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The Fracture Strength of Ceramic Brackets : A Comparative Study

Daniel A. Flores

ABSTRACT

THE FRACTURE STRENGTH OF CERAMIC BRACKETS: A COMPARATIVE STUDY

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The purpose of this study was to determine the effect of different surface conditions and different ligation methods on the fracture strength of ceramic brackets and the yield strength of metal brackets.

Ceramic brackets followed the Griffith model, which was used to interpret their fracture strength with respect to their surface condition. With surface damage (scratching), their fracture strength decreased, while metal brackets experienced work hardening and an increased yield strength. Undamaged single-crystal brackets had a higher fracture strength than undamaged polycrystalline brackets, but after scratching, their strength decreased to value near to that of polycrystalline brackets. The fracture strength of polycrystalline brackets was not affected by scratching. Thus, single-crystal brackets were more susceptible to surface damage than polycrystalline brackets.

Using an analysis of variance (ANOVA), a statistically significant difference was found between the strength of different bracket types. No significant difference was found between the strength of elastic ligated and wire ligated brackets. A significant difference was found between the strength of non-scratched and scratched brackets, with the non-scratched brackets having a higher strength.

Five different types of brackets (two polycrystalline, two single-crystal, and one metal) were tested under four categories. The four categories were: elastic ligation without scratch, elastic ligation with scratch, wire ligation without scratch, and wire ligation with scratch. A total of 200 brackets were tested, with each category containing 10 brackets from each type.

An acceptable testing method, which allowed the brackets to be tested in an accurate and reproducible manner, was developed. A "hard" bracket holding fixture was designed and attached directly to an Instron machine.

A torsional wire bending force, similar to the clinical torquing force placed on brackets, was used to test the failure strength of the brackets.

LOMA LINDA UNIVERSITY

Graduate School

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by

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of the Requirements of the Degree Master of Science
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Each person whose signature appears below certifies that this thesis in his opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

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INTRODUCTION

In the past few years, Orthodontists have given more attention to the esthetic aspect of the appliances they use to achieve tooth movement, especially brackets. Not only is the final result supposed to be esthetic, but today, the way a patient looks while undergoing treatment is also important.

Among the reasons for this trend toward esthetic brackets are the following: 1) the increasing number of adults who are seeking orthodontic treatment and requesting esthetic appliances, 2) the competitive environment in the orthodontic market, 3) the demand and need by orthodontists for hygienic appliances, and 4) the need to improve patient comfort during treatment.

In an attempt to fill the need for esthetic brackets, manufacturers responded by making smaller and smaller metal brackets. In the recent past a few manufacturers answered the demand for esthetic appliances by developing lingual or "invisible brackets." The latest attempt to satisfy the market's need for "invisible brackets" has been the introduction of translucent and transparent alumina brackets.

Ceramic brackets have gained such popularity and demand in the past few months, that demand has exceeded production with some manufacturers. The nature of ceramics is very different from that of stainless steel, which orthodontists are accustomed to working with. These differences need to be discussed and understood. One of the major differences between ceramic brackets and metal brackets is that ceramic brackets will fracture, instead of bend, when excessive forces are applied to them.

The purpose of this study was to test and see if there was a significant difference between the fracture strength of ceramic brackets and the yield strength of metal brackets, and if different ligation methods and/or scratches significantly affected their respective strength.

REVIEW OF THE LITERATURE

Types of Material

Metal, Ceramics, and Polymers are the three basic types of materials. Each of these materials exhibit different physical properties which are important and must be understood by the orthodontist, if they are to be used correctly.[5] This study will focus on ceramics and metals.

Physical properties are a result of the following: 1) the elements present in the material, 2) how the atoms of the elements are arranged and structured into unit cells, 3) how the unit cells are arranged into grains (crystals), and 4) how the grains are bonded together.[3, 5]

Metallic, ionic, covalent, and Van der Waals forces are the four basic types of bonds which hold materials together and they help explain why metals and ceramics behave differently under similar conditions. Metallic bonds take place when metal atoms take up a regular arrangement and give up their electrons to an electron gas. Ionic bonds, which are stronger than metallic bonds, take place when a metal atom gives up its valence electron(s) to the outer shell of a non-metal atom, resulting in positive and negative ions which attract each other. Covalent bonding, the strongest type, occurs when atoms of the same element or different elements share electrons. Van der Waals bonding, the weakest type, occurs when there is a charge attraction between molecules.[3, 5, 11]

Metallic bonds explain why metals are conductive and ductile. The electrons in the metal bond are loosely bound in the electron gas and move readily when a current is applied. Since this electron gas does not produce a strong directional atomic bond, it allows the planes of the atoms to slide over one another when a stress is applied.[5, 11, 19]

Ceramics are primarily bound together with ionic and covalent bonds, which are strong and directional. This explains why they are so strong and brittle and usually non-conductive. When a stress is applied, the crystals fracture in a brittle fashion, because the planes cannot slide over one another. When a current is applied, the electrons, which are tightly held together with strong bonds, will not move readily.[5, 11, 19]

Properties of Ceramics and Metals

Metals and ceramics have been used for a variety of things, but their applications have always been limited by their physical properties, which explains why ceramics have usually been used in static and non-moving capacities, such as pottery, bricks, chemical containers, and fine china.[3] Metals have been used in dynamic and moving capacities, such as motors, springs, armour, and tools.[5]

Tensile strength, yield strength, surface energy, modulus of elasticity, and fracture toughness are among the different physical properties which can be measured and used to understand the difference between metals and ceramics. Stress (the load/original area) and strain (change in length/original length) play an integral part in some of these measurements.[5, 11, 19]

Tensile strength (TS) is the maximum stress of a material on the stress-strain curve, and ceramics usually have a higher TS value than metals. Yield strength is the stress at which permanent deformation or plastic strain occurs in a material and this property does not apply to ceramics, due to their brittle nature. Surface energy (Ys) is the increase in energy of a system per unit area when a new surface is created and metals usually have a higher Ys than ceramics. Modulus of elasticity (E) is the slope of the stress/strain line in the elastic, non-permanent deformation, range of a material. Ceramics usually have a higher E value than metals. Fracture toughness (K_{Ic}) is the minimum stress intensity required to cause a fracture in a material, or stated differently, is the material's ability to resist damage and fracture, and metals have a much higher K_{Ic} than ceramics.[4, 5, 11, 15, 19]

The Stress-Strain Curve

The ductile nature of metals and the brittle nature of ceramics can be understood by considering the work required to fracture an object of the same size from each material, like copper and glass for instance. Copper usually fractures after considerable plastic deformation, while glass fractures without any plastic deformation, as shown in Figure 1. This is illustrated by comparing the stress-strain curves for each of these materials as shown in Figure 2. The amount of work or energy needed to cause a fracture in each material is represented by the area under their respective curves. The area under the stress-curve for glass is very small (Fig. 2a) compared to the area under the stress-strain curve for copper (Fig. 2b). Thus it can be said that copper is a tougher material than glass.[5, 18, 15]

FIGURES 1 & 2

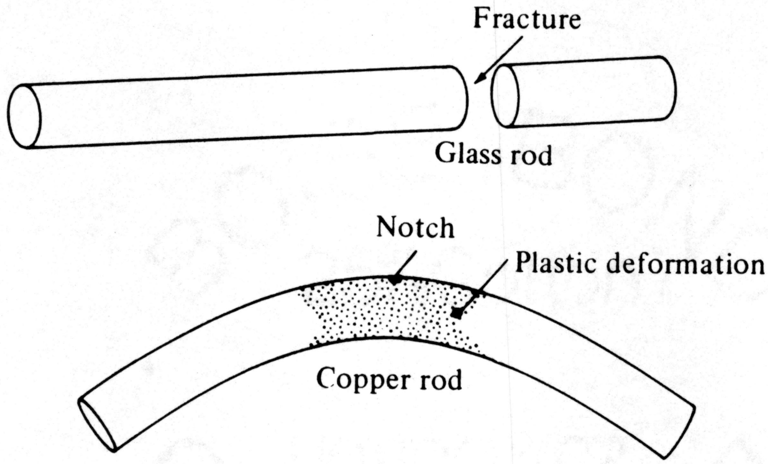


Fig. 1. Results of bending tests of glass and copper rods.[5]

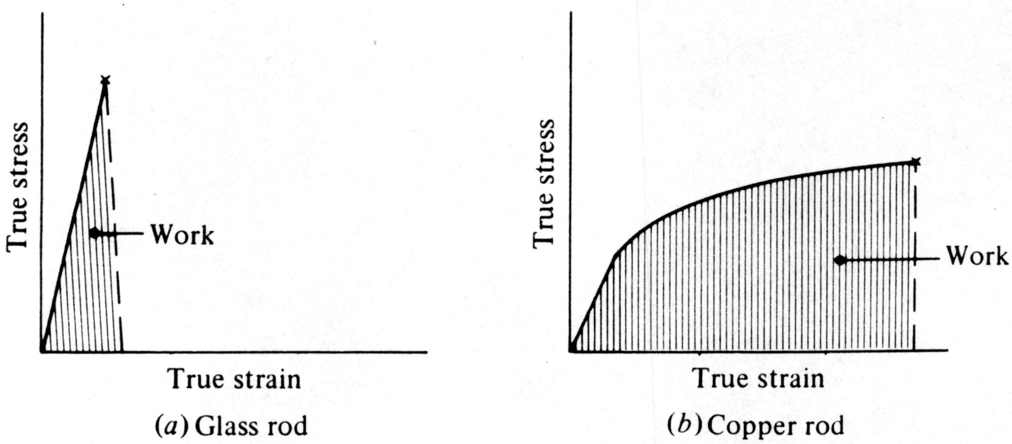


Fig. 2 True-stress/true strain curves for glass and copper.[5]

As long as engineers worked in moderate temperatures with low strength and high ductility materials, they could design for stresses below the yield strength to avoid failure with good success. But with high strength and brittle materials, designed for stresses below their yield strength or fracture strength, there were many failures which resulted from fractures. The fractures were brittle and did not exhibit even the lower levels of ductility from tensile test bars.[5]

Griffith's Principle

The brittle fracture of ceramics, their major drawback, led A. A. Griffith to further study this property and its causes in the 1920's. His research resulted in a new method for testing brittle materials called fracture mechanics.[5, 15] New design criteria, based on the concept of fracture toughness and new equations developed from fracture mechanics were the result of his pioneering work.[5, 6, 12]

Griffith calculated the minimum energy needed to make a crack grow by testing several glass specimens of the same size, which he had scratched. He reasoned that a crack grows when the mechanical energy applied exceeds the energy of the new surfaces created by the fracture. Until the minimum energy is exceeded, the applied stress is stored in the glass, as in a spring. By applying his knowledge of surface energy and using calculations for the stresses around the surface of the cracks, Griffith determined the breaking load for cracked plates.[13]

Griffith stated that the smaller the initial crack or flaw was, the greater the applied stress must be to make it grow. He also suggested that the surface chemistry of a brittle material is also important. Water has been found to reduce the surface energy of a material, and thus reduce the stress necessary to propagate a crack by a factor of nearly 20.[13, 12] Thus, both the surface condition and the environment play an important role in determining the amount of energy needed to cause a fracture in a material.

Griffith postulated that a brittle body contains small flaws which act as stress concentrators when an external stress is applied. Thus, the local stress at the root of the most severe flaw may reach the theoretical strength of the material, and cause a fracture to occur. This concept is still used today to explain the strength of brittle ceramics.[4, 5]

Griffith developed an equation which related the fracture stress (S_F) to the flaw size (a)[4, 5, 15, 11]

$$S_F = \left(\frac{2EYs}{pi*a}\right)^{1/2}$$

S_F = fracture stress

a = the crack length (depth)

E = modulus of elasticity

Ys = surface energy

Griffith's equation is used to understand the relation between stress and flaw size for ceramics.

The relationship between Griffith's theory and fracture toughness (K_{Ic}) is represented by the following equations:[1]

$$S_F = \left(\frac{2EYs}{pi*a}\right)^{1/2},$$

$$\text{and } K_{Ic} = (2EYs)^{1/2},$$

$$\text{then } S_F = \frac{K_{Ic}}{(pi*a)^{1/2}}$$

Fracture Mechanics

Since it is known that failure occurs at the most severe flaw, fracture mechanics allows for the calculation of the resistance of a material to crack growth due to a stress applied to the flaw. It separates the material's resistance to fracture from the flaw size distribution in the body. Stresses combine with the flaw, causing the defect to grow by magnifying the stress to a value which causes the atomic bonds at the tip of the flaw to break.[6]

Applying fracture mechanics to the design of fracture resistant structures and to the prediction of failure depends on: 1) the fracture toughness, 2) the existing crack length, and 3) the operating stress, a design variable. For optimum results, the allowable crack length should be only a fraction of the critical flaw length.[5, 22, 23]

In fracture mechanics, the magnified stress value at a flaw is measured by the stress intensity factor (K_I). $_I$ refers to a crack under a tensile stress applied perpendicular to the face of the crack. K_I is defined as the slope of a plot for crack tip stress vs. $(r)^{1/2}$, where r represents a distance measured away from the crack. Fracture occurs when the stress intensity factor (K_I) equals the critical stress intensity factor (K_{Ic}), the fracture toughness of the material.[6] Fracture toughness is a measure of the ability of a material to resist brittle failure, fracture.[3]

Fracture Toughness

Fracture toughness is a material property, with metals having a fracture toughness of about 20-40 MPa $m^{1/2}$ and with conventional ceramics having a fracture toughness of about 1-3 MPa $m^{1/2}$.[3]

Fracture toughness is a function of the environment, temperature, loading rate, strain rate, crack geometry, and test geometry.[6, 15, 17] It depends on how the material responds to high local stresses and how defects play a part in producing very high local stresses in the material.[5] As a general rule, as the strength of an alloy or ceramic increases, their fracture toughness decreases and their susceptibility to a brittle fracture increases.[5]

Modern Ceramics

Modern ceramic engineering has developed new ceramics and new uses for them by taking advantage of the properties of different atomic structures.[4] New uses include electrical conductors, electrical capacitors, transducers in sonar systems, human prosthesis, computer chips, laser technology, telecommunications, auto engines and orthodontic brackets.[4, 17, 20]

The diversity of atomic structures and the possibility of extensive substitution of one element for another, allows for a large variety of ceramics, with a wide range of properties.[3] Simple ceramics (a metal element and a non-metal element ionically and covalently bonded), such as silica (SiO_2), alumina (Al_2O_3), and magnesia (MgO), can be specially treated and combined to form new materials with different properties. For example, magnesia (MgO) and alumina (Al_2O_3) can be combined to make spinel ($MgAl_2O_4$), a material with special thermal and magnetic properties.[5]

Modern ceramics have new and different thermal properties, optical properties, dielectric properties, and magnetic properties.[11] They may be used in their single-crystal form or in their polycrystalline form.[20]

Alumina - Single-Crystal and Polycrystalline

Alumina (Al_2O_3), which is formed when aluminum is added to steel to remove oxygen dissolved in the steel, may be considered a typical member of the class of modern ceramics and it is one of the most studied ceramic structure.[4, 5, 11] It may have several different properties, depending on:

what other elements are added to it, how closely its grains are arranged, and the size of its grains.[3] It may be used as a single-crystal material or as a polycrystalline material.[5] These two materials are being used to manufacture the ceramic orthodontic brackets being used today.[20]

Some of alumina's favorable properties include: high harness, high wear resistance, resistance to chemical and temperature corrosion, thermodynamic stability, no phase changes in the solid state, strength retention at high temperatures, and a low fraction coefficient.[10] Some of alumina's unfavorable properties include: a low strength compared to theoretical strength, a large scatter in strength values, great brittleness, susceptibility to thermal and mechanical shock loading, and a time-dependant strength.[6, 10]

There is an increasing number of applications in which single crystal alumina is necessary or desirable because of its special optical, electrical, magnetic, or strength properties. For example, single-crystal alumina is transparent, while polycrystalline alumina is translucent.[20] Also, single-crystal alumina (SCA) is mostly anisotropic (directional with its properties), while polycrystalline alumina (PCA) is generally isotropic (having similar properties in all directions).[5]

It is important to understand the fracture behavior of single-crystals, because they form the basis for understanding the behavior of polycrystalline ceramics. The fracture properties of single-crystal ceramics should be the lower limit of the fracture properties for polycrystalline ceramics.[6]

Cracks tend to occur along preferential planes in SCA (cleave), depending on the temperature. Certain planes fracture more readily under stress than others and thus, they exhibit lower fracture toughness values. As with most ceramics, stressing SCA will cause a fracture to occur at the largest flaw with the lowest toughness.[9] Fracture toughness values for SCA range from 2.43-4.54 MPa $m^{1/2}$, depending on the crystallographic plane.[9]

Another way of understanding the different fracture toughness values for SCA is to consider the surface energy of the different planes. Fracture surface energy is a function of the orientation of the crack plane in relation to the crystallographic axis of the crystal. Atomic bonding across some planes is stronger than in others and this makes it more difficult to propagate a crack parallel to the strongly bonded planes. SCA has different fracture planes, all having a different surface energy, which helps to explain why it has different fracture toughness values.[24]

SCA is anisotropic in strength, surface energy, and fracture toughness.[2, 9, 24] In general, SCA follows the Griffith principle (fracture will occur at the largest flaw with the lowest toughness) and forms a basis for understanding PCA.[9] SCA, compared to PCA, is more time consuming to manufacture and more difficult to mill commercially.[20] The Czochralski process, the EDFG process, and the Verneuil process are the methods used in forming SCA.[11]

PCA has been shown to be tougher than SCA, with fracture toughness values reported to be in the 3.0-5.3 MPa $m^{1/2}$ range.[8] PCA may be tougher than SCA for the following reasons: 1) its true fracture surface is greater than the surface used to calculate the fracture surface energy per unit area, 2) the tortuosity of its fracture surface causes many microscopic deviations of the local crack front from the path of the macrocrack, thereby consuming more energy, 3) high local stresses that align the tortuous crack front may cause increased occurrences of microplasticity 4) the crack propagation may be accompanied by other forms of non-conservative energy consumption, such as the generation of heat at the emission of sound and light, and 5) subsidiary cracking may occur in the stress field ahead of the main crack. All these reasons depend on: 1)the location, size, and shape of pores, 2) the grain size, 3) the presence and location of second phases, and 4)the temperature.[4]

Other important parameters include the environment and the length of time under stress. Alumina will undergo slow crack growth while under stress, because flaws are not stable, even under steady stress and modest environments.[17, 23] Also, cracks will grow faster in a wet environment, because water decreases the surface energy of the material and that causes the energy necessary to create a crack to decrease.[6, 23] Precautions that account for the loss in strength under service conditions should be taken in order to make ceramics under structural use more reliable.[4]

Variables Affecting Strength

In general, the initial strength of a ceramic depends on: the material's surface finish provided by the fabrication, the material's microstructure, and the material's constants.[4] But as time under stress increases, the material decays from its initial strength value and its strength will be dependant on: the properties of the material, the geometrical properties of the flawed specimen, and the stress history of the specimen.

