

**TWENTY-FOUR HOUR AND SIX MONTH
EVALUATION OF THE SHEAR-PEEL BOND
STRENGTHS OF THREE TYPES OF CERAMIC
BRACKETS TO COMPOSITE RESIN**

BY

PASCAL CARRIÈRE, DMD

A Thesis

Submitted to the Faculty of Graduate Studies

In Partial Fulfilment of the Requirements

For the Degree of

MASTER OF SCIENCE

Section of Orthodontics

Department of Preventive Dental Science

Faculty of Dentistry

University of Manitoba

Winnipeg, Manitoba

©



National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-76903-8

**THE UNIVERSITY OF MANITOBA
FACULTY OF GRADUATE STUDIES

COPYRIGHT PERMISSION PAGE**

**Twenty-four Hour and Six Month Evaluation of the Shear-Peel Bond Strengths of
Three Types of Ceramic Brackets to Composite Resin**

BY

Pascal Carrière

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree
of**

MASTER OF SCIENCE

PASCAL CARRIÈRE ©2002

Permission has been granted to the Library of The University of Manitoba to lend or sell copies of this thesis/practicum, to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film, and to University Microfilm Inc. to publish an abstract of this thesis/practicum.

The author reserves other publication rights, and neither this thesis/practicum nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

ABSTRACT

Currently, the demand for aesthetic dentistry strongly encourages the use of materials that blend in with the natural dentition. Accordingly, in our investigation of orthodontic attachments, three types of ceramic brackets (Clarity™, 3M Unitek; MXi®, TP Orthodontics; Allure®, GAC; in addition to a metal bracket control group, Victory Series™, 3M/Unitek) were tested at 24 hours and 6 months for shear-peel bond strengths to composite resin. Ninety-six cylindrical samples were made using Z100™ restorative resin (3M). Forty-eight brackets of each type were bonded to both ends of air abraded resin composite samples with either Transbond™ XT (3M/Unitek) or Fuji ORTHO™ LC (GC America). One end was used for the 24-hour testing and the other end for the 6-month testing. Samples were stored in distilled water at 37°C for either 24 hours or 6 months and then tested for shear-peel bond strength using a Materials Testing Device (Zwick), with a crosshead speed of 0.5mm/min. The shear-peel bond strengths as a function of bracket type, adhesive type and storage time were analysed by a Split Unit Analysis of Variance and Duncan's multiple comparison test at a 5% level of significance. At 24 hours, MXi brackets bonded with either Transbond™ XT (6.41 ± 0.52 MPa) or Fuji ORTHO™ LC ($12.98 \text{ MPa} \pm 1.85 \text{ MPa}$) produced statistically lower bond strengths than all the other groups ($p < 0.001$). Shear-peel bond strengths after 6 months of storage were found to be significantly reduced for the Allure/Transbond™ XT group ($18.97 \text{ MPa} \pm 4.32$ vs. $14.01 \text{ MPa} \pm 6.43$), the Allure/ Fuji ORTHO™ LC group ($17.33 \text{ MPa} \pm 4.05 \text{ MPa}$ vs. $6.73 \text{ MPa} \pm 3.33 \text{ MPa}$) and the Clarity™/Fuji ORTHO™ LC group ($20.26 \text{ MPa} \pm$

5.99 MPa vs. 14.91 MPa \pm 7.10 MPa) ($p < 0.05$). Minimal composite resin surface damage occurred at either 24 hours or six months of debonding ceramic brackets but a high incidence of fracture occurred when debonding the control brackets (Victory SeriesTM) at six months. The results of the various materials tested for this study showed material specificity, making generalizations difficult. Ceramic brackets, however, generally retained adequate shear-peel bond strengths to composite following long-term storage.

Dedication

This thesis is dedicated
to my
lovely family
Vickie, Gabriel and my second son to be,
who inspire me every day,
and also
to
my parents,
who help me to become what I am.

ACKNOWLEDGEMENTS

My sincere thanks and appreciation are due to:

- My thesis advisors:
 - Dr. W.A. Wiltshire** (Supervisor), University of Manitoba, Faculty of Dentistry, Department of Preventive Dental Science
 - Dr. P.T. Williams**, (Internal Examiner), University of Manitoba, Faculty of Dentistry, Department of Restorative Dentistry, Section Biomaterials
 - Dr. C.L.B. Lavelle**, (External Examiner), University of Manitoba, Faculty of Dentistry, Department of Preventive Dental Science
- Dr. T. Hassard and P. Martens for their expert assistance with the statistical analysis
- 3M Unitek, TP Orthodontics, GAC, GC America, and 3M Dental Products for supplying the materials used in this study

