastic and plastic) of 2.5 ° for the stainless steel brackets, 5.2° for the Spirit brackets and 5.2° for the Elan brackets. These calculations were based

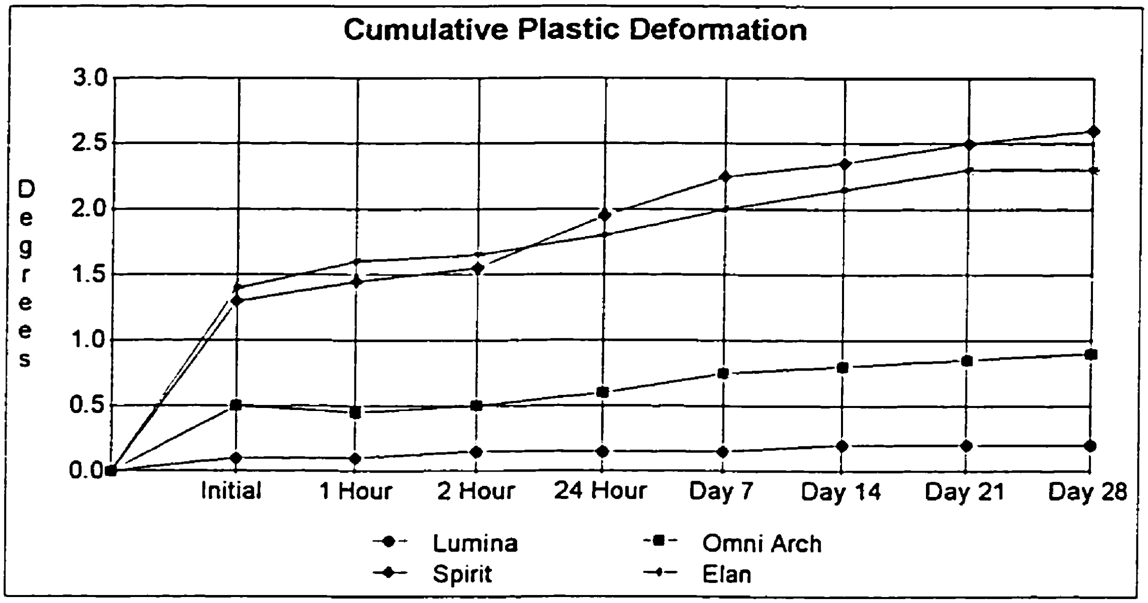

Figure XVII
Graphic representation of the mean plastic deformation as it occurred during the measurement intervals with a time scale which does not have equal time intervals. It can be seen that the greatest amount of plastic deformation occurred upon initial application of the moment. Note that the total amount of plastic deformation recorded at day 28 is greater than the plastic deformation recorded in Table IV. This is due to the inclusion of plastic deformation in the working archwire during the interval readings.

on the elastic and plastic deformation of the ceramic brackets being equal to zero. Given a central incisor bracket prescription of 12°, there would be approximately a 21% decrease in the effective torque prescription for stainless steel brackets and a 43% decrease in the effective torque prescription for the Spirit and Elan brackets. Considering Meling et al. (1997) reported that 2.6° of twist in a 0.018 x 0.025 inch stainless steel archwire produced a moment of 1000 g-mm, a loss of 5.2° due to bracket deformation could be expected to decrease the moment by 2000 g-mm. The result of which would be inadequate stress being applied to the periodontal attachment apparatus and lack of tooth movement.

5.6 Limitations of the Present Study

This study was an *in vitro* investigation and therefore any extrapolation to the *in vivo* situation should be done with caution.

The brackets were tested in air and not in an aqueous environment. Due to the water absorptive capabilities of the polycarbonate material there may have been more creep detected had the test been performed in a simulated oral environment. Alkire et al. (1997) stated that their test was performed in water because creep may be increased in an aqueous environment. The reason given for this increase in creep was water being absorbed by the polycarbonate resin or reduction in the adhesion between the ceramic fillers and polycarbonate resin.

The assumptions that neither the apparatus nor the ceramic brackets experienced elastic and/or plastic deformation may have resulted in lower than expected values of deformation for the brackets tested.