Another variable to keep in mind while evaluating a material is testing methods. Different testing methods for fracture strength will give different values for the fracture strength a given material. For example, bending tests usually give higher fracture strength values than tension tests.[1] Also, different procedures for testing fracture toughness will give different results for a given material. For example, a three point loading test will give different fracture toughness values than a double conslive loading test. Thus, when evaluating a given material for a certain purpose, it is important to know which testing method and procedure was used to arrive at a particular value.[21]

Weibull and the Reliability of Ceramics

Several methods have been attempted at developing a statistical theory which would give a measure of the reliability of the fracture strength of brittle solids, but there is no generalized theory that applies to all brittle materials. Probably the best known statistical theory was developed by W. Weibull, who stated that the risk of failure is proportional to a function of the stress and the volume of the body.[11, 22]

The importance of Weibull's modulus (m) is that it has made it possible to do the following with brittle materials: 1) express the scatter in test strengths and project a threshold stress which will be reliable, 2) allow designers to downgrade the projected threshold stress, by realizing the importance of the lower bound values, 3) allow for the increasing chance of a critical flaw as the specimen increases in size, and 4) allow for the stresses being spread uniformly through the object instead of being localized in a typical fracture test, like the bend test.[1, 22]

With the Weibull modulus (m), the higher its value for a given material, the more reliable the material is said to be within a given parameter.[10, 22] But the Weibull modulus is just one method of rating a material and it should be considered along with fracture toughness values, because they are independent of each other for materials that follow the Griffith principle of cracks.[10] For example, it is possible to have two materials with the same scatter in flaws and fracture strengths (the same Weibull modulus), and have one tolerate loads and flaws better than the other (different fracture toughness). The material with the higher fracture toughness seems to be more reliable during service because it has special properties that allow it to withstand more accidental damage.[10]

Rational forecasts of long term reliability must be attempted for ceramic applications if they are to be used with any degree of confidence. Among the methods used for assuring reliability are: 1) nondestructive testing (NDT), 2) stress, probability and time testing (SPT), and 3) proof testing. Each method has its own distinct advantages and disadvantages, but they provide a way to get rid of the flaws which will limit the service life of a ceramic specimen to less than an acceptable minimum.[23]

As mentioned previously, alumina is the modern ceramic material being used to manufacture orthodontic brackets. With an understanding of the material's different properties, it was the purpose of this study to: 1)test the fracture strengths of the ceramic brackets accurately, 2) see if they were different from one type to another, 3) see if they responded differently under different conditions, and 4, see if they followed basic ceramic engineering principles, like the Griffith principle.

METHODS AND MATERIALS

Test Design

Aluminum oxide (Al_2O_3) is used to make all of the ceramic brackets tested. Since both polycrystalline (polysapphire) and single crystal (sapphire) materials are used, both types of ceramic brackets were tested for their fracture strength. Because metal brackets have been the standard bracket used in orthodontics, they were included in this study as a base from which to make comparisons. Metal brackets were tested for their yield strength. In order to keep the testing variables to minimum, only maxillary central brackets with an .018" slot size were used. A total of 200 brackets, 40 from five different companies, were tested.[A] Figure 3 illustrates the brackets tested in this study.

The experimental design was a 2 * 2 factorial. Four categories were developed in order to see if ligation methods and/or scratches affected the fracture strength of the different ceramic brackets and the yield strength of the metal brackets. Elastic ligation with non-scratched (E/NS), elastic ligation with scratched (E/S), wire ligation with non-scratched (W/NS) , and wire ligation with scratched (W/S) were the four categories. 10 brackets from each bracket type and a total of 50 brackets were tested under each category.

Testing Requirements

Before definite testing could begin, an acceptable testing method was necessary. An acceptable testing method does not introduce major experimental errors, is repeatable, and can be duplicated by other testing facilities. Also, the testing method must simulate the type of force brackets experience in a patient's mouth during treatment. No such method was available. Therefore, a project was established to develop a technique and procedure which would meet these requirements.

The result was a hard bracket holding design which provided accurate and reproducible data. A hard fixture is one that will not flex or deform under testing conditions. Fifteen different testing methods, which are discussed in further detail in the appendix, were evaluated prior to developing a satisfactory testing method.

[A] American Orthodontics' Master Series brackets were metal, Ormco's GEM and"A"- Company's Starfire brackets were single crystal, and GAC's Allure III and Unitek's Transcend brackets were polycrystalline.

In this study, bracket fracture strength or yield strength was determined with an archwire torque test. The archwire torque test involved ligating a rectangular archwire into the slot of a bracket bonded to a steel base, securing the base in a holding vice, engaging a torquing key to the archwire, and then torquing the archwire with the torquing key until the bracket failed. Figure 4 illustrates this archwire torque test.

FIGURES 3 & 4

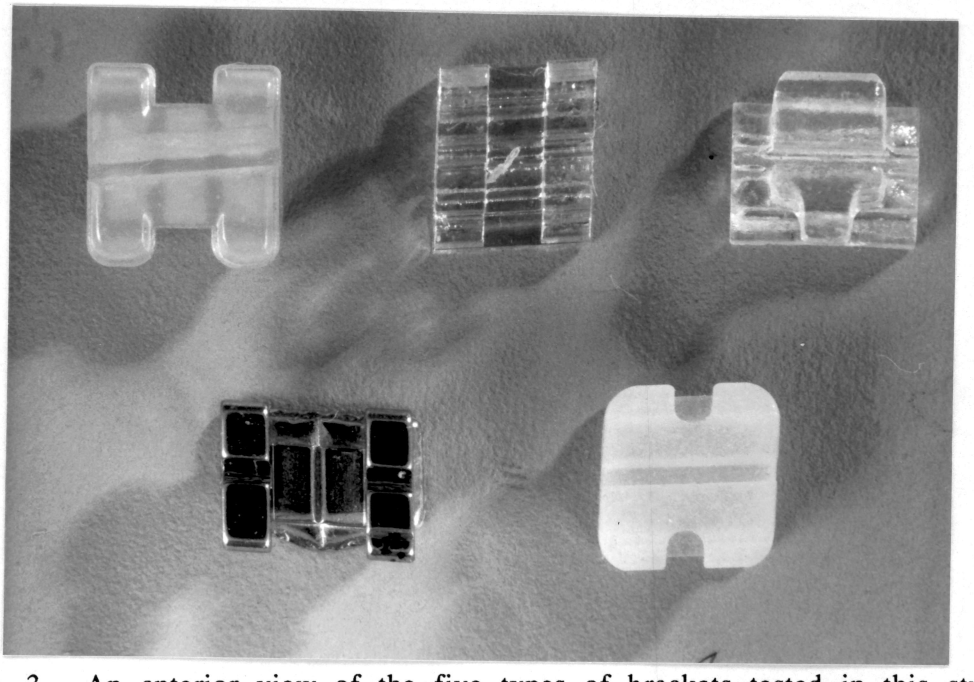


Fig. 3. An anterior view of the five types of brackets tested in this study. Clockwise from top left: PC, ME, PC, SC, and SC type brackets.

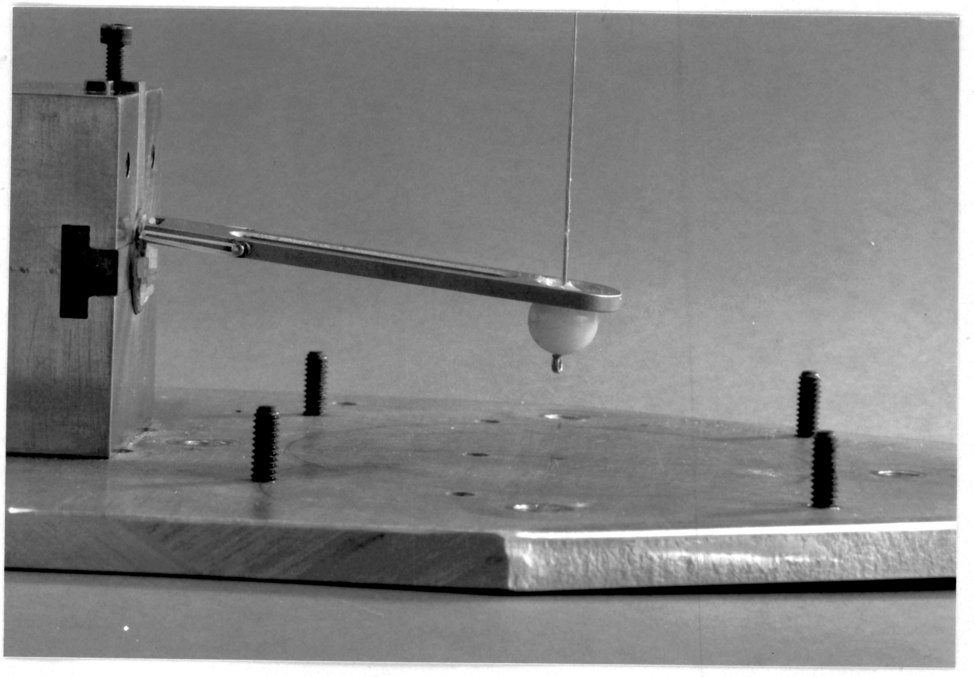


Fig. 4. A side view of the testing fixture, with the metal vice gripping a bracket mounting disc and the torquing key engaged to the archwire.

Failure, is defined as: when a bracket fractures or deforms. Due to their different physical properties, ceramic brackets fracture when they fail and metal brackets deform when they fail. Fracture strength for the ceramic brackets was considered to be the point where they fractured and yield strength for the metal brackets was considered to be the point where they permanently deformed.

Bonding and Mounting of Brackets

To prepare the brackets for the archwire torque test, they brackets were bonded to 3/4" metal discs, that were approximately 10mm in height. The discs were cut from a cold drawn, 1018 grade, steel rod, which had a tensile strength of 64,000psi, a yield strength of 54,000psi, and a Brinell hardness of 126. Top and bottom surfaces of the discs were squared to the long axis with a lathe machine and then sanded.

One flat surface from each disc was prepared for bonding by spot welding a small 3/4" round wire cloth to it with a dental spot welding machine. The round metal cloth pieces were cut from 100 x 100/sq. in. wire cloth, made from .0045" round stainless steel wire, type 304, and having openings .0055" wide. This type of wire cloth was chosen because it was similar to the mesh on the bonding surface of metal brackets, which has successfully helped to bond brackets to teeth. Prior to spot welding, the discs and the wire cloth pieces were ultrasonically cleaned in acetone to provide a good weld. Several welding spots were evenly applied in order to securely weld the wire cloth and have a flat bonding surface. Around the perimeter, the welding spots were placed closer together to further prevent the wire cloth from separating. To ensure a good bond, the bonding surface of the disc and mesh were sandblasted. Trapped sand was blown off the meshed discs with pressurized air and any remaining sand particles and contaminants were further removed by ultrasonically cleaning the meshed discs in acetone. Thus, the discs' bonding surface was similar to a tooth's etched enamel, because it was hard, rough, and mechanically interlocking.

Dental Concise, by 3M, was the adhesive used to bond the brackets to the meshed discs, because its bonding strength and strength was considered the standard for dental adhesives.[25] Pastes A and B were thinned by mixing them with approximately 15 drops of their respective liquids. The thinning allowed the adhesive to flow better into the undercuts and spaces of the mesh, and thus provide a stronger bond. Equal parts of pastes A and B were mixed as directed and applied to the bonding surface of the brackets and discs. Then the brackets were placed on the discs and held in place with large paper clamps, which applied a constant pressure as the adhesive set. Excess adhesive was removed from the brackets and the adhesive was allowed to set for 24 hours. Each disc contained 4 brackets, all of the same material and design. The brackets were evenly spaced and placed along the perimeter of the discs, with their incisal edge toward the center, as illustrated in Figure. 5.

Ligation Methods and Techniques

A straight stainless steel archwire, .018" * .025" and approximately 1.5" long, was then ligated to a bonded bracket. A full size archwire was used in order to minimize the play of the archwire in the slot and to transmit the load directly to the brackets. Hi T II, by Unitek, was the archwire type used because it had strong physical properties: the ultimate tensile strength was 340ksi, the fracture strength was 300ksi, and the modulus of elasticity was 30 * 10^6psi. The archwire was ligated to the brackets with either elastic rings or metal ligature ties. A-lastiks by Unitek were the elastic rings used and .010" metal ties by Ormco were the metal ties used. Care was taken not to touch the brackets with any instruments during the ligation procedure, in order not to introduce any surface flaws. A Mathieu elastics inserting plier, with a hooked tip, was used to place the elastic rings. When wire ligatures were used, they were closely adapted to the brackets with a How plier and then tightened with a Mathieu ligating plier in order to equalize the ligating force around the bracket.

Technique for Scratching Brackets

If the brackets were to be scratched, they were scratched prior to ligating the wire. A 1" diameter diamond cutting disc, which fit into the brackets' slot, was used to apply a scratch along the base of the brackets' slot. The diamond disc was hand held by the same person during all scratching procedures and only one pass was made through the slot. In order to minimize variations in the scratches, the same diamond disc was used to scratch the brackets and the scratches were placed on different brackets in an orderly and rotating manner. For example, four brackets, each from the same bracket type, bonded to a mounting disc were scratched and then four brackets on another mounting disc were scratched next, and so forth, until all the scratching was complete.

The Testing Fixture

After, an archwire was ligated to a bracket, the metal disc was placed into a custom made steel vise. The metal vice (2.125" x 2.5" x 1") had a hole (3/4" diameter and 10mm deep) centered on one of the sides for holding the metal discs. To grip the metal discs firmly, the vise had three sliding arms which could be adjusted and tightened, as illustrated in Figure 6 The vise was mounted to a metal platform, so that it stood 2.5" tall, and the platform was, in turn, mounted to the Instron machine, so that when the brackets were tested, they were 3" away from the vertical pull of the Instron (Fig. 4). Thus, the brackets were tested in a vertical position, with their incisal edge down, similar to the position they would assume if bonded to a standing patient's central incisor.

A custom made torquing key (3.5" x 19/32" x 1/8"), was then engaged to the archwire. The torquing key had two slots to engage .018" wire which were .380" apart. This design allowed the key to engage the wire on both sides of a bracket. The torquing key and archwire were held together with two 2oz, 1/4" elastics, which wrapped around the archwire and a hook on the torquing key, on each side. On the opposite end of the torquing key, there was a ball and socket arrangement. The ball was made of hard nylon (about 1/2" in diameter) and the socket (about 5/16" in diameter) was a bowl shaped opening on the bottom surface of the torquing key. The ball was held in the socket by a loop at the end of a round wire (.030" in diameter, 12" long, and looped on each end), which ran through the nylon ball's long axis and the socket, and attached to a hook fastened to the Instron. In order to maintain a continuous vertical pull on the torquing key, the distance from archwire to the center of the nylon ball was 3" and the nylon ball rotated within the bowl as the key was pulled up by the Instron. Figures 4 and 6 illustrate the the torquing key and its engagement.

FIGURES 5 & 6

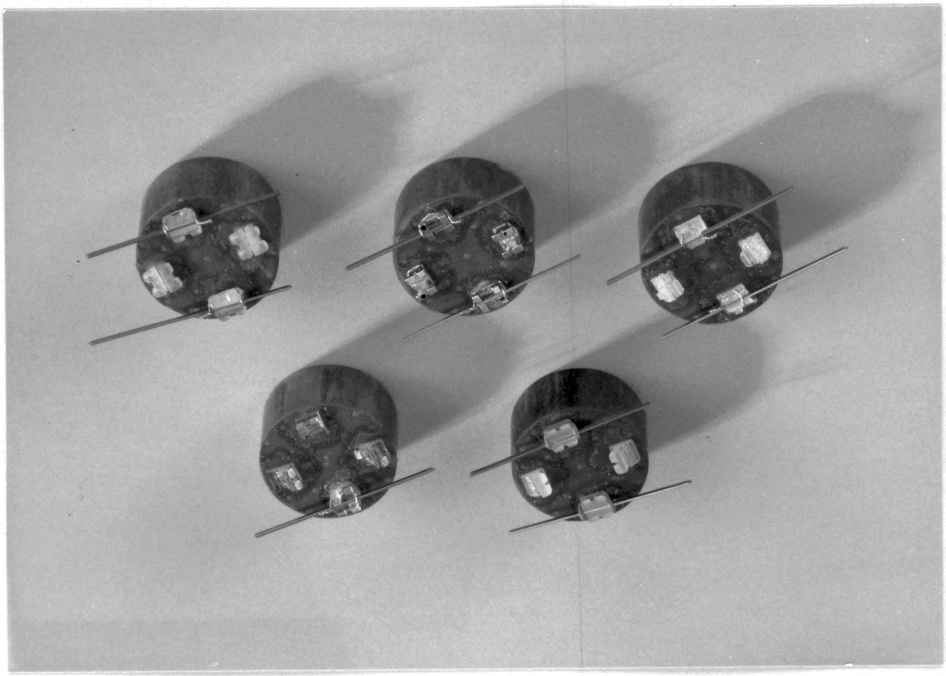


Fig. 5. A top view of the bracket mounting discs with the brackets mounted and the archwires ligated after the brackets had been fractured.