TABLE OF CONTENTS	Page
ABSTRACT	i
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	x
1. INTRODUCTION	1
1.1. Objective of the study	2
1.2. Null Hypothesis	3
2. REVIEW OF THE LITERATURE	4
2.1. Direct Bonding	4
2.2. Adhesion	5
2.3. Bonding Materials	9
2.4. Bond Strengths	13
2.4.1. Bond strength testing protocol	13
2.4.2. Recommended bond strengths in Orthodontics	15
2.5. Bonding to Different Materials	16
2.5.1. Composite	16
2.5.2. Enamel	19
2.5.3. Porcelain	21
2.5.4. Metal	22
2.6. Ceramic Brackets	24
2.6.1. Manufacturing process	25

2.6.2. Physical properties	26
2.6.3. Bracket base designs	28
2.6.4. Bonding properties of ceramic brackets	29
2.7. Restorative Composite Resins	29
2.7.1. Overview	29
2.7.2. Constituents	31
2.7.3. Composite repairs	34
2.7.4. Water sorption and solubility	36
3. MATERIALS AND METHODS	39
3.1. Materials used in this study	39
3.1.1. Brackets	40
3.1.2. Composite Orthodontic Adhesive systems	43
3.1.3. Restorative Resin Composite	45
3.2. Experimental method	46
3.2.1. Experimental design outline	46
3.2.2. Preparation of the composite specimens	48
3.2.3. Surface area of the brackets	49
3.2.4. Bonding procedures	50
3.2.5. Storage conditions	54
3.2.6. Shear-peel bond strength testing	54
3.2.7. Site failure evaluation	56
3.3. Statistical analysis	57

4. RESULTS	58
4.1. Surface area of the brackets	58
4.2. Shear-peel bond strengths	58
4.2.1. Twenty-four-hour bond strengths	58
4.2.2. Six-month bond strengths	70
4.2.3. Twenty-four-hour vs. six-month bond strengths	81
4.2.4. Adhesive Remnant Index (ARI) Scores- modified	89
5. DISCUSSION	98
5.1. Shear-peel Bond Strengths	98
5.1.1. Clinical versus laboratory findings	98
5.1.2. Variables affecting inter-study comparison	99
5.1.3. Twenty-four-hour bond strengths	101
5.1.4. Six-month bond strengths	103
5.2. ARI Scores	106
5.3. Evaluation of the null hypotheses	108
6. CONCLUSIONS AND RECOMMENDATIONS	110
6.1. Conclusions	110
6.2. Recommendations	111
7. REFERENCES	113

List of Figures

- Figure 2.1 Contact angles, wettability and adhesion
- Figure 2.2 Air trapped between adhesive and adherend
- Figure 2.3 Adhesion failure
- Figure 2.4 Setting reaction of the GIC
- Figure 2.5 Stress-strain curve for sapphire and stainless steel
- Figure 2.6 Chemical Structure of Monomers Used in Dental Composites
- Figure 2.7 Vinyl silane compound (γ -methacryoxypropyl trimethoxysilane)
- Figure 3.1 Clarity™ brackets
- Figure 3.2 Description of the MXi® bracket
- Figure 3.3 MXi® brackets
- Figure 3.4 Allure® brackets
- Figure 3.5 Victory Series™ brackets
- Figure 3.6 Transbond™ XT
- Figure 3.7 Fuji ORTHO™ LC
- Figure 3.8 Z100™
- Figure 3.9 Study design
- Figure 3.10 Composite resin sample mould
- Figure 3.11 Composite resin sample with two brackets
- Figure 3.12 Ortholux™ XT
- Figure 3.13 Jig
- Figure 3.14 Bencor™ Multi-T testing apparatus

- Figure 3.14 Bencor™ Multi-T testing apparatus
- Figure 3.15 Bencor™ Multi-T testing apparatus (close-up)
- Figure 3.16 Zwick Universal Testing Machine
- Figure 4.1 Comparative Data for 24-hour Bond Strengths
- Figure 4.2 Comparative Data for 6-month Bond Strengths
- Figure 4.3 Comparative Data for 24-hour and 6-month Bond Strengths
- Figure 4.4 Typical debond at the resin composite/adhesive junction with an ARI score of 2
- Figure 4.5 Typical debond at the resin composite/adhesive junction with an ARI score of 3
- Figure 4.6 Typical debond at the resin composite/adhesive junction with an ARI score of 4
- Figure 4.7 Typical debond at the resin composite/adhesive junction with an ARI score of 5
- Figure 4.8 Overall Modified Adhesive Remnant Index Scores
- Figure 4.9 Comparative Adhesive Remnant Index Scores at 24 hours and 6 months