There have been more precise measuring apparati to detect angular change reported in the literature (Odegaard, 1994) than was used in this experiment. The measurement apparatus designed for this study was deemed as having adequate precision for clinical relevance and was fabricated within budgetary limitations.

Creep is highly temperature dependent. The present investigation was performed at room temperature, approximately 20° Celsius, whereas mouth temperature is around 37° Celsius. With hot food and drink intake the mouth temperature may experience episodic temperature increases above 37° Celsius. These temperature increases may increase the amount of creep which occurs *in vivo*.

5.7 Conclusions

1. There was significant ($p < 0.05$) elastic / plastic deformation in the Spirit and Elan brackets compared to the Omni Arch and Lumina brackets upon initial application of a 2500 g-mm moment.

2. Significant plastic deformation of the Spirit and Elan brackets was observed upon initial application of a 2500 g-mm moment when compared to the Omni Arch and Lumina brackets ($p < 0.05$).

3. The Spirit and Elan brackets experienced an increase in the plastic deformation over the 28 day test period due to creep. There appeared to be a pattern of continual creep over the measurement intervals with the Spirit and Elan brackets.

4. There appeared to be no creep in either the Lumina or the Omni Arch brackets.

5. The Omni Arch, Elan and Spirit brackets experienced an unacceptably high incidence of debond failure when subjected to a 2500 g-mm moment.

5.8 Suggestions for Future Research

In future studies, consideration could be given to the following:

1. Determine the magnitude of the moment which initiates plastic deformation of stainless steel and polycarbonate brackets.

2. Using a moment in the same manner as used in this investigation, apply a concurrent lingually directed force and observe if the debonding and deformation characteristics change.

3. Determine the deformation in polycarbonate brackets under conditions of temperature and moisture similar to that of the oral environment.

4. Determine the affect of changing archwire size on the amount of bracket deformation using an identical moment.

5. Measure the elastic and creep deformation of the apparatus described here, and if their effects justify, redesign the apparatus to negate them.

6. Determine the true elastic deformation of polycarbonate, stainless steel and ceramic brackets.

Aesthetic brackets in orthodontics are expected to enjoy increased use in the future. Biomaterials research directed toward improvement of these products and their clinical performance, is considered a worthwhile avenue to explore in future studies.

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Appendix I

Detailed Description of the Test Apparatus

An apparatus was developed to evaluate the creep deformation in orthodontic brackets when subjected to simulated lingual root torque. The apparatus was constructed from industrial acrylic (Cyrolite Acrylic f.f. Cyro Industries Ltd. Toronto, ON). The base of the apparatus was fabricated with the dimension of 22.2 mm (height) x 88.9 mm (width) x 76.2 mm (length) (Figure XVI and Figure XVII). A second section of acrylic with a dimension of 25.4 mm (height) x 12.7 mm (width) x 76.2 mm (length) (Figure XVI and Figure XVII) was centred along the width of the base of the apparatus and was bonded to the base using an acrylic solvent. The bonded assembly formed an inverted "T" (Figure XVI). A slot with a depth of 3 mm and a width of 2 mm was milled along the superior surface of the inverted "T" at a distance of 2 mm from the edge (Figures XVI). This slot supported a protractor which was used to record angular changes (Figure XVI and Figure XVII).

The bracket to be tested (test bracket) was bonded to the superior surface of the inverted "T" such that it was located at the edge of the acrylic opposite the protractor slot and the bracket slot was 15 mm from the posterior edge of the inverted "T". The bracket slot was oriented perpendicular to the protractor slot and the gingival aspect of the bracket was closest to the anterior aspect of the apparatus. All brackets tested had a slot size of 0.018 x 0.025 inches.

A full dimension (0.018 x 0.025 inch dimension) stainless steel archwire was used to produce the desired moment. A thin piece of plastic was glued to the 0.025 inch dimension of the archwire, perpendicular to the straight archwire blank. The archwire was positioned in the bracket slot such that the plastic pointer was positioned between the bracket and the protractor slot (Figure XVI and Figure XVII). As the archwire rested in the bracket slot it also rested passively on two support pins positioned on either side of the inverted "T" aspect of the acrylic. The support pins were placed into holes drilled into the base of the apparatus. The hole diameter approximated the 6.35 mm diameter of the support pin. The centre of one support pin was located 14.5 mm away from the side of the apparatus nearest the protractor slot. The centre of the other screw was located 20.5 mm away from the other side of the apparatus (Figures XVI). With the archwire in place a protractor which had a hole made from the inferior aspect superiorly to the focal point of the protractor was placed in the protractor slot such that the archwire would be located at the focal point of the protractor.