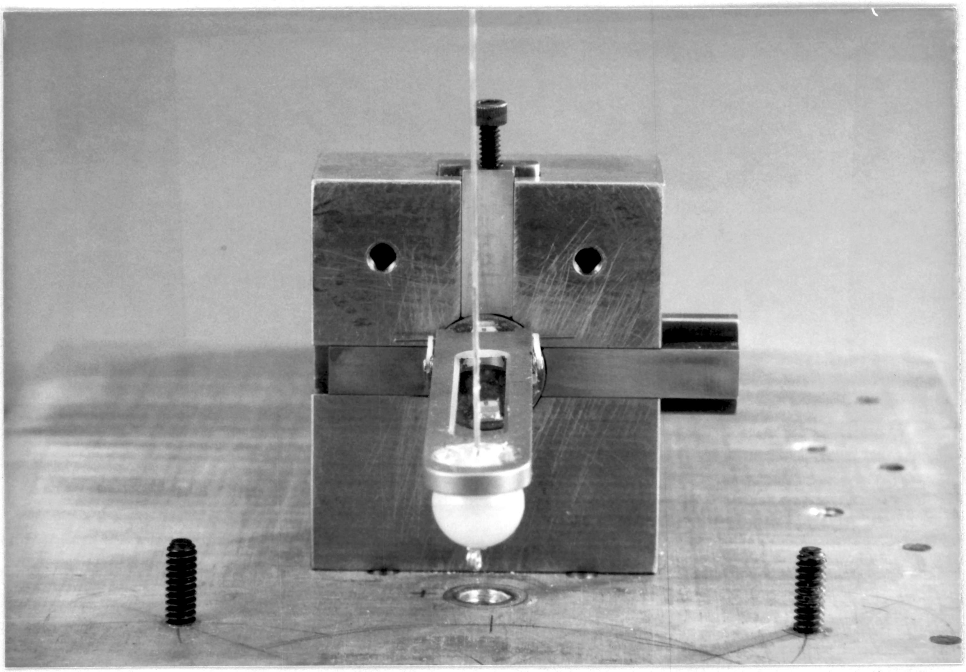


Fig. 6. A front view of the testing fixture, showing the engaged torquing key and its ball and socket arrangement with the nylon ball.

Before the Instron was activated, the metal disc and the torquing key were adjusted so that the brackets were level. Leveling was done to insure that all brackets were tested equally and to insure that the forces transmitted from the torquing key, through the archwire, and to the brackets were equal on both sides. A spirit level was placed on the engaged torquing key and the key was then rotated until it was level, which, in turn, leveled the archwire and the bracket to be tested, as illustrated in Figure 7. Once the bracket was leveled, the metal disc was tightened using the three sliding arms on the vice. Thus the bracket holding and testing fixture was securely mounted and would not bend or distort during testing procedures.

Testing Procedure

At this time, the bracket was ready to be tested and the Instron was activated to pull up on the torquing key until the bracket failed. The crosshead speed was set at 10mm/min. When the ceramic brackets fractured, the slope of the line measuring the applied torsional force dropped instantly, but when the metal brackets deformed, the slope of the line measuring applied torsional force began to slowly decrease in steepness. The fracture strength of a ceramic bracket was determined to be the point where the slope of the line dropped down and the yield strength of a metal bracket was determined to be the point where the steepness of the line's slope began to decrease. Measurements were made from the graph paper for each bracket tested and then categorized for future statistical analysis.

FIGURE 7

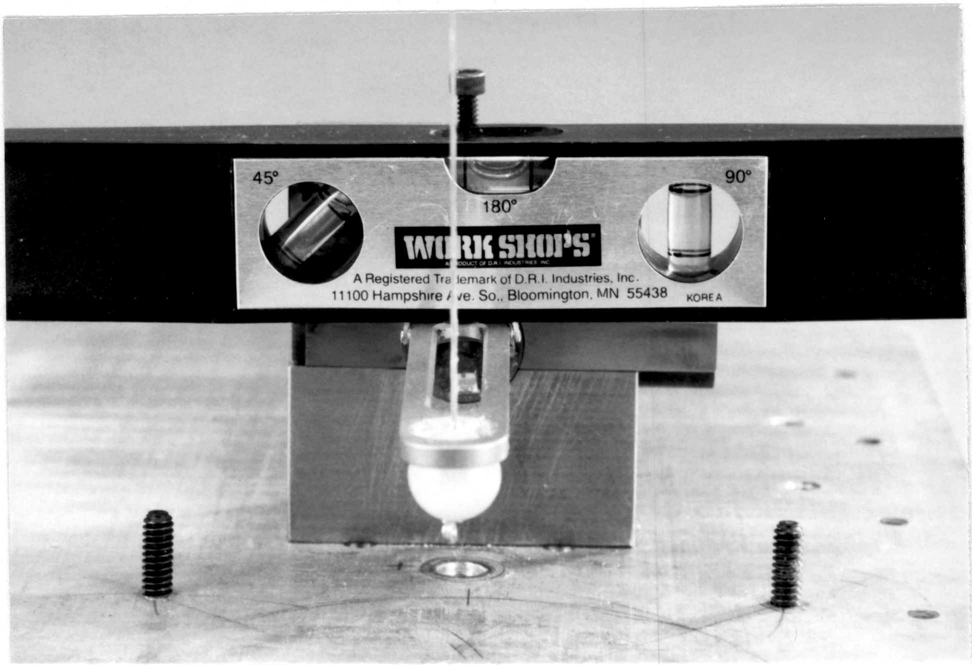


Fig. 7. A front view of the testing fixture showing the spirit level leveling the torquing key. This was done prior to testing each bracket

Converting Load to Stress

In order to standardize the torsional load measurements (P, measured in lbs.) applied to the different bracket types, they were converted into stress (S_F, measured in psi), where $S_F = \frac{force}{area}$) by using the Beam Bending (Flexure) Formula, ($S_F = \frac{MC}{I}$). S_F is the maximum stress at the outermost fiber of the beam M is the bending moment at the section of interest, C is the distance from the centroidal axis of the beam to the outermost fiber, and I is the moment of inertia of the cross section with respect to its centroidal axis.[14]

The Bending Formula took into account the following important dimensions from the testing model: 1) the width of the bracket's wing or wings (a), 2) the depth of the bracket's wing at the base of the slot (c), 3) the width of the archwire being bent or the distance of the applied force of the bracket (d), and 4) the length of the torquing key in inches (3), the distance of the applied force to the point where the fracture or bend started on the bracket (D). These dimensions and measurements and the derivation of S_F from the testing model to the Beam Bending Formula are illustrated in Figure 8. S_F was derived from $\frac{MC}{I}$ as follows:

$$S_F = \frac{MC}{I}$$

$$M = R_B D$$

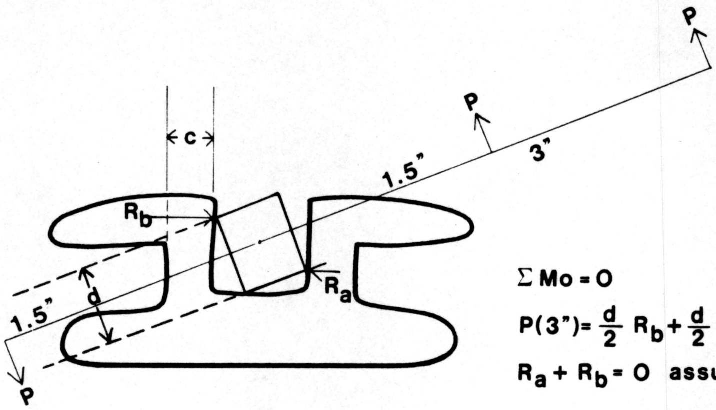
$$C = c/2$$

$$I = \frac{1}{12} a c^3$$

$$R_B = \frac{3P}{(d/2)}$$

$$S_F = \frac{\frac{3P}{(d/2)} D (c/2)}{\frac{1}{12} a c^3}$$

FIGURE 8

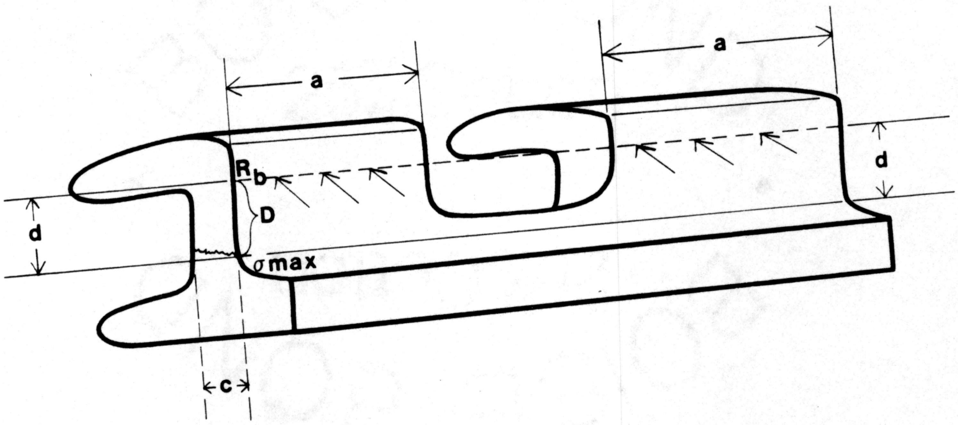


$\Sigma Mo = 0$

$P(3") = \frac{d}{2} R_b + \frac{d}{2} R_a$

$R_a + R_b = 0$ assume $R_a = R_b \gg P$

ie apply moment of (3"P)



$$\sigma max = \frac{MC}{I}$$

$$\downarrow$$

$$\sigma max = \frac{R_b D (c/2)}{\frac{1}{12} ac^3}$$

$M = R_b D$, $R_b = \frac{3P}{d/2}$

$C = c/2$

$I = \frac{1}{12} ac^3$

$$\boxed{\sigma max = \frac{\frac{3P}{d/2} D (c/2)}{\frac{1}{12} ac^3}}$$

includes expressions for P

Fig. 8 The derivation of S_F from the Beam Bending Formula, as it was applied to the bracket testing design

Calculating Crack Length

After the the mean S_F (the maximum stress at fracture) was derived and calculated for each bracket type within each category, the mean length (depth) of the crack needed to cause the fracture (a_f) was calculated using Griffith's equation as follows:[4, 11, 15]

$$S_F = \left(\frac{2EYs}{pi * a_f}\right)^{1/2}$$

$$a_f = \frac{2EYs}{pi(S_F)^2}$$

$$Ys \text{ for SCA} = 2.8554 * 10^{-3} \frac{\text{Ft-lbs}}{\text{in}^2}$$

$$Ys \text{ for PCA} = 9.518 * 10^{-3} \frac{\text{Ft-lbs}}{\text{in}^2}$$

$$E \text{ for SCA} = 60 * 10^6 \text{ psi}$$

$$E \text{ for PCA} = 55 * 10^6 \text{ psi}$$

$$K = \frac{2EYs}{pi}$$

$$K_{Ic} \text{ for SCA} = \frac{(2)(60 * 10^6)(2.8554 * 10^{-3})}{pi} * \frac{12in}{Ft} = 1.308819 * 10^6$$

$$K_{Ic} \text{ for PCA} = \frac{(2)(55 * 10^6)(9.518 * 10^{-3})}{pi} * \frac{12in}{Ft} = 3.999169 * 10^6$$

$$a_f = K\left(\frac{1}{S_F^2}\right)$$

$$a_f \text{ for SCA} = 1.308819 * 10^6 \left(\frac{1}{S_F^2}\right)$$

$$a_f \text{ for PCA} = 3.999169 * 10^6 \left(\frac{1}{S_F^2}\right)$$

Fractography

A scanning electron microscope (SEM) was used to examine and take photographs of the fractured brackets (fractography). Where and how the different types of ceramic brackets fracture was investigated. Any distinct patterns and characteristics of fracture was evaluated to determine if there was any correlation to the data.

Statistical Method and Variables

Statistical analysis included the use of several Analysis of Variance (ANOVA) with either the torsional load (P) or stress (S_F) measurements as the dependent variable and the following three independent variables: 1) bracket type (1-PC, 2-PC, 3-SC, 4-SC, and 5-ME) or material type (1. polycrystalline (PC) vs. single crystal (SC) vs. metal (ME), or 2. ceramic (C) vs. metal, or 3. polycrystalline vs. single crystal), 2) ligation (elastic (EL) vs. wire (WL)), and 3) scratch (non-scratched brackets (NS) vs. scratched brackets (S)). For each bracket type, means (M) and standard deviations (SD) for P and S_F were computed under the four categories their brackets were tested: 1) elastic ligation with non-scratched brackets (EL/NS), 2) elastic ligation with scratched brackets (EL/S), 3) wire ligation with non-scratched brackets (WL/NS), and 4) wire ligation with scratched brackets (WL/S). and then statistically analyzed using ANOVA to test the null hypothesis (H_o): there is no significant difference ($p < 0.05$) between the fracture strengths of the ceramic brackets and the yield strength of the metal brackets from each bracket type tested or written in equation form:

$$H_o: M_1 = M_2 = M_3 = M_4 = M_5$$

Using various combinations of the four categories, other ANOVA tests were also run to see if there was a significant difference ($p < 0.05$), between each bracket type, within each bracket type, between material types, and within material types.

RESULTS

General Results

The results of the study are summarized in the following tables and charts. These list and graphically illustrate the mean values for the load at failure (P) and/or the stress at failure (S_F). Units for P are listed in lbs. and units for S_F are listed in psi. P values represent the load exerted by the Instron at the point of bracket failure and S_F values represent the stress placed on the brackets at the point of failure. The S_F values for ceramic and metal brackets may be considered their fracture strength and yield strength respectively.

An Analysis of Variance (ANOVA 1) was done with P or S_F as the dependent variable and with bracket type, elastic ligation vs. wire ligation, and non-scratched vs. scratched as the independent variables. With P as the dependent variable, ANOVA 1 showed a significant difference ($p < .05$) between bracket types (1, 2, 3, 4, and 5) ($F_{(4,180)} = 19.67$, $p = 0.0$), no significant difference between elastic (EL) and wire ligation (WL) ($F_{(1,180)} = .55$, $p = .459$), and a significant difference between non-scratched (NS) and scratched (S) brackets ($F_{(1,180)} = 70.78$, $p = 0.0$). With S_F as the dependent variable, ANOVA 1 showed similar results between bracket types ($F_{(4,180)} = 54.66$, $p = 0.0$), between EL and WL ($F_{(1,180)} = 1.33$, $p = .249$), and between NS and S brackets ($F_{(1,180)} = 70.78$, $p = 0.0$).

Comparing the Four Categories

Tables 1 and 2 list the mean P and S_F values and their SDs, respectively, for each bracket type, under the four categories their brackets were tested. These tables list all of the possible interactions ANOVA 1 took into account in determining what independent variables were significantly different. The four categories were: 1) elastic ligation and non-scratched (EL/NS), 2) elastic ligation and scratched (EL/S), 3) wire ligation and non-scratched (WL/NS), and 4) wire ligation and scratched (WL/S).

In table 1, the total differences between EL/NS (.174) vs. WL/NS (.180) and EL/S (.114) vs. WL/S (.119) are not great. On the other hand, the total mean differences between EL/NS (.174) vs. EL/S (.114) and WL/NS (.180) vs. WL/S (.119) are great. These differences agree with ANOVA 1. Chart 1 graphically illustrates the values in Table 1 for each bracket type.