List of Tables

Table 3.1	Materials; manufacturer and batch number
Table 4.1	Surface area of the brackets
Table 4.2	24-hour Shear-Peel Bond Strengths in MPa of Clarity™ Brackets Bonded with Transbond™ XT
Table 4.3	24-hour Shear-Peel Bond Strengths in MPa of Clarity™ Brackets Bonded with Fuji ORTHO™ LC
Table 4.4	24-hour Shear-Peel Bond Strengths in MPa of MXi® Brackets Bonded with Transbond™ XT
Table 4.5	24-hour Shear-Peel Bond Strengths in MPa of MXi® Brackets Bonded with Fuji ORTHO™ LC
Table 4.6	24-hour Shear-Peel Bond Strengths in MPa of Allure® Brackets Bonded with Transbond™ XT
Table 4.7	24-hour Shear-Peel Bond Strengths in MPa of Allure® Brackets Bonded with Fuji ORTHO™ LC
Table 4.8	24-hour Shear-Peel Bond Strengths in MPa of Victory Series™ Brackets Bonded with Transbond™ XT
Table 4.9	24-hour Shear-Peel Bond Strengths in MPa of Victory Series™ Brackets Bonded with Fuji ORTHO™ LC
Table 4.10	Comparative Data for 24-Hour Bond Strengths
Table 4.11	6-month Shear-Peel Bond Strengths in MPa of Clarity™ Brackets Bonded with Transbond™ XT
Table 4.12	6-month Shear-Peel Bond Strengths in MPa of Clarity™ Brackets Bonded with Fuji ORTHO™ LC
Table 4.13	6-month Shear-Peel Bond Strengths in MPa of MXi® Brackets Bonded with Transbond™ XT
Table 4.14	6-month Shear-Peel Bond Strengths in MPa of MXi® Brackets Bonded with Fuji ORTHO™ LC
Table 4.15	6-month Shear-Peel Bond Strengths in MPa of Allure® Brackets Bonded with Transbond™ XT

Table 4.16	6-month Shear-Peel Bond Strengths in MPa of Allure [®] Brackets Bonded with Fuji ORTHO [™] LC
Table 4.17	6-month Shear-Peel Bond Strengths in MPa of Victory Series [™] Brackets Bonded with Transbond [™] XT
Table 4.18	6-month Shear-Peel Bond Strengths in MPa of Victory Series [™] Brackets Bonded with Fuji ORTHO [™] LC
Table 4.19	Comparative Data for 6-month Bond Strengths
Table 4.20	Comparative Data for 24-hour and 6-month Bond Strengths
Table 4.21	Comparative data as a function of Adhesive type/Time of debonding
Table 4.22	Comparative data for the MXi [®] brackets group
Table 4.23	Comparative data for the Allure [®] brackets group
Table 4.24	Comparative data for the Clarity [™] brackets group
Table 4.25	Comparative data for the Victory Series [™] brackets group
Table 4.26	Modified Adhesive Remnant Index for Clarity [™] brackets
Table 4.27	Modified Adhesive Remnant Index for MXi [®] brackets
Table 4.28	Modified Adhesive Remnant Index for Allure [®] brackets
Table 4.29	Modified Adhesive Remnant Index for Victory Series [™] brackets
Table 4.30	Overall Modified Adhesive Remnant Index Scores
Table 4.31	Comparative Adhesive Remnant Index Scores at 24 hours and 6 months
Table 4.32	Comparative Data for the 24-hour Composite Resin Fracture Incidence
Table 4.33	Comparative Data for the six-month Composite Resin Fracture Incidence

1. INTRODUCTION

In the present era of dentistry, aesthetics is a major concern. As a result, orthodontists feel obligated to provide their patients, particularly the increasing number of adults seeking orthodontic treatment for cosmetic reasons, with a more pleasing or appealing appliance. According to Gottlieb and Vogels (1984) and Watson (1979), adults account for up to almost 25% of the private practice patient load. This reality has led orthodontists and manufacturers of orthodontic appliances to seek alternatives for metal brackets. Four methods have been attempted to improve aesthetics during orthodontic therapy: First, altering the appearance of the metal by adding a tooth coloured coating onto the bracket; secondly, reducing the size of the metal brackets; thirdly, repositioning the appliance onto the lingual surfaces of the teeth; and finally, changing the material from metal to tooth coloured or translucent materials (Birnie, 1990; Winchester, 1992).

Currently, the demand for aesthetic dentistry strongly encourages the use of materials that blend in with the natural dentition. In the early 1970's, aesthetic plastic brackets were introduced into the market and have shown some disadvantages, including moisture absorption, which progressively weakened the bond strength, bracket discoloration on exposure to foods and liquids, bracket wear and tie-wing fractures, excessive distortion, especially torque control and inability to be securely bonded with normal diacrylate adhesives (Reynolds, 1975). In the mid 1980's, a new

generation of aesthetic brackets, the ceramic brackets, were introduced in orthodontics (Britton *et al.*, 1992; Gibbs, 1992).

From the perspective of adults seeking orthodontic treatment, extensive composite restorations are commonly found on teeth needed for bracket bonding. Composite restorations are also commonly used for the replacement of missing portions of the teeth resulting from caries, fractured teeth, microdontia and attrition. Few articles in the literature, however, focus on ceramic brackets bonded to composite (Kao *et al.*, 1995; Chunchacheevachaloke and Tyas, 1997; Lai, Woods and Tyas, 1999), especially in the long-term (6 months). The present study is therefore intended to evaluate both the long-term (6 months) as well as the short-term (24 hours) *in vitro* bond integrity.