The position of the support pins permitted two torquing beams to be positioned equidistant from the test bracket. The two torquing beams, which were used to supply the moment, were fabricated from acrylic with the dimensions of 12.7 mm (height) x 6.35 mm (width) x 210 mm (length) (Figure XVI and Figure XVII). A 2 mm wide positioning groove was made 5 mm from either end of the torquing beams on their superior aspect. The purpose of placing a groove at either end of the torquing beams was to balance the torquing beams and permit the attachment of weights to the torquing beams. This would allow the weight which would be added to one end of the torquing beam to be the only influence on the beam. A 6.35 mm wide channel was made across the centre of the inferior surface of the torquing beam at a depth half way through the acrylic (Figure 6). A ceramic bracket (Lumina ®, Ormco Corp. Glendora CA.) with a "Roth" prescription and a 0.018 x 0.025 inch slot dimension was bonded with a resin bonding agent (Transbond ®, Unitek, Monrovia, CA.) into the area of the channel on the inferior aspect of the torquing beam. The bracket was bonded in the middle of this channel such that the angulation of the bracket slot was perpendicular to the length of the torquing beam, the bracket slot was equidistant (100 mm) from both positioning grooves and the gingival aspect of the bracket was placed closest to the posterior end of the torquing beam. Excess bonding resin was displaced from beneath the bracket with manual pressure. The excess resin was then removed before being light cured. The purpose of the ceramic bracket bonded to the torquing beams was to provide a means of attaching the torquing beams to the archwire. The torquing beams were placed on top of the archwire such that the ceramic bracket bonded to the archwire would seat on the archwire. The positioning groove at the front of each torquing beam received the weight which caused the torquing beam to rotate and twist the archwire thereby producing a moment.

As the archwire twists it is resisted by the test bracket. The deformation which occurs in the test bracket is determined by the plastic pointer which rotates with the archwire and can be measured with the protractor.