TABLE 1

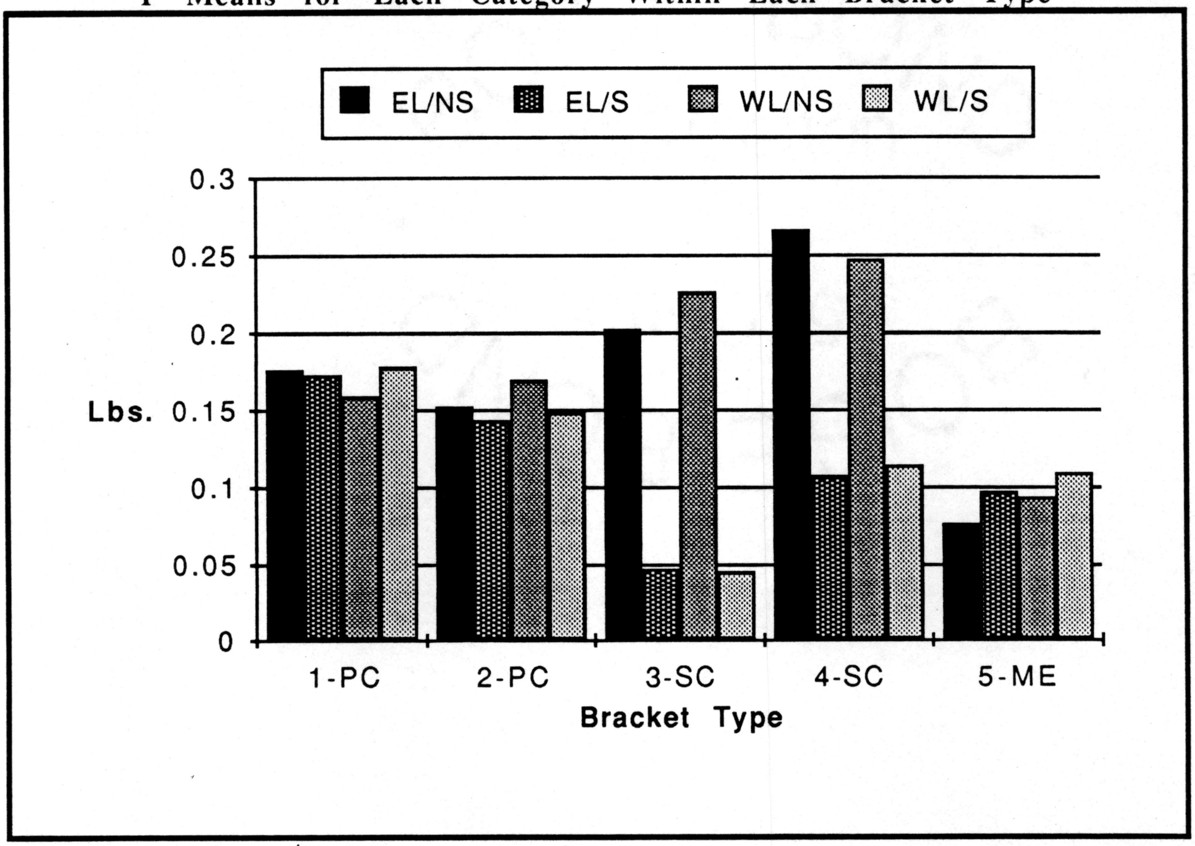
P Means and SDs for Each Category Within Each Bracket type

Bracket Type	Number Per Box	EL/NS Mean	EL/NS SD	EL/S Mean	EL/S SD	WL/NS Mean	WL/NS SD	WL/S Mean	WL/S SD	Total Mean	Total SD
1-PC	10	.176	.016	.173	.010	.159	.027	.179	.010	.172	.018
2-PC	10	.152	.024	.143	.022	.170	.011	.148	.030	.153	.024
3-SC	10	.202	.086	.047	.014	.227	.082	.046	.020	.131	.103
4-SC	10	.267	.157	.108	.031	.248	.076	.115	.041	.184	.115
5-ME	10	.076	.014	.097	.016	.094	.012	.109	.010	.094	.017
TOTAL	50	.174	.100	.114	.047	.180	.074	.119	.051	.147	.077

Units are in lbs.

CHART 1

P Means for Each Category Within Each Bracket Type



In Table 2, the total mean differences between ligation methods, EL/NS (76.78) vs. WL/NS (81.90) and EL/S (48.03) vs. WL/S (51.16), are not great. However, the total mean differences between non-scratched and scratched brackets, EL/NS (76.78) vs. EL/S (48.03) and WL/NS (81.90) vs. WL/S (54.16), are much greater. These differences, once again, are in agreement with ANOVA 1. Chart 2 graphically illustrates the values in Table 2 for each bracket type.

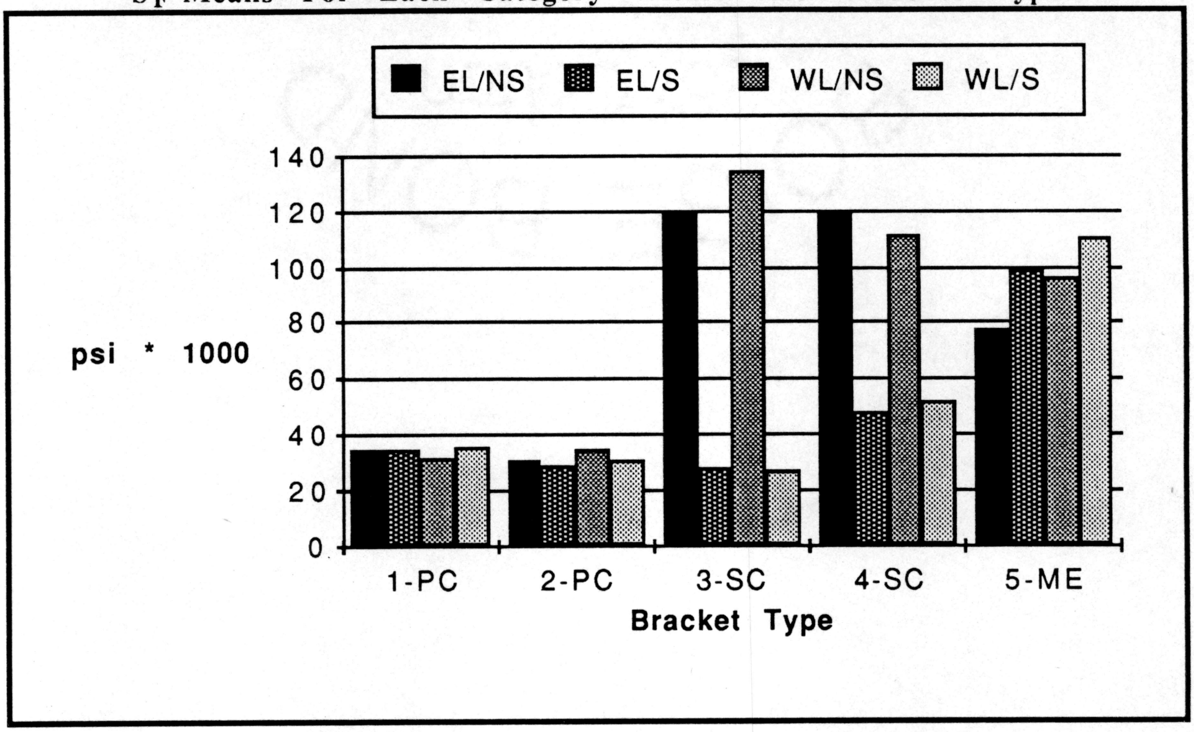
TABLE 2

S_F Means and SDs for Each Category Within Each Bracket Type

Brckt	#	EL/NS		EL/S		WL/NS		WL/S		TOTAL	
Type	Box	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	10	35.23	3.29	34.75	2.06	31.96	5.33	35.81	1.92	34.44	3.62
2	10	31.26	4.99	29.55	4.50	35.00	2.34	30.60	6.27	31.60	5.01
3	10	119.53	51.04	28.17	8.25	134.38	48.30	26.98	11.77	77.26	61.22
4	10	120.12	70.87	48.50	14.04	111.82	34.44	51.70	18.37	83.03	54.76
5	10	77.76	14.32	99.18	16.20	96.33	12.64	110.71	9.77	95.99	17.62
TOTAL	50	76.78	54.56	48.03	28.67	81.90	49.27	51.16	33.02	64.47	45.04

Units are in $lbs._{psi} * 10^3$.

CHART 2
S_F Means For Each Category Within Each Bracket Type



Non-Scratched vs. Scratched

Tables 3 and 4 list the differences between the means of non-scratched and scratched brackets for P and S_F, respectively.

In Table 3, the P means and SDs are listed for NS and S brackets within each bracket type. The difference between the total means for NS (.177) and S (.116) is great (.061 or 34% of .177) and agrees with ANOVA 1. A larger difference was noted between the means of the NS and S brackets within bracket types 3 (.215 vs. .047) and 4 (.257 vs. .111), which are single crystal, when compared to the difference within bracket types 1 (.167 vs. .176) and 2 (.161 vs .146), which are polycrystalline. In fact, the mean value for S brackets in bracket type 1(.176) was higher than the mean value for their NS brackets (.167). Chart 3 graphically illustrates Table 3, by showing the differences between the P means for NS and S brackets within each bracket type.

TABLE 3

P Means and SDs for Non-Scratched and Scratched Brackets Within Each Bracket Type

Bracket Type	Number Per Box	Non-Scratched Mean	Non-Scratched SD	Scratched Mean	Scratched SD	Total Mean	Total SD
1	20	.167	.023	.176	.010	.172	.018
2	20	.161	.021	.146	.026	.153	.024
3	20	.215	.083	.047	.017	.131	.103
4	20	.257	.121	.111	.036	.184	.115
5	20	.085	.016	.103	.014	.094	.017
TOTAL	100	.177	.088	.116	.049	.147	.077

Units are in lbs. Elastic and wire ligation were combined according to non-scratched or scratched.

CHART 3

P Means For Non-Scratched and Scratched Brackets Within Each Bracket Type

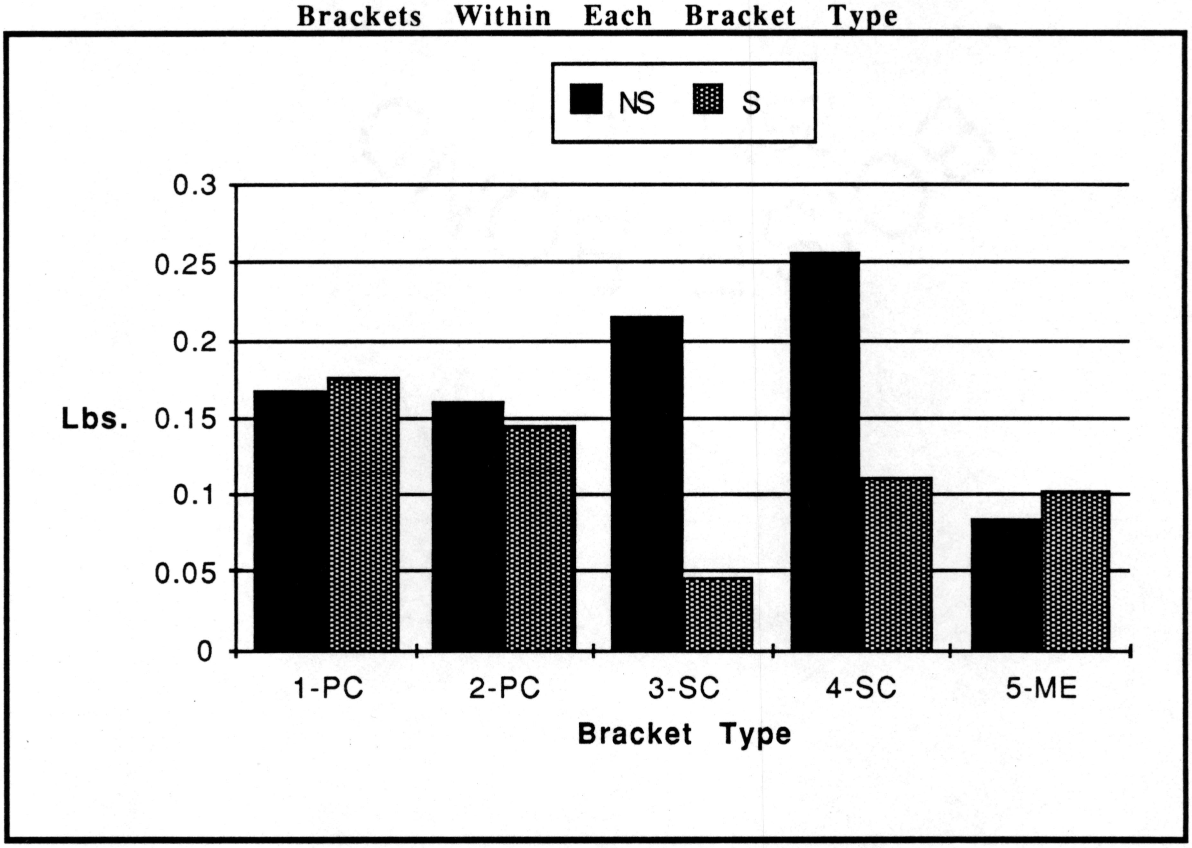


Table 4 lists the S_F means and SDs for NS and S brackets within each bracket type. As in Table 4, the difference between the total means for NS (79.34) and S (49.60) is great (29.74 or 37% of 79.34) and agree with the results of ANOVA 1. Once again, a larger difference was noted between the means of the NS and S brackets within bracket types 3 (126.95 vs. 27.57) and 4 (115.97 vs. 50.10), which are single crystal, when compared to the differences within bracket types 1 (33.60 vs. 35.28) and 2 (33.13 vs 30.08), which are polycrystalline. Again, bracket type 1 showed the mean value for their S brackets (35.28) was higher than the mean value of their NS brackets (33.60). Chart 4 graphically illustrates the S_F means listed in Table 5 for NS and S brackets within each bracket type.

TABLE 4

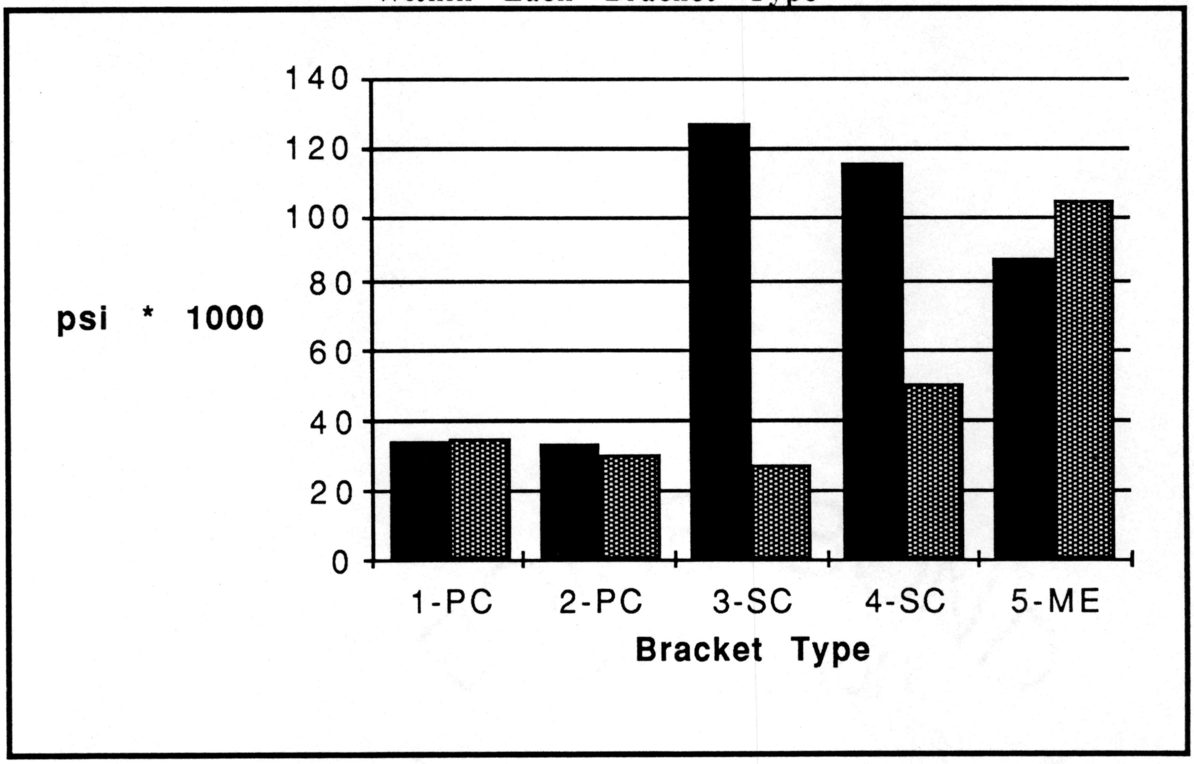
S_F Means and SDs for Non-Scratched and Scratched Brackets Within Each Bracket Type.

Bracket Type	Number Per Box	Non-Scratched Mean	Non-Scratched SD	Scratched Mean	Scratched SD	Total Mean	Total SD
1-PC	20	33.60	4.63	35.28	2.01	34.44	3.62
2-PC	20	33.13	4.25	30.08	5.34	31.60	5.01
3-SC	20	126.95	48.96	27.57	9.91	77.26	61.22
4-SC	20	115.97	54.40	50.10	16.00	83.03	51.76
5-ME	20	87.04	16.24	104.95	14.30	95.99	17.62
TOTAL	100	79.34	51.78	49.60	30.80	64.47	45.04

Units are in psi * 10^3. Elastic and wire ligation were combined according to non-scratched or scratched.

CHART 4

S_F Means for Non-Scratched and Scratched Brackets Within Each Bracket Type



Elastic Ligation vs. Wire Ligation

Tables 5 and 6 respectively list the P and S_F means ,with SDs, of elastic (EL) and wire (WL) ligation within each bracket type

In Table 5, the difference between the total P means of EL (.144) and WL (.149) is not great (.005 or 3%of .149) and this result agrees with ANOVA 1. This equality between EL and WL is also evident within each bracket type, with the largest difference being in bracket type 5 (.014 or 14% of .101), which has metal brackets. Chart 5 graphically illustrates the means listed in Table 6 for each bracket type.