1.1 Objectives of the study

The purpose of this study was to evaluate the 24-hour and the 6-month shear-peel bond strengths of three different porcelain brackets (ClarityTM/3M Unitek, MXi[®]/TP Orthodontics and Allure[®]/GAC) to a composite resin (Z100TM/3M) using two different types of adhesives (TransbondTM XT/3M Unitek and Fuji ORTHOTM LC/GC America) and assess the sites of failure.

1.2 Null Hypothesis

1. The null hypothesis for this study stipulates that there are no statistical differences between shear-peel bond strengths of four types of attachments bonded to popular composite resin restorative material (Z100TM). Three types of ceramic brackets (Allure[®], ClarityTM, MXi[®]) and one type of metal brackets (Victory SeriesTM) were tested.
2. The null hypothesis stipulates that there are no statistical differences in shear-peel bond strengths using either a composite resin adhesive (TransbondTM XT) or a resin-modified glass ionomer cement (Fuji ORTHOTM LC).
3. The null hypothesis stipulates that there are no statistical differences in shear bond strength between the 24-hour and the 6-month evaluations.

2. REVIEW OF THE LITERATURE

This review is intended to summarize the current orthodontic bonding research and is divided into seven major sections to provide the reader with an overall appreciation of the problem.

2.1 Direct bonding

The development of acid-etch technique led to a new era in the field of bonding orthodontic brackets (Buonocore, 1955). Buonocore used 85% phosphoric acid to increase enamel adhesion for restorative dentistry purposes. This technique offered great improvements for aesthetics and oral hygiene in orthodontics, and significant reductions in chairside time. Other advantages associated with direct orthodontic bonding include: ease of manipulation, decrease of patient discomfort, elimination of need for adjacent teeth separation, decreased soft tissue irritation, ability to bond to unerupted and to partially erupted teeth, elimination of post-treatment band space closure and facilitated both detection and treatment of caries (Reynolds, 1975). Disadvantages of direct bonding include: difficulty in satisfactorily removing adhesives following debonding, enamel damage, reduced surface area for bracket retention, and reduced protection against interproximal caries compared to that provided by a well-contoured cemented band (Reynolds, 1975).

Bracket bonding in orthodontics is achieved by the mechanical locking of adhesives to irregularities in the enamel surfaces of the tooth and by either mechanical locks within the base of the bracket or by chemical bonding. Three components are important in the process of bonding: the tooth surface and its preparation, the attachment base design and the adhesive itself (Proffit, 1999).

The surface preparation involves removal of enamel surface contaminants and the creation of enamel bonding surfaces. Following a prophylaxis, the surface is usually treated with an unbuffered phosphoric acid (35-50%) for 20-30 seconds to remove some of the enamel. This opens up pores both between and within the enamel prisms allowing the adhesive to penetrate into the enamel surface.

The base of a metal attachment is designed to create a mechanical interlock between the adhesive and the attachment (Proffit, 1999). The base of a ceramic bracket, however, can be designed to achieve a mechanical bond (e.g. ClarityTM, 3M/Unitek), a chemical bond (e.g. Allure[®], GAC), or a combination of both (e.g. MXi[®], TP Orthodontics). According to Proffit (1999), since the strength of a chemical bond is sometimes high enough to create enamel surface damage in debonding, mechanical retention is now preferred for ceramic brackets fixation.

2.2 Adhesion

Adhesion may be defined as the attraction forces exerted between molecules at the surfaces of different materials when surfaces are brought into close proximity or

contact (Buonocore, 1975). Mechanical bonding differs from true adhesion in that molecular attraction is not required. The molecular attraction forces involved in adhesion may be categorized into physical and chemical. Physical forces include van der Waals' forces, which result mainly from attraction forces between atoms and molecules, and hydrogen bonding, which is a special kind of dipole-dipole interaction. Hydrogen bond formation is present in bonding materials, such as the hydroxyl group (OH) and the carboxyl group (COOH). The chemical forces come mainly from ionic, covalent, and metallic bonds and are much stronger than physical forces (Buonocore, 1975).

Factors that encourage bracket adhesion to tooth surfaces include low surface contact angle, good wettability and low viscosity. The nature and the condition of the surface contact are important, since surface imperfections, even at a molecular level, influence the degree of adhesion (Buonocore, 1975). Smoother surfaces will adhere to each other more readily than rough surfaces. Surface contamination also decrease the level of adhesion (Buonocore, 1975). The wettability of a material is related to its ability to establish a close interfacial contact. Such interfacial contacts may be measured by the contact angle between the two materials (**Figure 2.1**) where zero contact angle illustrates a perfect wettability indicative of the adhesive molecules being attracted to the adherend molecules as much as, or more than, they are to themselves (Buonocore, 1975).