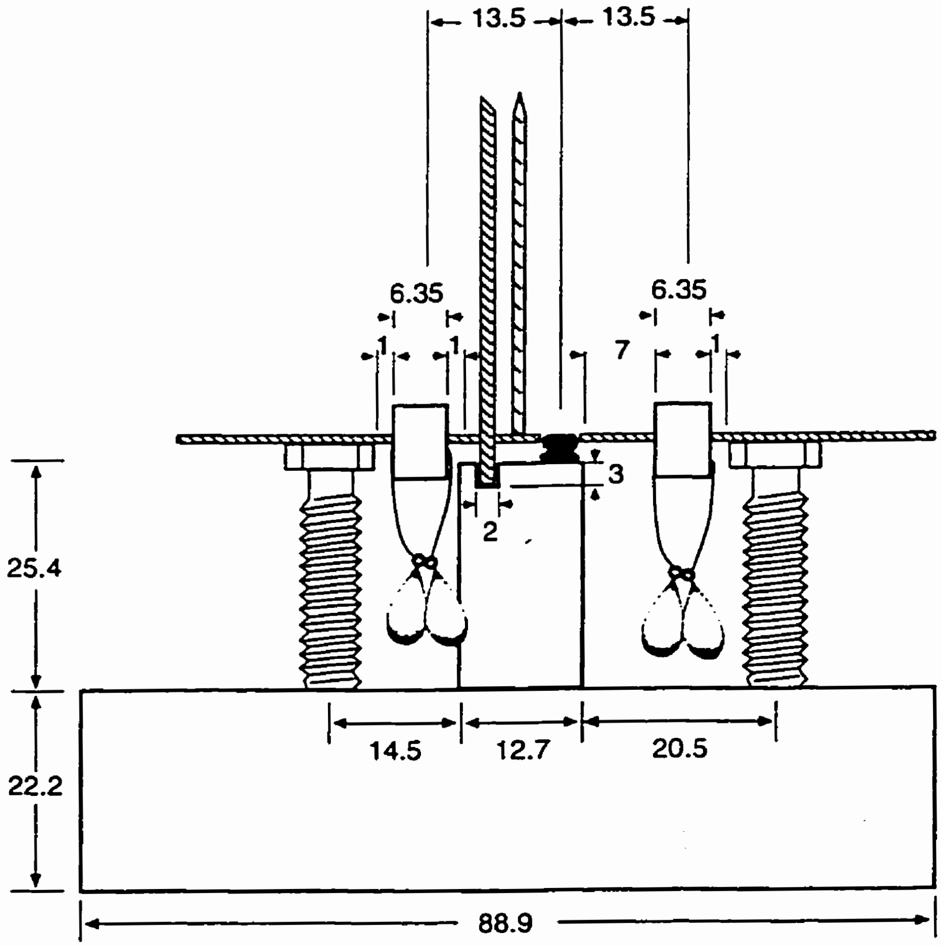


Figure XVIII Rear view of test apparatus

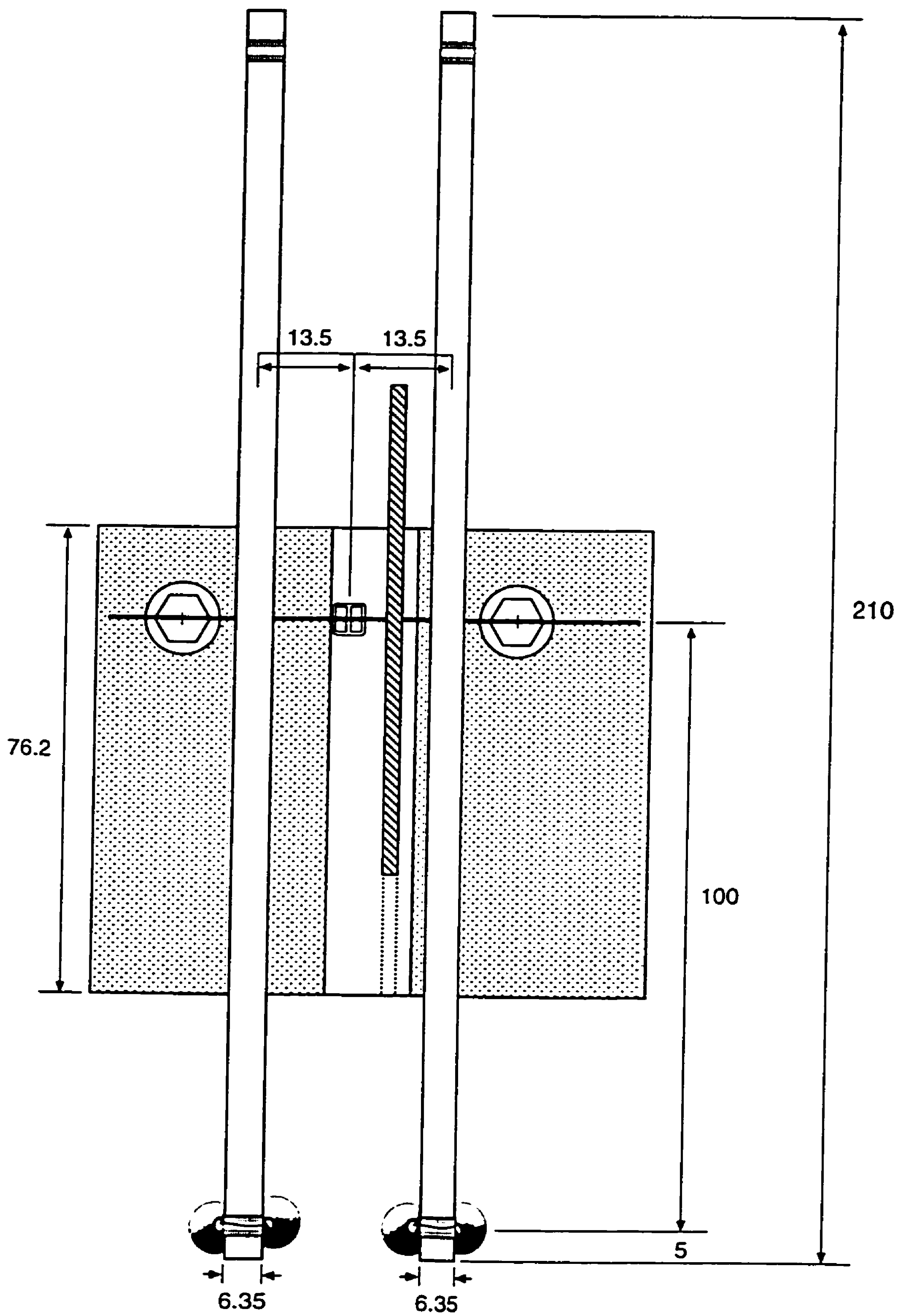
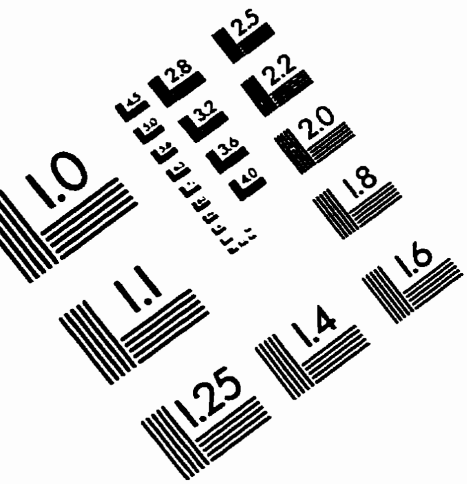
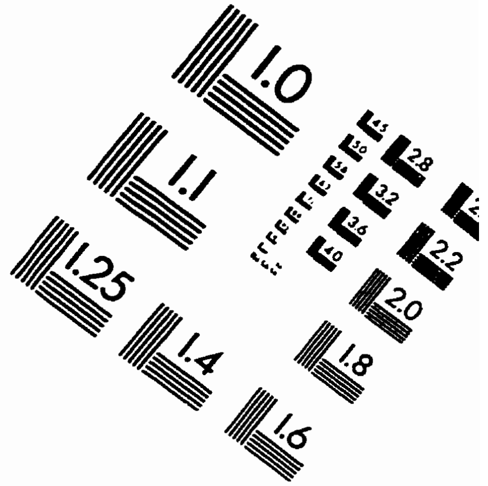
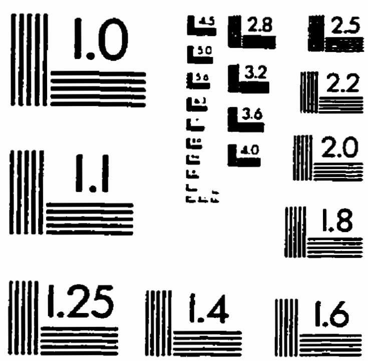