TABLE 5

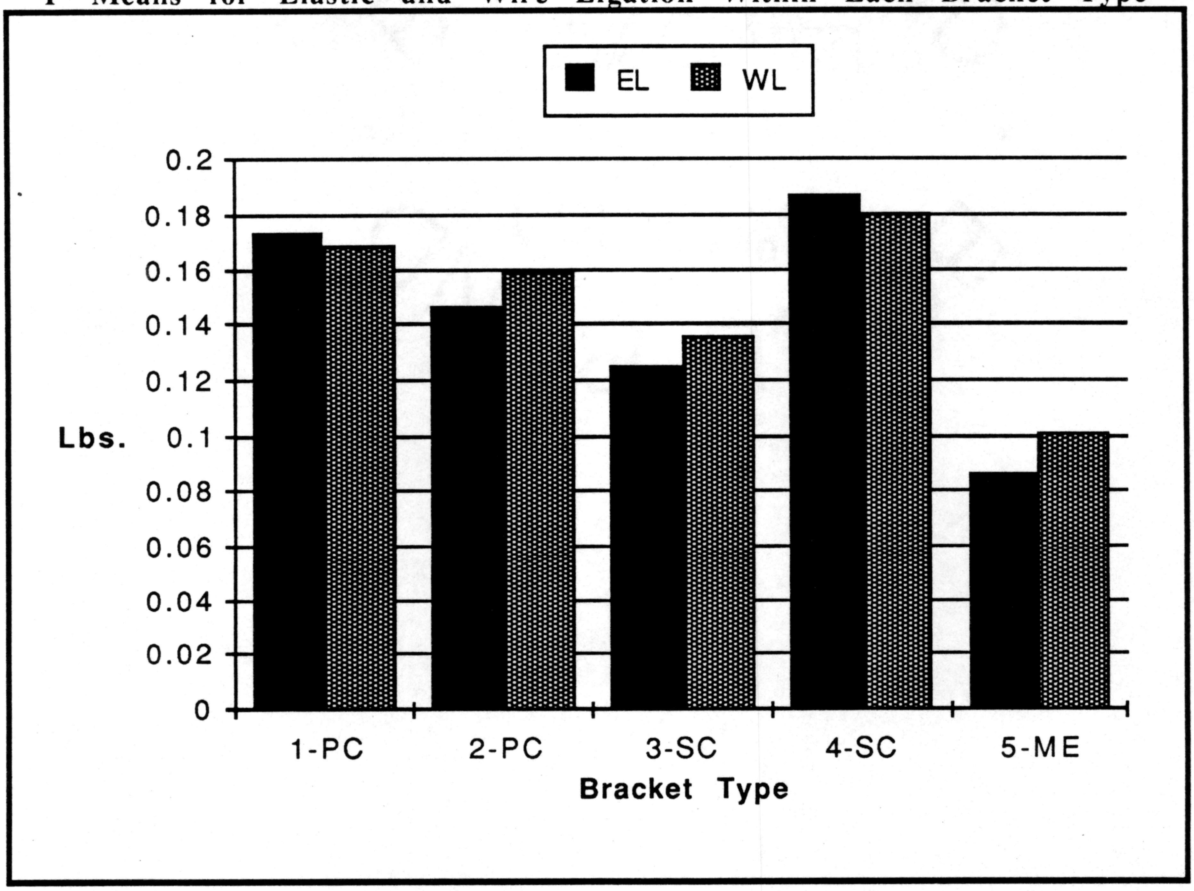
P Means and SDs for Elastic and Wire Ligation Within Each Bracket type

Bracket Type	Number Per Box	Elastic Mean	Elastic SD	Wire Mean	Wire SD	Total Mean	Total SD
1-PC	20	.174	.013	.169	.022	.172	.018
2-PC	20	.147	.023	.159	.025	.153	.024
3-SC	20	.125	.099	.136	.110	.131	.103
4-SC	20	.187	.137	.181	.091	.184	.115
5-ME	20	.087	.018	.101	.013	.094	.017
TOTAL	100	.144	.084	.149	.070	.147	.077

Units are in lbs. Non-scratched and scratched.brackets were categorized according to elastic and wire ligation.

CHART 5

P Means for Elastic and Wire Ligation Within Each Bracket Type



In Table 6, the difference between the total S_F means of EL (62.40) and WL (66.53) is, once again, not great (4.13 or 6% of 66.53) and agrees with ANOVA 1. This equality between EL and WL is also evident within each bracket type, with the largest difference being in bracket type 5 (15.05 or 15% of 103.52), which has the metal brackets. Chart 6 graphically illustrates the means listed in Table 6 for each bracket type.

TABLE 6

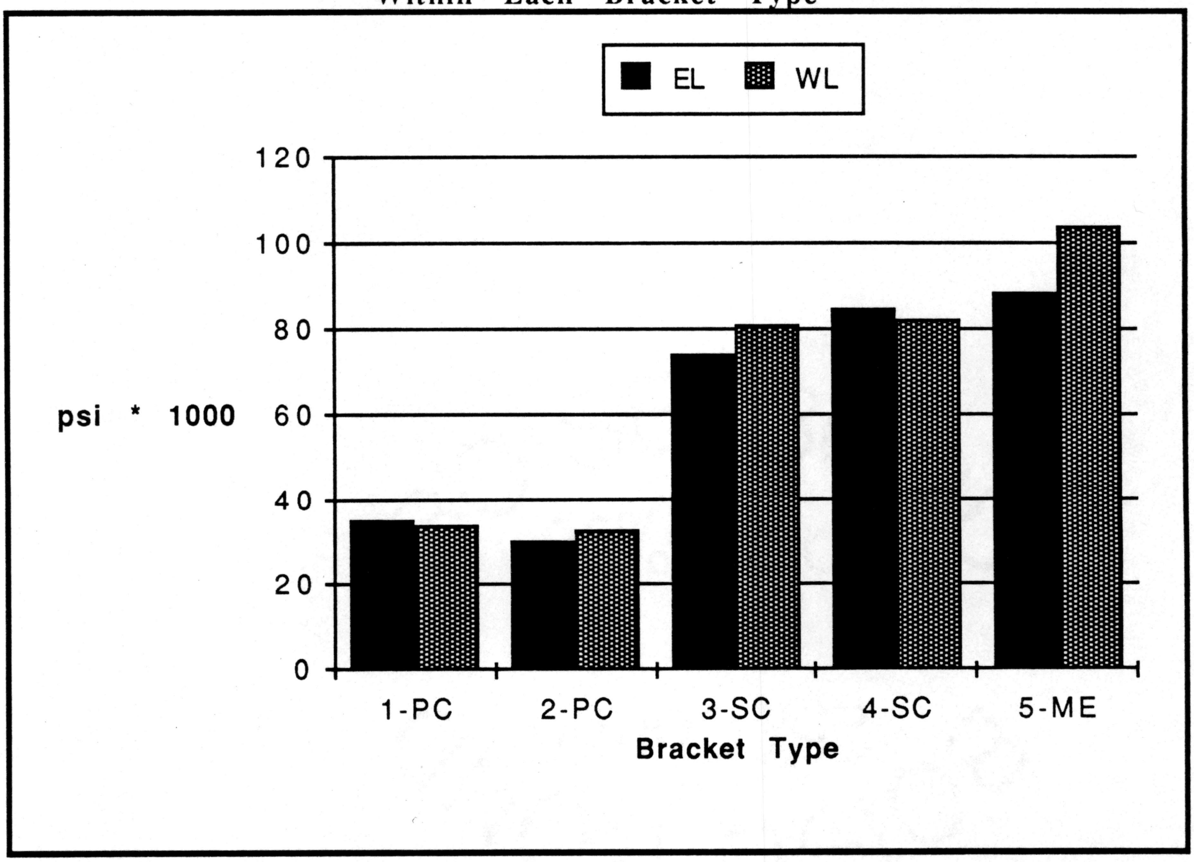
S_F Means and SDs for Elastic and Wire Ligation Within Each Bracket type

Bracket Type	Number Per Box	Elastic Mean	Elastic SD	Wire Mean	Wire SD	Total Mean	Total SD
1-PC	20	34.99	2.68	33.89	4.37	34.44	3.62
2-PC	20	30.41	4.71	32.80	5.13	31.60	5.01
3-SC	20	73.85	58.84	80.68	64.85	77.26	61.22
4-SC	20	84.31	61.83	81.76	40.90	83.03	51.76
5-ME	20	88.47	18.50	103.52	13.24	95.99	17.62
TOTAL	100	62.40	45.70	66.53	44.49	64.47	45.04

Units are in psi * 10^3. Non-scratched and scratched.brackets were categorized according to elastic and wire ligation.

CHART 6

S_F Means for Elastic and Wire Ligation Within Each Bracket Type



Ceramic vs. Metal

A second Analysis of Variance (ANOVA 2) was done with P or S_F as the dependent variable and with ceramic vs. metal, elastic ligation vs. wire ligation, and non-scratched vs. scratched brackets as the independent variables. With P as the dependent variable, ANOVA 2 showed a significant difference ($p < .05$) between ceramic (C) and metal (ME) brackets ($F_{(1,192)}$ = 34.05, p = 0.0), no significant difference between EL and WL ($F_{(1,192)}$ = .351, p = .554), and a significant difference between NS and S brackets ($F_{(1,192)}$ = 45.07, p = 0.0). With S_F as the dependent variable, ANOVA 2 showed similar results between C and ME ($F_{(1,192)}$ = 34.22, p = 0.0), between EL and WL ($F_{(1,192)}$ = .586, p = .445), and between NS and S brackets ($F_{(1,192)}$ = 30.46, p = 0.0).

Single-Crystal vs. Polycrystalline

Since ANOVA 2 stated that there was a significant difference between C and ME, a third Analysis of Variance (ANOVA 3) was done to see if there was a significant difference between polycrystalline (PC) and single crystalline (SC) brackets. ANOVA 3 had P or S_F as the dependent variable and PC vs. SC, EL vs. WL, and NS vs. S brackets as the independent variables. With P as the dependent variable, ANOVA 3 showed no significant difference ($p < .05$) between PC and SC brackets ($F_{(1,152)}$ = .283, p = 596), no significant difference between EL and WL ($F_{(1,152)}$ = .102, p = .750), and a significant difference between NS and S brackets ($F_{(1,152)} \doteq 72.56$, p = 0.0). With S_F as the dependent variable, ANOVA 3 showed a significant difference between PC and SC brackets($F_{(1,152)}$ = 116.12, p = 0.0), no significant difference between EL and WL ($F_{(1,152)}$ = .102, p = .750), and a significant difference between NS and S brackets ($F_{(1,152)}$ = 90.72, p = 0.0). Thus, with ANOVA 3,the significant difference changed between P and S_F for PC vs. SC brackets. This change in significant difference is graphically illustrated by comparing PC and SC brackets in Charts 1 and 2.

Results of Specific ANOVA

An ANOVA was done for each bracket type and material type to see if there were any changes in significant differences within each one that differed with ANOVA 1, 2, and 3. These ANOVA were done with P or S_F as the dependent variable and with, EL vs. WL, and NS vs. S brackets as the independent variables and are summarized in Table 7

TABLE 7

ANOVA Table For Bracket Types and Material Types

Bracket or Material	P or S_F	EL vs. WL	NS vs. S
1-PC	P	F(1,36) = 1.03, p = .316	F(1,36) = 2.41, p = .129
	S_F	F(1,36) = 1.03, p = .316	F(1,36) = 2.41, p = .129
2-PC	P	F(1,36) = 2.55, p = .119	F(1,36) = 4.15, p = .049
	S_F	F(1,36) = 2.55, p = .119	F(1,36) = 4.15, p = .049
3-SC	P	F(1,36) = .363, p = .551	F(1,36) = 76.79, p = .000
	S_F	F(1,36) = .363, p = .551	F(1,36) = 76.79, p = .000
4-SC	P	F(1,36) = .038, p = .846	F(1,36) = 25.74, p = .000
	S_F	F(1,36) = .038, p = .846	F(1,36) = 25.74, p = .000
5-SC	P	F(1,36) = .12.54, p = .001	F(1,36) = 17.75, p = .000
	S_F	F(1,36) = .12.54, p = .001	F(1,36) = 17.75, p = .000
PC	P	F(1,76) = .336, p = .564	F(1,76) = .370, p = .545
	S_F	F(1,76) = .338, p = .535	F(1,76) = .437, p = .511
SC	P	F(1,76) = .027, p = .871	F(1,76) = 75.60, p = .000
	S_F	F(1,76) = .061, p = .806	F(1,76) = 90.50, p = .000
ME	P	F(1,36) = .12.54, p = .001	F(1,36) = 17.75, p = .000
	S_F	F(1,36) = .12.54, p = .001	F(1,36) = 17.75, p = .000
C	P	F(1,156) = .072, p = .788	F(1,156) = 51.65, p = .000
	S_F	F(1,156) = .045, p = .833	F(1,156) = 39.76, p = .000

$p < .05$ is significantly different.

Crack Length Results

The crack lengths derived and calculated from Griffith's equation are listed in Table 8 and graphically illustrated in Chart 7. Crack lengths needed to fracture non- scratched PCA brackets and scratched PCA brackets were almost the same. But the crack length needed to fracture a non-scratched SCA bracket was about 5-20 times smaller than the crack length needed to fracture a scratched SCA bracket. Comparing SCA brackets with PCA brackets: without scratching, the crack length needed to fracture SCA brackets was about 35-45 times smaller than the crack length for PCA brackets and, with scratching, the crack length needed to fracture SCA brackets was about 3-8 times smaller than the crack length for PCA brackets.

TABLE 8

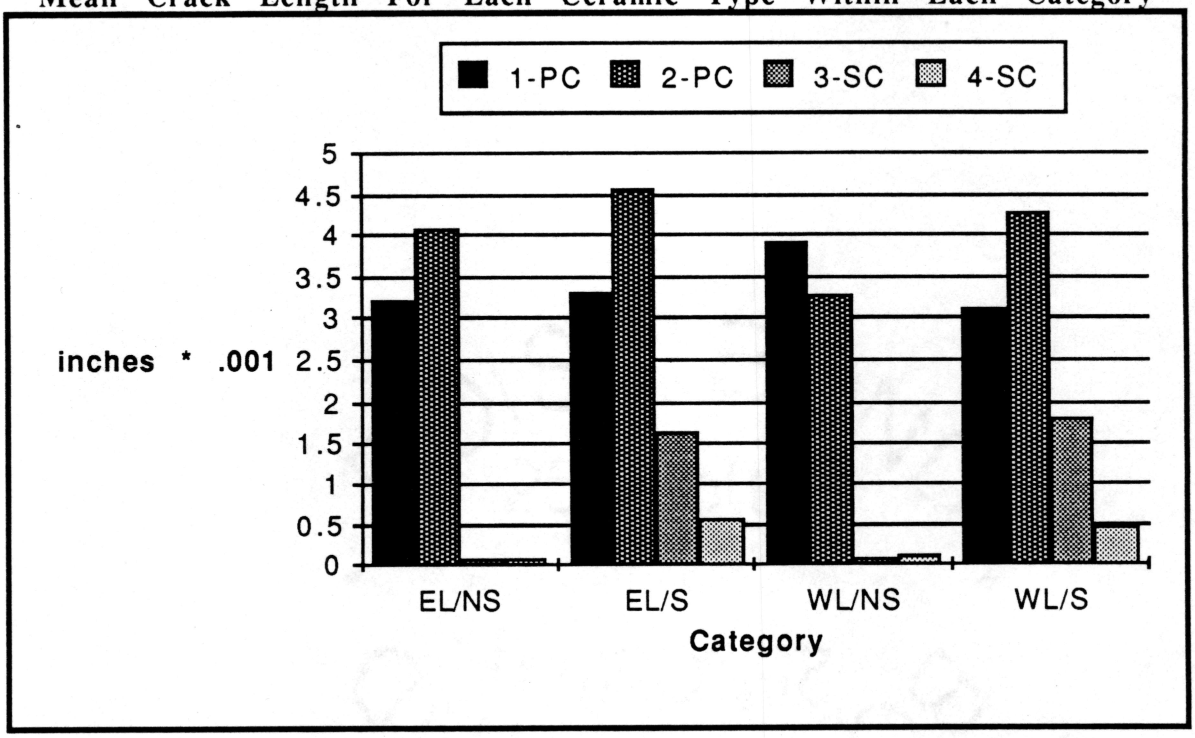
Mean Crack Length For Each Ceramic Type Within Each Category

Ceramic Type	Number Per Box	EL/NS Mean	EL/S Mean	WL/NS Mean	WL/S Mean	Total Mean
1-PC	10	3.222	3.311	3.915	3.119	3.372
2-PC	10	4.093	4.580	3.265	4.271	4.005
3-SC	10	0 092	1.649	0 072	1.798	0.219
4-SC	10	0.091	0.556	0.105	0.490	0.190

Units are in inches * 10^{-3}

CHART 7

Mean Crack Length For Each Ceramic Type Within Each Category



Fractography Evaluation

Figure 9 (a & b) shows the typical fracture pattern of the PCA type brackets. These SEM photographs are of scratched PCA brackets, but their fracture pattern was similar to the fracture pattern of non-scratched PCA brackets. Note that the scratch placed on the brackets was not larger that the flaws already present on the their surface

Figure 10 (a & b) shows fractured SCA brackets with scratching. These SEM photographs reveal the smooth surface finish on SCA brackets. Non-scratched SCA brackets tended to fracture in a random and uncontrolled fashion, while the scratched SCA brackets tended to fracture as shown, in a more predictable and controlled manner.

FIGURE 9

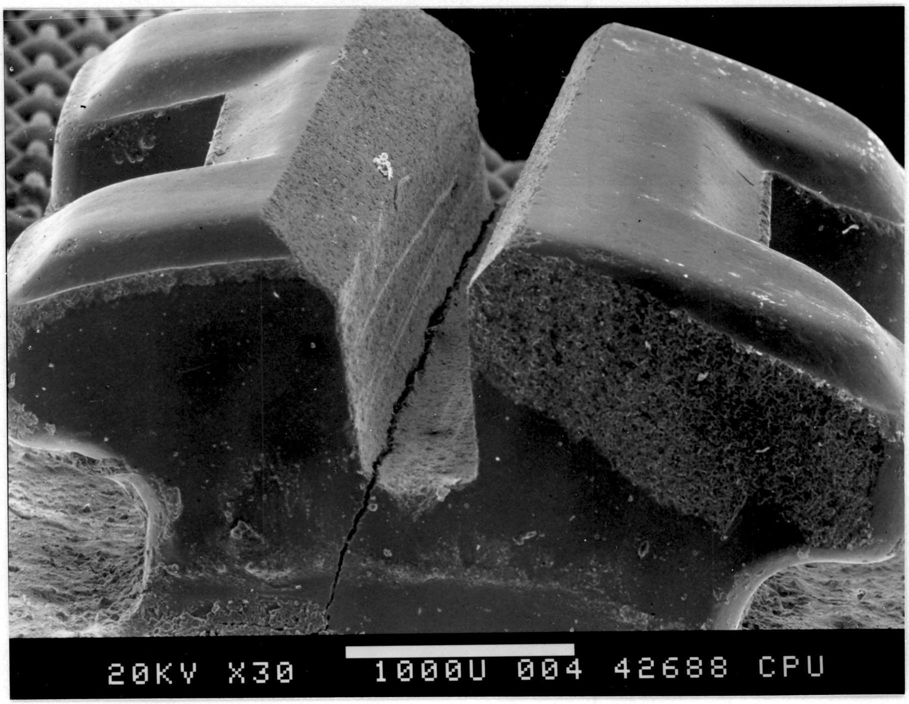


Fig. 9a. An SEM photograph of a PCA type bracket magnified 30 times.