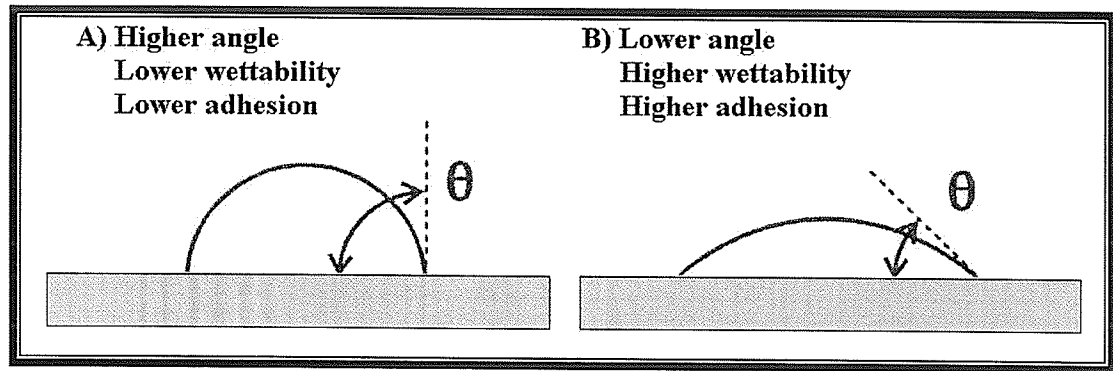


Figure 2.1. Contact angles, wettability and adhesion. (After Darvell, 1998)

In **Figure 2.1**, (A) The adhesive has a lower attraction to the substrate than that in (B), whereas in (B) the adhesive has a higher attraction to the substrate and potentially a higher level of adhesion. Bonds resulting from good wetting and small contact angles are usually extremely strong (no actual values were stated) (Buonocore, 1975).

Viscosity is also an important consideration since it interferes with establishing maximum wetting in spite of the strong attraction between the adhesive and the adherend surface (Buonocore, 1975). The adhesive should flow readily over the surface to avoid trapping air pockets as shown in **Figure 2.2**. Also, a viscous adhesive may not have flowed into all the retention points before setting.

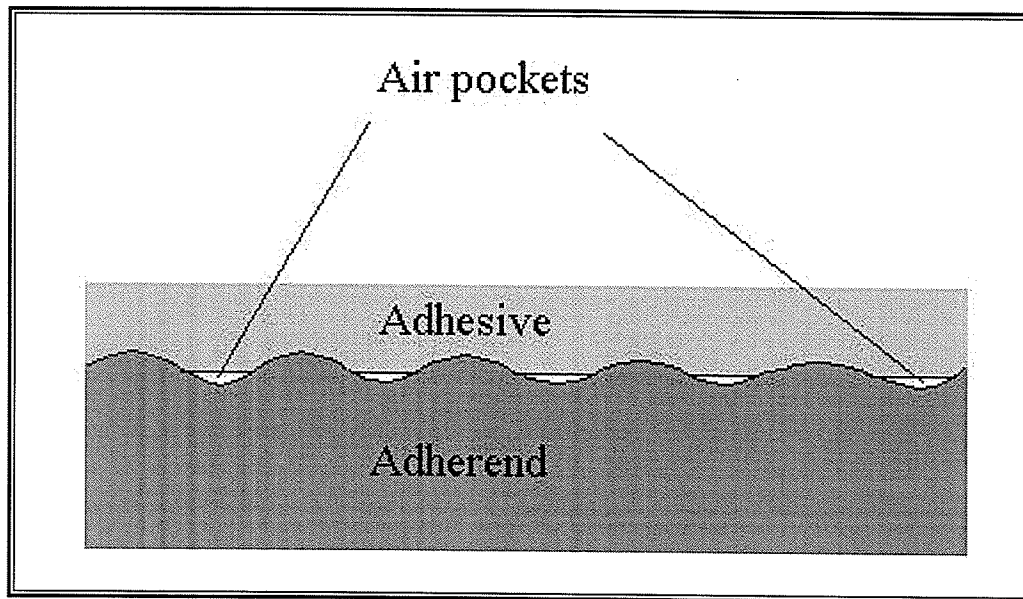


Figure 2.2. Air trapped between adhesive and adherend. (After Combe, Burke and Douglas, 1999)

Failure may then occur as an adhesive failure, a cohesive failure or a combination of both (**Figure 2.3**). Adhesive failures occur when the adhesive is displaced from the adherend, whereas cohesive failures may occur when the adherend itself fractures or the adhesive itself fractures (Combe, Burke and Douglas, 1999).