Figure XIX   Superior view of test apparatus

IMAGE EVALUATION TEST TARGET (QA-3)







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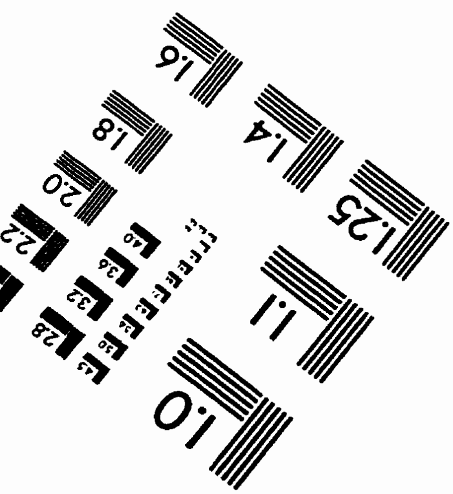
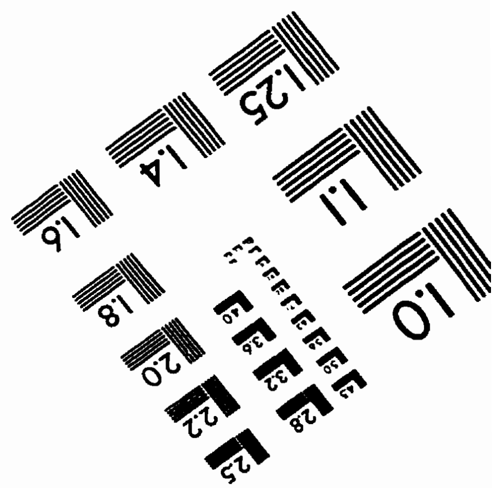
6"





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