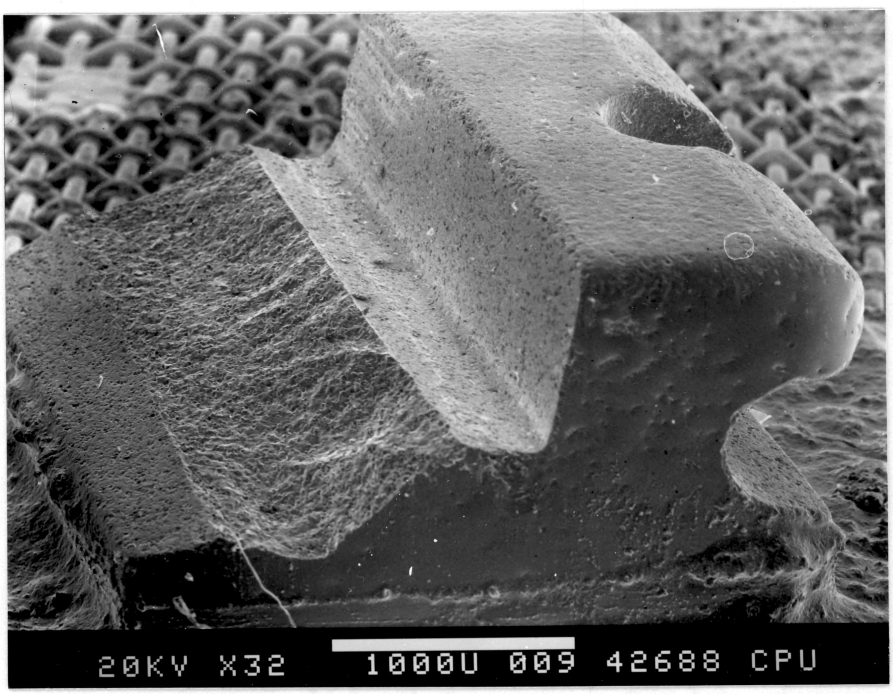


Fig. 9b. An SEM photograph of a PCA type bracket magnified 32 times.

FIGURE 10

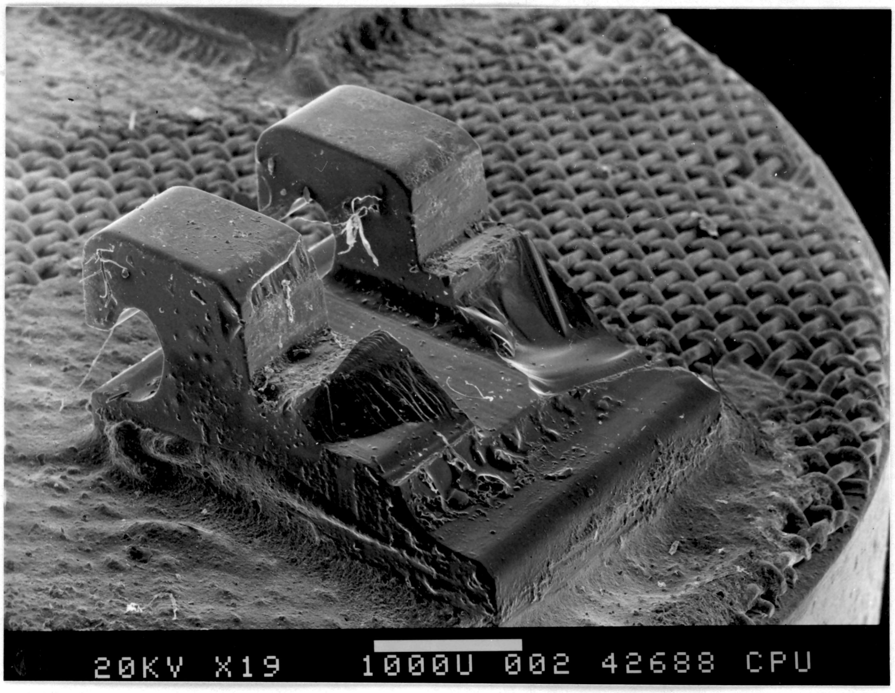


Fig. 10a. An SEM photograph of a scratched SCA type bracket magnified 19 times.

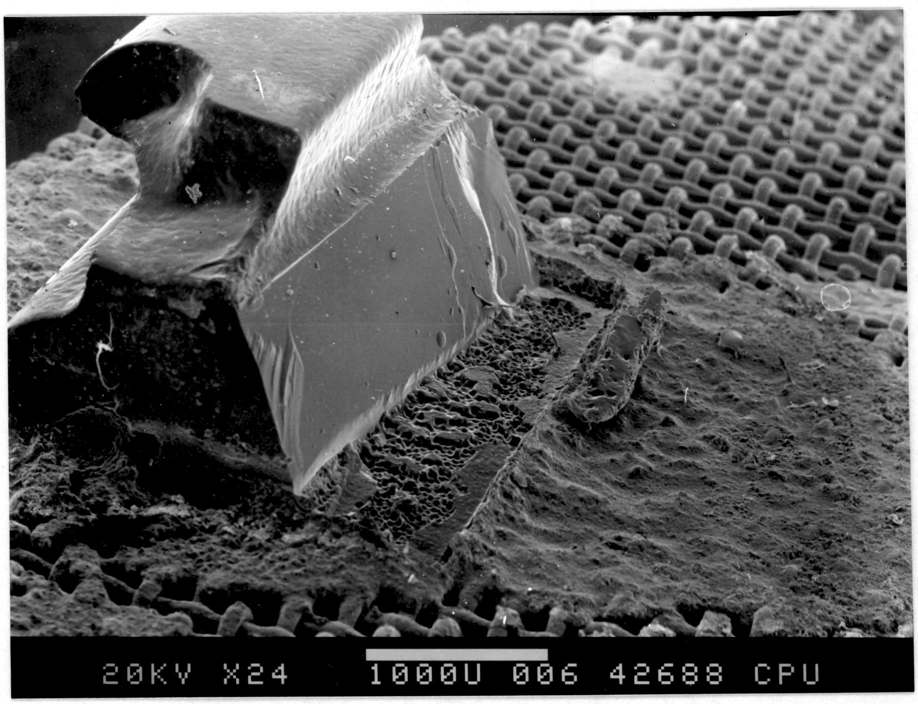


Fig. 10b. An SEM photograph of a scratched SCA type bracket magnified 24 times.

DISCUSSION

Ceramic Brackets and Griffith's Model

The ceramic bracket failures can be explained by use of the Griffith fracture model and fracture toughness.

With scratching, the failure loads and strengths of the single crystal brackets dropped dramatically, while the strength of the polycrystalline brackets stayed relatively the same. This can be explained as a direct result of the differences between the surface finish present on both type of ceramic brackets.

Surface Finish and Scratching

The finished surface of the single-crystal brackets is very smooth and glassy because they have been specially treated to remove almost all the surface flaws. Though the smoother surface makes the single-crystal brackets initially stronger in their pure form, it also makes them very susceptible to surface flaws, and when the scratch was introduced to their surface, their strength decreased drastically.

Polycrystalline brackets have a much rougher surface because of the grinding they undergo during fabrication. These surface flaws make the polycrystalline brackets initially not as strong as the single-crystal brackets, but when they were scratched their strength values stayed relatively unchanged. This can be explained by the fact that the surface flaws already present were probably larger or similar to the scratch placed on their surface.

After they were scratched, the strengths of the single-crystal and polycrystalline were much closer in range, but the loads that the single-crystal brackets could withstand dropped far below the load level the polycrystalline could withstand. This decrease in fracture strength for the single-crystal brackets confirms the findings by Griffith, which state that flaws introduced to a smooth surface will decrease the force required to fracture it.

Metal brackets on the other hand increased in strength after they were scratched. This can be explained by the possibility that they were work hardened by the scratch.. Work hardening is a metal property which increases the strength of the metal after the experience deformation. Since the stresses were placed on in the slot, any work hardening in the slot would have a positive effect on their yield strength.

The Effect of Scratching

Charts 8 and 9 graphically illustrate the effect scratching had on the P and S_F values of the different materials, respectively. The scratched P and S_F values are illustrated as a % of the non-scratched P and S_F values. Note that the scratched values for the polycrystalline brackets did not change very much compared to its non-scratched values. However, single-crystal brackets show a large decrease in their scratched values in terms of their non-scratched values. Metal brackets show an increase in their scratched values over their non-scratched values, which would indicate the scratch work-hardened the slot area.

CHART 8

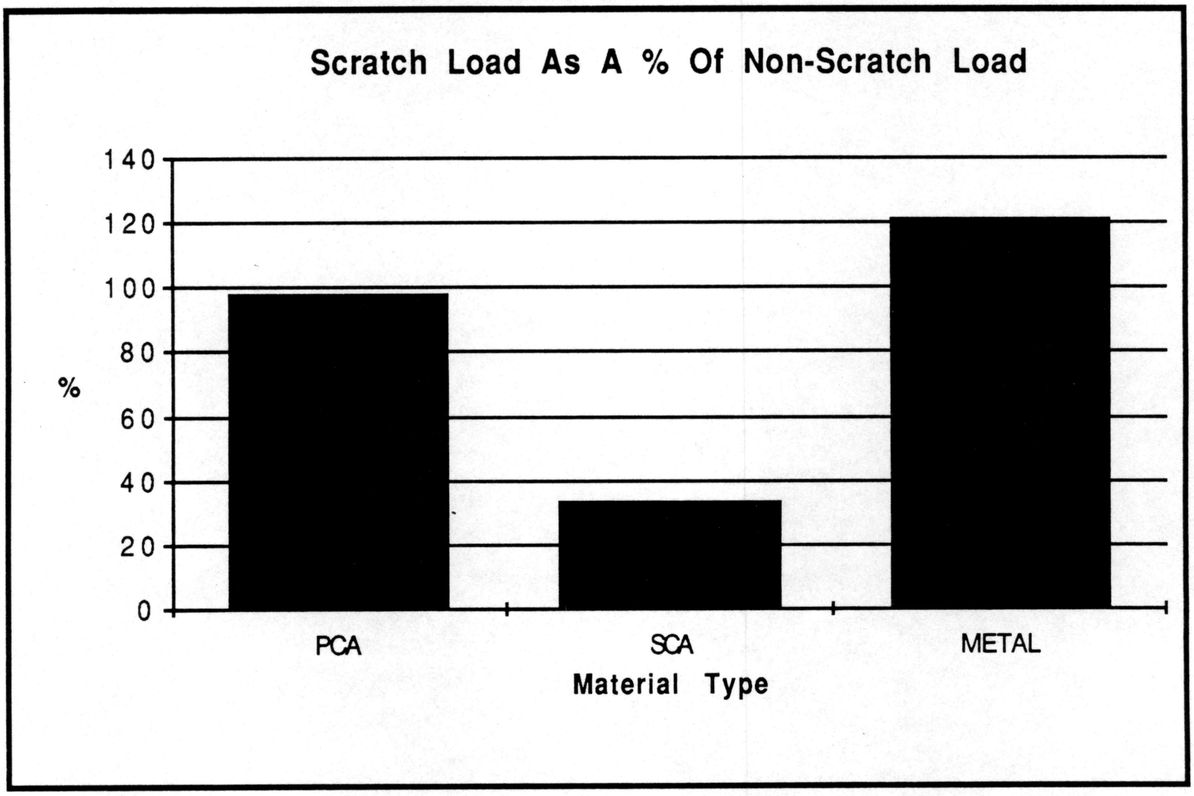
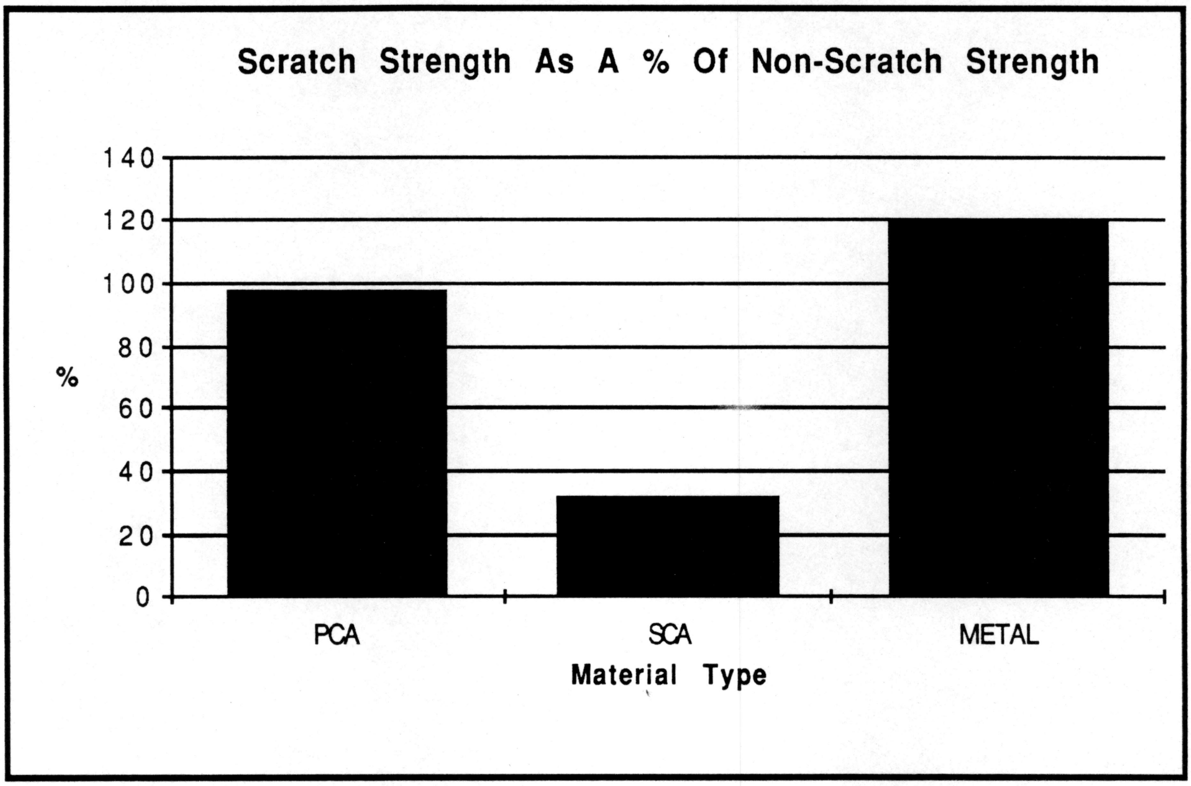


CHART 9



The Effect of Different Ligation Methods

Different wire ligation methods had no effect on the failure load or the failure strength of the ceramic brackets, but they did have an affect on the metal brackets, with the metal brackets exhibiting a higher failure loads and strengths when ligated with metal ligatures.

The lack of effect on the ceramic brackets can be explained by the fact the they are very brittle and if their surface was not damaged by either method, then their failure loads and strengths would not differ dramatically from one method to the other. The applied stressed due to the ligatures were probably small compared to the stress being applied by the archwire.

However, with the metal brackets, the wire ligature probably reinforced and maybe even deformed the metal brackets by bending them into the slot. This prevented their plastic deformation until a load.higher than that needed to deform elastic ligated brackets was applied. This had the effect of giving the metal brackets a higher failure load and strength value with the metal ligatures which was significant.

The Standard Deviation

An interesting point to note is the large standard deviation values the single-crystal brackets exhibited, which confirm the fact that higher strength materials have a larger scatter for their strength values. Before scratching, the standard deviation for single-crystal brackets was 20 times greater than the standard deviation for polycrystalline brackets. Even after scratching, the standard deviation for single-crystal brackets was twice that of the polycrystalline brackets. This confirms findings from other studies: that high strength brittle materials have a larger standard deviation than low strength materials.

The Interplay of Load and Stress

The interplay between failure load and failure stress was also seen in this study.

Load values are confounded because they take into account both the design and material parameters and combine them into one value. For example, if the metal bracket had the some dimensional values as the ceramic brackets, their failure load values would have been much higher.

Strength values separate the design and material parameters, and show the behavior of the material alone under a given stress. For example, the strength of the metal brackets was shown to be high, but due to their design, they were not able to withstand as high a failure load as the ceramic brackets.

This interplay between design and material is an important differentiation orthodontists have to make when choosing a ceramic bracket, because both design and material parameters go together in determining the load the brackets can support during orthodontic treatment.