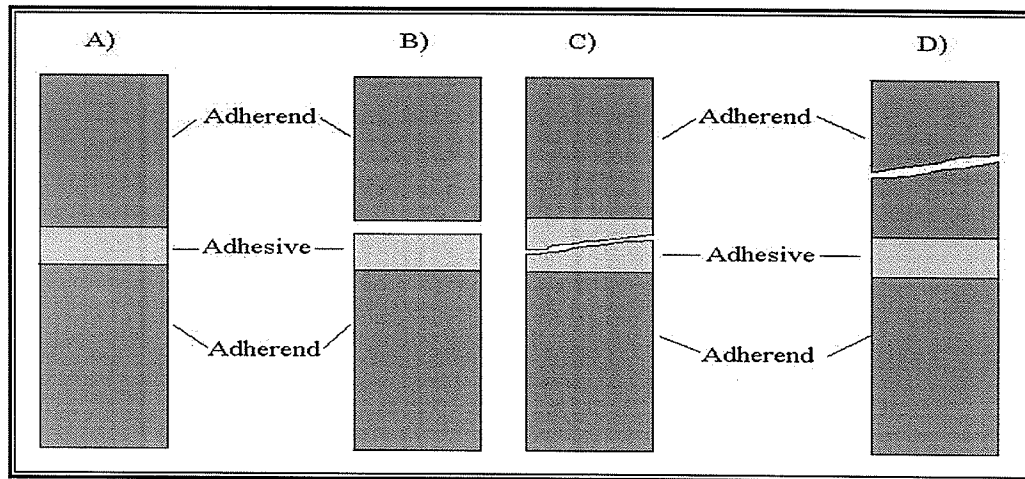


Figure 2.3. (A) Intact sample; (B) adhesive failure; (C) cohesive failure of adhesive; (D) cohesive failure of adherend. (After Combe, Burke and Douglas, 1999)

Ideally, bonding failure should occur at the adhesive/adherend interface (adhesive failure) so no adhesive is left on the adherend surface (less time consuming for adhesive removal). On the other hand, adhesive failure could increase the risk of adherend surface damage when compared to cohesive failure of the adhesive.

2.3 Bonding materials

According to Proffit (1999), a successful bonding material should be dimensionally stable. Stability would be achieved by materials that have low setting shrinkage and a low thermal coefficient of expansion. Bonding materials should also be quite fluid to penetrate the enamel surface, it must have excellent cohesive strength, and be easily used in the clinical situation.

Two types of adhesives are commonly used for orthodontic bonding: Glass Ionomer materials and diacrylate resins. Glass Ionomer Cements (GIC) were first introduced to clinical restorative dentistry 30 years ago (Wilson and Kent, 1972) and its use for orthodontic bonding has been reported since 1986 (White LW, 1986; Tavas and Salem, 1990; Cook, Luther and Youngson, 1996). GIC has an acid-base type of setting reaction (Combe, Burke and Douglas, 1999). The cement powder is a $\text{Al}_2\text{O}_3 - \text{CaF}_2 - \text{SiO}_2$ glass and the liquid is a polyacid. The overall cement-forming reaction can be summarized as follows:

1. Attack on the glass particles by the acid
2. The outer layer of the glass particles is depleted of metal ions (Ca^{2+} , Al^{3+} , F^-) and degraded to a silica gel
3. Ions and polyanions from the Polyacid liquid react together to form Calcium and Aluminum polysalts

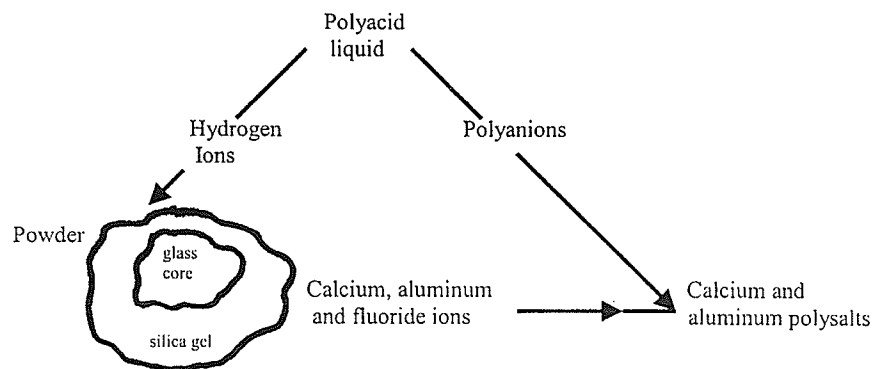


Figure 2.4 Setting reaction of the GIC (After Wilson and McLean, 1988)

Other elements added to the material include: itaconic acid to prevent thickening of the liquid for a satisfactory shelf life, and tartaric acid to speed up the setting reaction (Darvell, 1998; Combe, Burke and Douglas, 1999). Fluoride is also added by the manufacturer as a flux to help make the glass (Wilson and McLean, 1988).

The GIC's have lower bond strengths than resin composite adhesives with metal brackets (Rezk-Lega and Øgaard, 1991; Wiltshire, 1994; Miguel, Almeida and Chevitarase, 1995; Powers, Kim and Turner, 1997). Rezk-Lega and Øgaard (1991) found that GIC's (0.34 to 1.34 MPa) had significantly lower bond strengths than the composite (9.68 MPa) after 24 hours (*in vitro*). Miguel, Almeida and Chevitarase (1995) evaluated the clinical failure rate of metal brackets bonded with either a resin composite adhesive (Concise) or a GIC (Ketac-Cem) and reported that the composite group showed a statistically significant lower failure rate (7.96%) than the glass ionomer cement group (50.89%) over a 12 months period.

Resin-Modified Glass Ionomer cements (RMGIC) are another group of Glass Ionomer Cements, developed to overcome some of the problems associated with the original cement such as short working time, long setting time, solubility in the oral environment and brittleness (Combe, Burke and Douglas, 1999). RMGIC present superior mechanical properties (*in vivo*) than the conventional GIC's (Cattani-Lorente *et al.*, 1999). RMGIC shares the same acid-base reaction between the glass powder and the polyacrylic acid as the GIC, but also contains polymerisable water soluble

resins such as 2-hydroxyethyl methacrylate (HEMA), together with light activators such as camphorquinone. A number of advantages have been claimed for this system over the GIC's. These include extended working time as a result of command curing, fluoride release similar to conventional glass ionomers and improved physical properties, especially tensile strength (no indication were given whether it was *in vivo* or *in vitro*) (Combe, Burke and Douglas, 1999).

RMGIC, used with metal brackets, *in vitro*, were shown to have significantly lower bond strengths than resin composite adhesives (Rezk-Lega and Øgaard, 1991; Meehan, Foley and Mamandras, 1999).

The second type of adhesive is a diacrylate resin or composite resins (also named resin-based luting materials), which includes several sub-types such as polyacid-modified resin composites and ionomer-resin suspensions. Resin composite luting materials were developed in the early 1970s for use with adhesive dental bridges. These cements were less heavily filled chemically cured composites (Combe, Burke and Douglas, 1999).

The resin composite adhesive is formulated from glass particles and dimethacrylate monomers (Powers, Kim and Turner, 1997), with the glass filler loading ranging from 28% (lightly filled) by weight of glass filler to 60-80% (highly filled). Ostertag *et al.* (1991) evaluated the bond strengths of ceramic brackets to bovine enamel using different filler concentrations (30% by weight, 55% and 80%). They found that the

80% filled adhesives displayed greater shear bond strengths than the 30% or 55% filled adhesives. The available materials may be classified according to their method of curing, which may be by visible light, chemical curing or a combination of both (Combe, Burke and Douglas, 1999). *In vitro* bond strengths of resin composites have been shown to be unaffected by the curing mechanism (Joseph and Rossouw, 1990; Chaconas, Caputo and Niu, 1991; Kao *et al.* 1995; Powers, Kim and Turner, 1997; Lai, Woods and Tyas, 1999). Since composite resin adhesives possess many ideal properties, including low solubility in oral fluids and good compressive and tensile strengths (Combe, Burke and Douglas, 1999), they appear ideal for bonding orthodontic brackets.

2.4 Bond strengths

2.4.1 Bond strength testing protocol

Bond strength testing is normally performed with tension, shear/peel or torsional loads (Katona, 1997). The most popular laboratory strength testing protocols are tensile and shear/peel testing. In the tensile test, the force is applied perpendicular to the cement layer and the bracket is pulled perpendicularly off the substrate (Powers, Kim and Turner, 1997); in the shear test, the force is applied in the plane of the bonding interface cement (Thomas, de Rijk and Evans, 1999). It is impossible to apply a pure shear load to a bracket because of an unavoidable bending moment. The further the applied force is from the tooth, the higher will be the applied moment

(Katona, 1994). When a force is applied in the plane of the bonding interface and at some distance away from the bonding interface, it is referred as a peel force. Torsion loading is less favoured, due to difficulties in their evaluation by most mechanical testing machines. Torsional strength is expressed in units of Newton/m, whereas tensile and shear/peel bond strengths are expressed in MPa. Because the units are different, comparisons between torsional strength and tensile or shear/peel strengths are difficult (Katona, 1997). Also there is no consensus on the test that most realistically duplicates the clinical situation (Katona and Moore, 1994). Retief (1991) concluded that because of the great variations in the test methodologies, the results obtained from different laboratory adhesion tests cannot be compared and those test cannot be extrapolated to the clinical situation. In spite of this limitation, they do serve a useful purpose as screening tests.

Many variables involved in the bond strength testing (such as tooth surface preparation, type of adhesive, bracket material, bracket base design, storage time and conditions before testing, time after bonding, loading rate and loading direction (Fox, McCabe and Buckley, 1994; Katona and Moore, 1994) are frequently neglected, in addition to material thickness and uniformity, location and method of force application and the alignment of the specimen which are often not controlled (Katona, 1997; Thomas, de Rijk and Evans, 1999). This variability impairs comparisons between different studies (Katona, 1994; Katona and Moore, 1994; Katona, 1997).