Charts 1 ,2, 10, and 11 graphically illustrate this interplay between design and material parameters. For example, the load required to fracture the ceramic brackets prior to scratching was about the some, with the single-crystal brackets having a slightly higher load value. After scratching, the single-crystal brackets required less load to break than the polycrystalline brackets. This is explained by the fact that the single-crystal had a significant loss in fracture strength (40,000-120,000 lbs./sq.in.), while there was no significant loss in the fracture strength of the polycrystalline brackets. For the single-crystal brackets, this loss in strength (a material parameter) coupled with their smaller geometrical size (a design parameter) results in the lower load values required to fracture them. This interplay directly impacts the orthodontist's technique in handling and working with the ceramic brackets.

CHART 10

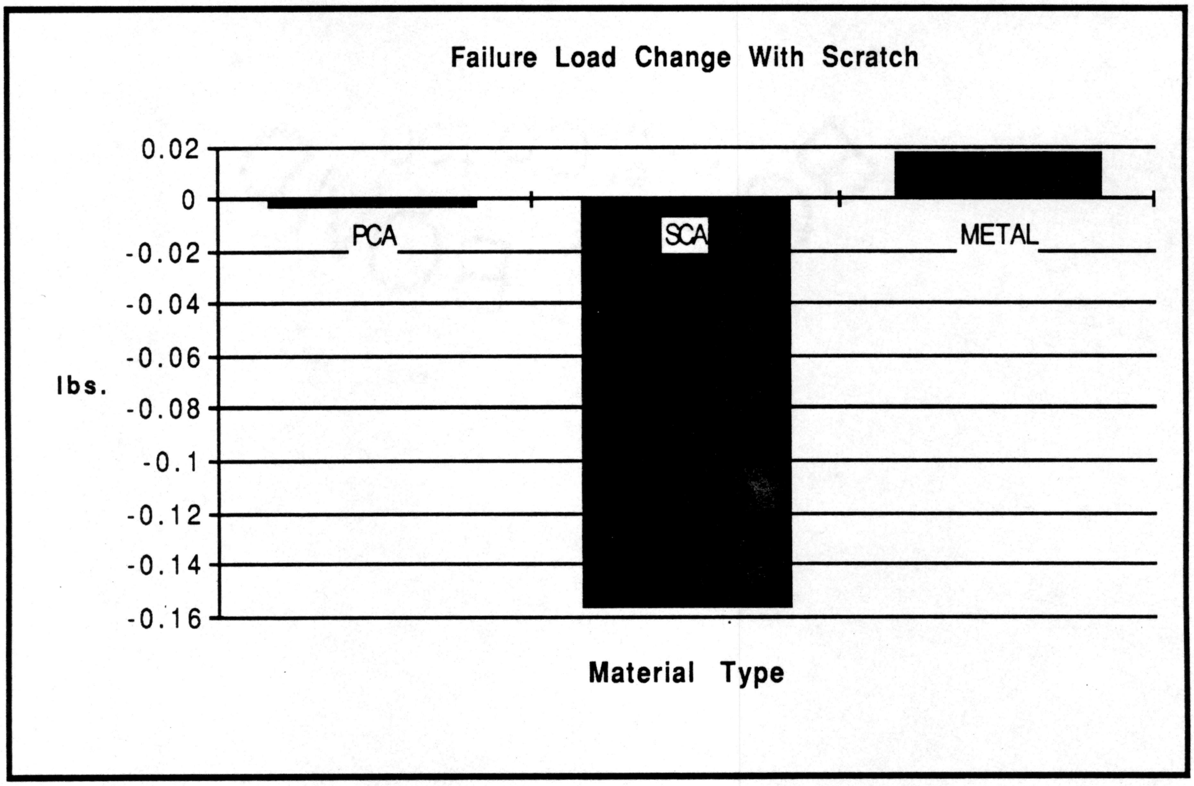
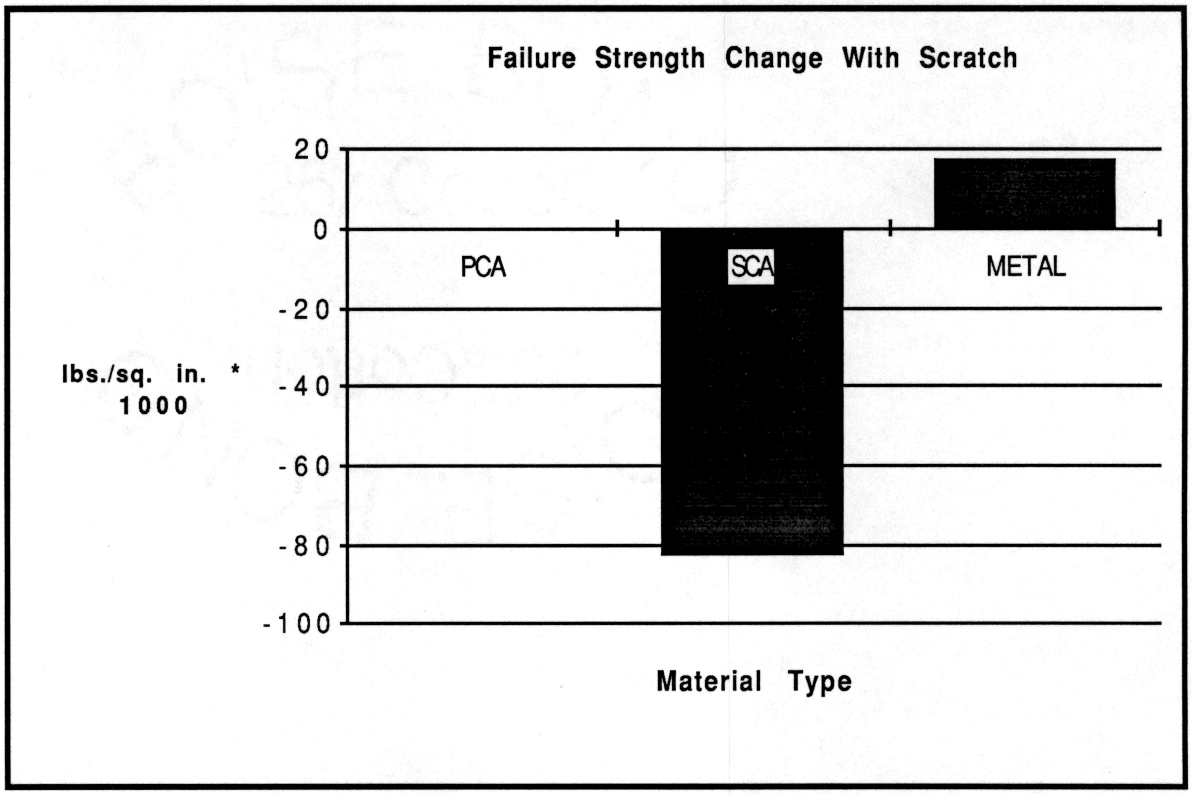


CHART 11



The Effects of Surface Condition

Surface condition is another material parameter which played an important role in this study. By calculating the estimated crack lengths that were necessary to produce the fractures, it is evident that the surfaces of the single-crystal brackets contained smaller cracks than the polycrystalline brackets. However, due to their smooth surface condition, the single-crystal brackets were very susceptible to the scratching, which decreased their strength. Polycrystalline brackets were able to tolerate the scratching, because their surface already contained flaws similar to the scratch, and their strengths stayed relatively the same. Thus, the fracture toughness for the polycrystalline brackets was higher than the one for single-crystal bracket.

Using the Griffith model, it is possible to estimate what crack length that would be needed for a given fracture strength. For example, knowing that a crack length of $9.16 * 10^{-5}$ in. was needed to produce a fracture for a single-crystal bracket at the fracture strength value of 119 * 10^3 psi., it possible to determine what crack length would be needed to fracture a polycrystalline bracket at the same fracture strength value. To have a fracture strength of 119 * 10^3 psi., a polycrystalline brackets would need a crack length of 2.80 * 10^{-4} in., which is about 3 times as large as the one needed for the single-crystal bracket.

Fractography Evaluated

In viewing fractured ceramic brackets,with scratches, under the SEM it is evident that SCA type brackets have a much smoother surface finish than PCA type brackets (Figs. 8 & 9). The way each bracket fractured is also important. Fractures in SCA brackets created smooth and flat surfaces, a result of cleavage. In contrast, the path of fracture for the PCA brackets is very tortuous, creating rough and irregular surfaces.

The different paths of fracture for SCA and PCA brackets are indicative of the work needed to fracture them. Scratched SCA brackets require less work to fracture than scratched PCA brackets because the tortuous fracture path of the PCA brackets requires and generates more energy than the smooth and straight fracture path of SCA brackets.

Clinical Implications

Also interesting was the fact that the ceramic brackets were able to withstand a higher load than the metal brackets. Since metal brackets have proven to work well in moving teeth, it is evident that ceramic brackets could work well in moving teeth also. The low load values for the metal brackets indicate that they may be distorting in the patients mouth when high loads are placed on them. Thus the orthodontist may not be getting all the torque, placed in the archwire, transmitted to the tooth. Since some clinically used ceramic brackets have fractured, it is evident that orthodontists have exceeded even the load limit needed to deform metal brackets. This finding indicates that lighter forces are needed to prevent deformation of the metal brackets and fracture of the ceramic brackets.

The different properties that interrelate to determine the load ceramic brackets can withstand and its reliability (surface energy, fracture strength, fracture toughness, elastic modulus, and Weibull modulus) are all important for orthodontists to know and understand if they are going to handle them properly. Orthodontists should seek to find out these properties in order to determine the toughness and reliability of a particular bracket.

Ceramic brackets offer orthodontists, universities, private testing facilities, and manufacturers an opportunity to work together to develop new and better ceramic brackets that are tougher and more reliable.

SUMMARY

Overview

Single-crystal and polycrystalline alumina brackets, along with metal brackets were tested for their fracture strength or yield strength. Failure loads and failure strengths were reported in order to separate the design and material parameters.

Different ligation methods (elastic and wire ligatures) and different surface conditions (non-scratched and scratched) were variables applied to the brackets to see if they would have a significant effect on the failure loads and strengths.

A testing method was developed which met the requirements of an acceptable testing method.

Using an analysis of variance, a significant difference was found in the failure loads and failure strengths between the material types. Different ligation methods showed no significant effect and scratches showed a significant effect.

Results and Conclusion

Results showed that the ceramic brackets (single-crystal and polycrystalline) followed the Griffith model for brittle materials. Ceramic brackets were less tolerant to surface defects than the metal brackets. Single-crystal brackets proved to be less tolerant to scratching than the polycrystalline brackets.

The mode of failure for ceramic brackets, fracture, is their major limitation. Material properties, whose values would help to understand and handle ceramic brackets better, like fracture toughness and fracture strength, should be sought after by the orthodontist.

Since ceramic brackets obey the Griffith principle, it is concluded that the maintenance of their initial high quality surface, their geometrical design, and the amount of load placed on them are of paramount importance to the orthodontist, because they determine the longevity of their service time.

Recommendations

It is recommended that further research be done to determine the effect other orthodontic variables might have on the fracture strength and fracture load of ceramic brackets. For example, different wire types (Nitinol, TMA, Braided, and Elgiloy), different wire sizes, and different bracket slot sizes might have and effect on the load and strength values of ceramic brackets. Also, further research needs to be done on the yield strength of different metal brackets, in order to understand what effect different forces might have on their ability of move teeth.

APPENDIX

Different Testing Models Attempted for Testing the Fracture Strength of Ceramic Brackets

Introduction

The following report describes the various attempts to develop a testing method to measure the fracture strength of different types of ceramic brackets, which could be used as a standard. Ceramic brackets from 4 companies ("A"-Company, GAC, Ormco, and Unitek) and a metal bracket (American Orthodontics) were tested, with the metal bracket used as the standard from which to base comparisons.

Though, some of the testing models may have worked with one or more particular type of bracket; they each failed to work with at least one type of bracket, and were abandoned in the search for a reliable and accurate testing model.

Several things were learned, as we tried different testing models, and they eventually led to the final testing model. The final testing model will be described in this report and will also be discussed in the "Methods" section of another report, which will have the test results obtained in this study. The following are the various testing models that were attempted to test the ceramic and metal brackets.

Testing Model 1

The 1st testing procedure and fixture was based on the concept of a mechanical holding technique. It involved placing the brackets, one at a time, in a metal vice-grip, which gripped their base from all four sides and supported the back of their base. The vice had three sliding arms which could be adjusted to grip the left, right, and top sides of a bracket, while the bottom side rested on a solid ledge. The sliding arms were at 90^o angles to each other and they were adjusted to grip the bracket firmly and passively. The base of the vice could be adjusted to move the bracket in and out along the solid ledge, so that just the base of the bracket would be gripped, leaving the wing portion of the bracket freestanding, out beyond the front surface of the vice.

A metal force applicator, which slid through a ramp at the top of the vice, was applied perpendicular to the top surface of the bracket wing. The force applicator was approximately 2cm wide, 6cm long, and 3mm thick. The bracket was placed in an Instron (a very sophisticated electronic machine that allows different types of forces applied to different types of material to be measured very accurately) and positioned vertically, as they would be in a standing patient's mouth.

The Instron applied a constant downward force on the wing of the bracket, via the force applicator. The crosshead speed was .1mm/min and the force was applied until the bracket fractured. The force required to fracture the brackets was recorded and then another bracket was tested the same way. This test was called the vertical wing shear test, because of the vertical position of the brackets during the test.

A second type of test, the archwire torque test, was also planned for the brackets. It involved placing the brackets vertically in the vice as in the vertical wing shear test. A straight stainless steel archwire, .018" * .025" and about 1.5" long, was placed into the slot of the brackets and ligated in place with an elastic tie. A metal torquing key, 3" long, was then engaged to the archwire and held in place with two, 1/4", 2oz., orthodontic elastics. The orthodontic elastics hooked around the ligated archwire, on one end, and around a small button attached to the sides of the torquing key, on the other end. There was one elastic on each side of the brackets.

On the other end of the torquing key, there was a round opening that held a round nylon ball on the bottom surface. The ball had an .030" round wire, about 12" long, that went through its center. One end of the roundwire was attached to a hook fastened to the Instron jaws and the other end held the ball up against the bottom surface of the torquing key. The vice was positioned in the Instron so that the round wire was lined straight up with the center of the Instron.

The wire was then pulled up by the Instron, lifting one end of the torquing key and causing the archwire to rotate in the slot of the brackets. This rotational movement of the archwire was what applied the torquing force to the brackets. The wire was pulled up at a crosshead speed of 10 mm/min. until the ceramic bracket fractured or the metal bracket deformed.

It was intended to test 10 brackets from each manufacturer with these two tests, but a pilot study proved this testing model to be inadequate. In both tests, the vice failed to hold the brackets firmly, while force was being applied; and thus, accurate readings of their fracture resistance could not be made.

Had the vice gripped the brackets any tighter, other compressive forces would have been introduced to the surfaces of the brackets. These holding forces alone, could have caused the brackets to fail. The test results would not have been indicative of just the one force being applied.

Also, positioning the brackets in the vice so that each type could be tested exactly the same every time, was very difficult with this testing model. If custom vice-grips had been made for each bracket type, it might have been possible to use this testing model. But even then, a passive grip on the brackets was not guaranteed.

Testing Model 2

The 2nd testing model used plastic rings filled with epoxy (Buehler Epo-Kwik) as the holding medium for the brackets. The epoxy was a quick setting, two part, A and B, type of epoxy. It was thought that the epoxy could firmly grip the base of the brackets passively, while the rings could be gripped as tight as necessary by the vice, without affecting the brackets.

The rings were cut from 3/4" plastic tube at approximately 10mm in length. The epoxy was mixed at a ratio of 5:1, by weight, base to catalyst, according to directions. Then the epoxy was poured into the rings, which had their bottom opening sealed with scotch tape, until they were almost filled.

Square wires, .016 * .016", 1.5-2" long, were then ligated to the brackets with elastic ligatures. Next, two .028 round wires were placed on opposite ends, on the top of each ring. The ligated brackets were then lowered into the epoxy filled rings until the square wire came to rest on the round wires. The brackets were placed in the epoxy only deep enough to have their base portion embedded, leaving their wing portion free standing.

The metal vice in testing model #1 was modified to accept the 3/4" rings, by having a hole, 3/4" in diameter and 10mm deep, bored into the center of its front surface. The hole was centered at the location where the brackets were previously gripped, incorporating the three sliding arms and the solid base into its perimeter. Thus, the plastic rings were gripped by the vice like the brackets were gripped.

It was planned to place rings in the vice and test the brackets with the vertical wing shear test as in testing model #1, but the epoxy, due to its low surface tension, wet the entire front surface of the brackets as it set up. Thus, the brackets engulfed by the epoxy could not be accurately tested in their condition.

Testing Model #3

This model was almost like testing model #2, except for the way the brackets were embedded in the epoxy. Scotch tape was placed on one end of the plastic rings and small openings were cut out at the center of the tape using a surgical blade. Prior to cutting the openings, the outline of the brackets' bases had been traced on the tape. Thus, the openings were shaped like the base of the brackets, only cut out to be a little smaller. The brackets were then placed through the openings so that only their bases were inside the rings. Melted inlay wax was placed over the tape-bracket margin outside the ring, to provide a seal for the epoxy. The rings were then turned over, open end up, and placed on paper cups. The paper cups were upside down and had a small opening cut out of their bottom surface to allow the free standing portion of the brackets to go through and allow the rings to rest flush on the surface.

The epoxy was then poured into the open end of the rings and allowed to set for 24 hours, to insure a complete set. The scotch tape made a flat epoxy surface with the base of a bracket firmly embedded into it and leaving the rest of the bracket free to be tested. The rings were then placed into the vice and the vertical wing shear test was run as in testing model #1.

Due to the different base designs introduced by each manufacturer, some of the brackets were gripped long enough by the epoxy to fracture during the tests; but most of the brackets were dislodged from the epoxy prior to failure. Also, on all the tests, deformation of the epoxy was noted on the graphs printed out by the Instron. When the line on the graph began to slope downward, deformation of the epoxy was responsible.

Further attempts were made to make the epoxy harder by changing the base to catalyst ratio to 5:2, 5:3, 4:1, and 3:1, but the new combinations were also unsuccessful in holding the brackets to failure and in eliminating distortion of the epoxy.

Testing model #4

The fourth testing model was similar to testing model #3, except for the holding medium. This time cold cure acrylic, the material used to make retainers, was used to hold the brackets in the plastic rings. It was thought that the acrylic would set up hard enough to avoid deformation and also provide a mechanical and a chemical bond for the brackets. Some of the brackets had a silane coating placed on their bonding surface, which chemically bonds to the methyl methacrylate present in dental composites and cold cure acrylics.

A combination of powder and liquid was mixed that allowed the acrylic to be poured into the prepared rings and flow freely before it set up. The acrylic was allowed to set for 24 hours and then the brackets were tested for vertical wing shear strength.

Due to the shrinkage experienced by the acrylic upon setting, it pulled away from the brackets' bases and did not provide a bond strong enough to hold the brackets to failure. Also, the quick setting time of the acrylic sometimes caused an uneven set to occur as it was being poured into the rings. Thus cold cure acrylic proved to be an inadequate holding medium for the brackets.

Testing Model #5

A different two part epoxy (Master Bond) was tried as the holding medium and the force applicator was modified in this testing model. Otherwise, this model was identical to testing model #2.

The new epoxy was a trifunctional epoxy,. with crossbonding between its two parts, that was supposed to be harder and more brittle than the first type, and therefore, hold the brackets better and not deform.

The epoxy was mixed with equal parts, by volume, of part A and B as directed. Then it was poured into the prepared plastic rings, and allowed to set for 24 hours. The rings were then placed in an oven (set at 300^{o}F) for 1 hour, to insure a complete set of the epoxy.

The modified force applicator had one end beveled at a 45^{o} and it was placed on the bracket so that it came down between the base and the wing of the bracket. The beveled side was up against wing and the straight side was up against the base. It was thought that the vertical force being applied to the top surface of the wings was being absorbed by the entire bracket. Thus, with the force diffused throughout the entire bracket and transferred to the holding medium, the wings were not fracturing. The beveled force applicator was supposed to isolate the force to the wings better, while holding the base of bracket at the same time. From this point on, the force applicator was applied to the brackets in this manner when conducting vertical wing shear strength tests.

When the brackets were thus tested for vertical wing shear strength, the holding medium failed to hold the brackets to failure once again. The force applied to the brackets was transferred through to the epoxy, causing it to deform before the brackets could fracture. This deformation allowed the brackets to dislodge as the force was being applied.

Testing Model #6

In this testing model, dental composite was used as the new holding medium and the brackets were placed into the rings differently. These were the only changes made from testing model #5.

The rings were first filled (1/2 to 3/4 full) with the new epoxy in order to save the amount of composite used. After the epoxy set, equal parts of the composite, pastes A and B, were mixed according to directions and then applied into the remainder of the partially filled rings so that they were now full. Excess composite was wiped off with a small spatula to provide a flat surface, flush with the top of the rings. The bracket bases were then placed into the composite, leaving the wing portion of brackets freestanding. The brackets were centered and held in place with cotton pliers until the initial set of the composite. Then the composite was allowed to set for 24 hours.

It was thought the composite would provide an excellent holding medium because it would mechanically and chemically bond to the brackets. A chemical bond was expected with brackets that had a silane coating applied to their bonding surface. Plus, when set, composite was very hard and brittle and would probably not deform very much when force was applied to the brackets.

The brackets were then tested for vertical wing shear strength, but the dental composite failed to hold the brackets to failure. It was decided at this time that the brackets would probably not fail with the vertical wing shear test, and that a new type of shear force test was needed to test the fracture strength of the wings. Thus, it was concluded that in the patient's mouth, the ceramic brackets would probably not fail due to a vertical shear force to the wings.

Testing Model #7

In this model, the brackets were prepared for testing as in model #6, but the position of the brackets, the location of the applied force, and the force applicator all changed.

Once the rings were fastened in the vice, the vice was placed in the Instron horizontally, so that the brackets were facing up. The brackets were positioned so that the force applicator would apply a shear force to the unsupported front surface area of the incisal wings. This testing model simulated the type of force the brackets would receive if a patient got a direct blow to the face. For example, an elbow to the mouth during a basketball game. Since the brackets were in a horizontal position, this test was called the horizontal wing shear test.

The force applicator was made of stainless steel and was fastened directly to the Instron. The force applicator was beveled, but the end surface that contacted the brackets was flat. The force was applied downward, perpendicular to the front surface of the brackets. If the brackets had double wings, the force was placed on one wing only, in order to increase the force per surface area.

This testing method proved to be successful in holding the brackets long enough to fail. Thus a testing model was found that could test the fracture resistance of the wings with a shear type force. But, once again, the graphs printed out by the Instron demonstrated that the holding medium was absorbing some of the force applied to the brackets and a firmer, less absorbing, holding medium was still needed for accurate results.

Testing Model #8

In this testing method, a solid base was bonded to the brackets, so that the force applied to the brackets would not be dissipated through to the holding medium. It was thought that this would yield a more accurate measure of the wings resistance to fracture. Also, the trifunctional epoxy (Master Bond), used in testing method #5, was used as the holding medium, so that a comparison with other holding mediums could be made.

Hard plastic was used to make the bases, because it could be surface treated to bond with composite. Small sections, approximately 7mm long and 1/2" in diameter, were cut off from a plastic rod, so that the ends were flat and at 90^{o}. The small plastic rods were cleaned with acetone, in an ultrasonic machine, and then allowed to dry. One end of the rod was treated with 3M plastic primer as directed. The treated end was sealed with a dental composite's liquid sealant, mixed with equal parts, A and B. Next, the brackets were bonded, with composite, to the sealed ends of the rods, one bracket per rod. Thus a bracket/rod component was created.

The bracket/rod components were prepared for testing much like the brackets in testing model #3 and the epoxy was prepared as it was in testing method #5. Thus, the front of the brackets were on one side of the scotch tape, outside the rings, and the base of the brackets bonded to the rods on the other side, inside the rings and embedded in epoxy. The brackets were then tested for horizontal wing shear strength as in testing method #7.

The bracket/rod components held in the epoxy until the the wings fractured, but the graphs showed that the epoxy still absorbed some of the force applied to the brackets, due to deformation. A different holding medium for the bracket/rod component was still needed.

Testing Model #9

In this testing model, the bracket/rod component was embedded in composite (Ormco Challenge) to see how the composite holding medium would compare to the epoxy (Master Bond) used in testing model #8.

The composite was mixed as in testing model #6 and then placed into the plastic rings, so that it filled the rings about half full. The bracket/rod component was then placed into the rings, causing the composite to rise to the top. The bracket/rod component was placed in the composite just far enough to embed the base of the brackets, leaving the front portion of the brackets freestanding. The excess composite was wiped off with a small spatula leaving a flat composite surface, flush with the top of the rings. The brackets and the composite were then prepared for testing as in testing model #6.

The horizontal wing shear test, of testing model #7, was applied to the brackets. Test results showed that the composite held the bracket/rod component long enough to allow the bracket wings to fracture. Also, the graphs showed that the composite was not absorbing as much of the applied force.

The wire torque test was also performed to see if the composite would hold the bracket/rod components during this test procedure without distortion. Relief cuts were made into the composite and along the side of the rings in order to allow the end of the torquing key to rotate freely as the wire was being pulled up. Test results showed that the composite would hold the bracket/rod components long enough to let the wire torque test fracture the brackets. Again, the graphs showed that the composite holding the bracket/rod components was not distorting as much as other holding mediums.

Testing Model #10

In this model, for comparative reasons, the horizontal wing shear test and the wire torque test were applied to brackets prepared for testing as in model #6.

Test results showed that the composite would hold the brackets to failure; but they also showed that the composite and epoxy combination absorbed more of the applied force, when compared to testing model #9.

Holding Mediums Compared

The graphs printed out by the Instron for testing methods #'s 7-10, which all used different holding mediums for the horizontal wing shear test, were then compared to see which holding medium was the most rigid and least deformed. A straight line on the graph was determined to show a rigid holding medium. Thus, the holding medium with the straightest lines on the graphs was the most rigid and so on.

Composite holding the bracket/rod component proved to be the most rigid holding medium. Composite holding the bracket alone, over set epoxy, was the 2nd most rigid holding medium. Epoxy holding the bracket/rod component was the 3rd most rigid testing model. Epoxy holding the bracket alone was the least rigid of the four testing models.

It was decided at this time to continue the search for a more rigid testing model, since the holding mediums were still absorbing too much of the applied force to the brackets. If one could not be found, the composite holding the bracket/rod component was the holding medium to be used for horizontal wing shear tests and the wire torque tests.

Testing Method #11

In this testing model, the brackets were glued to metal bases, because it was thought that the metal bases would not distort, as forces were applied to the brackets.

The metal bases were each cut approximately 10mm in length from a 3/4" diameter rod made of cold drawn steel. The steel was 1018 grade, having a tensile strength of 64,000psi, a yield strength of 54,000psi, and a Brinell hardness of 126. The top and bottom surfaces of the metal bases were then squared up at 90^{o} angles to the long axis on a lathe machine. Thus, the metal bases fit into the holding vice just like the plastic rings.

Cyanoacrylate (super glue) was used to glue the brackets to the center of the metal bases. Cyanoacrylate was used because it has strong adhesive properties with non-porous materials, such as ceramics and metals. Cyanoacrylate was applied to the bonding surface of the brackets and to the center of metal base bonding surface, and then the brackets were placed on the metal base. The brackets were held in place with a large paper clamp, which held the brackets and the bases up against each other with a constant holding force as the glue was setting. The super glue was allowed to set for 24 hours.

Horizontal wing shear tests and wire torque tests were then run, but as the force was applied to the brackets, the brackets debonded very quickly with both tests. This bonding failure was probably due to the lack of a tight or intimate surface contact between the bonding surfaces of the brackets and the metal bases. A tight surface contact was not possible because the bonding surfaces of the brackets had a slight concavity.

Testing Model #12

This testing model was very similar to testing model #11 and differed only in the type of adhesive used to bond the brackets to the metal bases.

A two part epoxy glue was used this time, because it was thought, as with super glue, that the epoxy glue would bond the metal bases and the ceramic brackets strong enough to hold the brackets to failure during the tests.

Equal parts of the epoxy glue, A and B, were mixed as directed and the brackets were bonded to the metal bases as in testing model #11. The epoxy was allowed to set for 24 hours prior to testing.

Horizontal wing shear tests and wire torque tests were run, but once again, the glue failed to hold the brackets long enough to fail under the applied force. The failure occurred at the bracket/epoxy glue interface and not at the epoxy/metal interface. Prior to the brackets debonding, the graphs showed no distortion in this testing model, but it was evident that a different bonding mechanism to the bracket bases was needed.

Testing Model #13

A dental composite adhesive was used to bond the ceramic brackets to the metal discs in this testing model and a wire mesh was spot welded to the bonding surface of the metal discs prior to bonding the brackets. These were the two major changes introduced in this testing model.

A dental composite was chosen as the adhesive for several reasons: 1) in previous testing models, it proved to be the superior holding medium; 2) it was a clinically proven strong adhesive of brackets to teeth; 3) it provided a chemical bond to the ceramic brackets coated with silane on their bonding surface; 4) it would provide a strong mechanical bond to brackets with undercuts on their bonding surface; and 5) it was a brittle material that would probably not distort under the forces applied to the brackets.

A wire cloth (mesh) was spot welded to the metal discs in order to provide a bonding surface very similar to the bonding surface on metal brackets. Since "meshed" metal brackets have bonded successfully to teeth, it was thought that the meshed discs would provide a successful bonding surface for the composite by allowing the composite to set beneath its undercuts, resulting in a strong mechanical bond. Thus, the brackets would be bonded in a non-clinical environment with a strong bond, similar to the bond between brackets and enamel on teeth.

Small, 3/4" round pieces were cut from a 100 x 100/sq. in. wire cloth mesh. The diameter of the wire was .0045", the width of the openings were .0055", and metal was a standard grade stainless steel, type 304, with 18% chrome and 8% nickel. Centered on the bonding surface of the discs, the round pieces were spot welded to the discs using a dental spot welding machine. The welding spots were evenly distributed along the surface, in order to have the mesh flat on the disc. Around the perimeter, the welding spots were placed closer together to prevent the mesh from coming off.

Several two part, A and B, dental composites (3M Dental Concise, Unitek Dyna-Bond, and Ormco Challenge) were tested to determine which one would bond the brackets to the meshed metal discs the best. They were mixed as directed and then applied to the brackets and the meshed surface. The brackets were then placed on the meshed discs and held in place with the paper clamps. Excess composite was removed and the composite was allowed to set for 24 hours. Horizontal wing shear tests and wire torque tests were then run to determine the success of this testing model and to see which dental composite would prove to hold the brackets the best.

When performing the horizontal wing shear test it was noted that the base holding vice was being deflected as the force was being applied to the brackets. Clamps were then used to stabilize the base holding vice and the horizontal wing shear tests were run again.

This time, it was noted that the force applicator was being deflected from some of the ceramic brackets, sliding down the sloped facial surface of their wings. It was felt that the deflection of the force applicator was due to the brackets resisting a compressive type of force instead of a shear type of force. Since ceramics are very strong in withstanding compressive forces, the ceramic brackets were able to withstand the force being applied and cause the metal force applicator to deflect.

At this time, it was decided to abandon the horizontal wing shear test, since it proved to be very difficult to run successfully with our current model. If a different force applicator and different testing method were developed, the horizontal wing shear test could probably be run successfully. A shorter force applicator, with a sharper tip, made from harder metal would be recommended. Also, a method that would allow the force applicator to be consistently placed at the same location for each bracket type would be needed to insure equality and reliability. The force applicator would have to be placed so that a shear force would be applied to the wing and not a compressive force that would be resisted by the entire bracket.

When the wire torque test was run, it was noted that Dental Concise bonded the brackets with the most consistency. Even though the other composite adhesives held the ceramic brackets most of the time, they were not consistent, and the brackets would debond much too often prior to fracturing. Thus, Dental Concise was chosen as the adhesive for this testing model.

With the Dental Concise adhesive bonding the brackets to the meshed metal bases, the archwire torque test proved to be quite successful. The graphs printed out by the Instron showed straight lines and the brackets held on long enough to fracture. Thus, an accurate measurement of the force required to fracture the brackets was now possible. A distortion free model that passively held the brackets long enough to fracture was found.

Testing Model #14

After running a few pilot tests using the archwire torque test, it was noted that the stainless steel archwire was sometimes deforming prior to the brackets fracturing and that some of the brackets were still debonding. So, new testing methods were needed to improve the current testing model.

In order to decrease archwire deformation, an archwire stronger than the regular type of stainless steel archwire previously used was needed. The new archwire, Hi T by Unitek, had an ultimate tensile strength of 340ksi, yield strength of 300ksi, and a modulus of elasticity of 30 x 10^6.

Also, a new torquing key, with a shorter distance between the wire slots was used. The shorter distance between wire slots allowed the torquing force to be applied closer to the brackets, made the wire between the slots stiffer, and decreased the amount of torque force lost due to wire flexure. The previous torquing key had an interslot distance of .58", but the new torquing key had an interslot distance of .38". On examining the metal discs with debonded brackets, it was found that most of the bond failures took place between the top of the mesh and the composite. In other words, the composite was getting underneath the mesh, but it was not consistently bonding to the top surface of the mesh strong enough. It was noted that the surface finish on the mesh was smooth and polished and that the bonding surface of the metal disc was also smooth. These smooth surfaces were difficult for the composite adhesive to bond to, so they were sandblasted roughen them up. It was felt that roughening up the bonding surfaces of the mesh and disc would increase the bonding surface area and provide a surface that was easier for the adhesive to bond to.

After the meshed discs were sandblasted to a dull finish, the excess sand was removed with compressed air and then the discs were ultrasonically cleaned in acetone for 5 minutes, to remove any residual sand and oils that might contaminate the bonding surface. The acetone was dried off the with compressed air and the meshed discs were now ready for bonding brackets. The brackets were bonded to the meshed discs as described in testing model #13.

Archwire torque tests with the new torquing key, the new archwire, and the sandblasted meshed discs proved to be very successful and it was decided to continue with this model until further changes were needed.

Testing Model #15

Since the vertical wing shear test and the horizontal wing shear test had been abandoned, it was decided to add other variables to the archwire torque test in model #14, which would be of clinical interest to the orthodontist. Two independent variables, ligation methods and scratches, were added to the model.

The first independent variable was the method of ligation. One set of each bracket type had the archwire ligated with elastic ligatures and the other set had the archwire ligated with .010" metal ligatures. This comparison was done to see if the different methods of ligation would have an effect on the amount of torquing force the brackets could withstand prior to failure.

The second independent variable was non-scratched vs. scratched brackets. A scratch was placed on half of each bracket type and then they were tested like the brackets without a scratch. Scratches were placed on the base of the slot with a diamond edged disc. This comparison was done to see if surface flaws on the brackets would affect the amount of torquing force the brackets could withstand prior to fracture.

10 brackets from each bracket type were in each category, so that: 50 brackets with no scratch, were ligated with elastic; 50 brackets with no scratch, were ligated with metal; 50 brackets with a scratch, were ligated with elastic; and 50 brackets with a scratch, were ligated with metal. Altogether, 200 brackets were tested with the archwire torque test.

This appendix was written so that researchers interested in this field, may save time and not go through the same procedures in testing ceramic brackets in a similar fashion. It is recommended that this final testing procedure be considered one of the standard testing methods for evaluating the fracture strength of ceramic brackets.

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