Despite the inaccuracy of this method as shown by finite element models and non-uniform stress field patterns, the accepted practice in reporting results is to divide the tensile or shear peel force at failure by the surface area of the bracket base (Katona, 1997). However, for practical purposes, the traditional measure of bond strength, (force-to-failure / area of the cement layer), remains a reasonable means of comparing different bonding systems (Katona and Moore, 1997).

2.4.2 Recommended bond strengths in orthodontics

The clinical force to debond a bracket is difficult to measure accurately due to the multiplicity of component stresses. Shear, shear-peel, torsional and tension bond strengths should all be considered when evaluating the minimal clinical bond strength required for orthodontic use. *In vitro* studies have used 6-8 MPa as an acceptable minimal bond strength guide (Reynolds, 1975), but this was not supported by any scientific evaluation. According to Reynolds, 60-80 kg/cm² appeared to be a reasonable value for tensile bond strength of an orthodontic adhesive. He recognized the difficulty for determining such a value clinically due to variable occlusal loads and the magnitude of forces transmitted to the attachment. Subsequently, many authors have used the “minimum reasonable value” suggested by Reynolds as a guide (Withlock III *et al.*, 1994; Bourke and Rock, 1999; Lai, Woods and Tyas, 1999). According to Katona and Moore (1994), there is no consensus regarding the minimum or maximum *in vitro* bond strengths necessary to predict clinical success.

Retief (1974) indicated that enamel fracture can occur with bond strengths as low as 8 MPa, depending on the test setup and also on the integrity of the enamel.

2.5 Bonding to Different Materials

2.5.1 Composite

Few articles could be found on bonding orthodontic attachments to composite resin surfaces. With the increased use of composite restorative materials in general dentistry over the past years, evaluation of the bond strengths to such surfaces is important.

In 1984, Newman, Dressler and Genadier evaluated the ability of silane to bond to ceramic and composite surfaces, *in vitro*. Silane is a coupling agent used for bonding glass fillers into polymer (Newman, Dressler and Genadier, 1984). Twenty meshback metal brackets were bonded to Isosit, a composite resin type of material, with or without silane. The study showed no significant differences between two experimental groups or between the experimental groups and the control group made of meshback metal brackets bonded to enamel using the acid-etch technique ($p > 0.01$). Newman, Dressler and Genadier (1984) concluded that orthodontic brackets can be bonded to the composite restorative material (Isosit) as effectively as they can be bonded to acid-etched enamel by a composite resin bonding system.

Kao *et al.* (1995) evaluated the torsional bond strength of ceramic brackets bonded to composite resin laminate veneers. Four different types of ceramic brackets, with different bonding mechanisms (mechanical, chemical or both) were used (Allure IV NSB, Starfire TMB, Transcend 2000 and Fascination). Brackets were bonded to etched (37% phosphoric acid) microfilled resin veneers (Silux Plus, 3/M) using either a light-cure or a chemically-cured adhesive. The highest bond strength was observed in the brackets which have a combination of mechanical and chemical retention (Fascination and Allure IV). Torsional bond strengths of 60-80 MPa for the chemically-cured adhesive and 70-90 MPa for the light-cured adhesive were observed. There was no significant difference in torsional bond strength between the light-cured and chemically-cured adhesive. Kao *et al.*, (1995) concluded that there were significant interactions among brackets, adhesives, and bonding substrates (composite resin or enamel).

Chunhacheevachaloke and Tyas (1997) evaluated the shear bond strength of ceramic brackets to resin composite surfaces, *in vitro*. Two types of ceramic brackets (polycrystalline and monocrystalline) were bonded to smooth and roughened resin-composite discs (light-cured resin Silux) using a light-cured orthodontic adhesive (Transbond). No significant difference was found between the four experimental groups (mean shear bond strength values of 17.1-19.2 MPa). The results also showed a high rate of resin composite damage on debonding.

Lai, Woods and Tyas (1999) evaluated the bond strengths of orthodontic brackets to resin composite surfaces. The study was design to compare the shear/peel bond strengths of two types of metal brackets (Victory and Optimesh), one type of ceramic bracket (Transcend) and one type of plastic bracket (Spirit MB) bonded to a microfilled resin composite, using either a light-cured resin-modified glass ionomer cement (Fuji ORTHO™ LC), a chemical-cured composite (System 1+) or a light-cured composite adhesive (Transbond™ XT), *in vitro*. Half of the seventy-two specimens of each bracket were thermocycled. Results showed significant differences in mean shear-peel bond strengths for the different bracket varieties. Metal brackets had generally greater bond strengths (10.4-30.1 MPa) than ceramic (10.0-17.2 MPa) and plastic brackets (3.06-10.9 MPa). All groups were found to have clinically acceptable mean bond strengths (over 6MPa) except for Spirit MB-System 1+ after thermocycling (4.09 MPa) and Spirit MB-System 1+ without thermocycling (3.06 MPa). After thermocycling, both Optimesh-Transbond™ XT (26.8 MPa) and Victory-System 1+ (24.4 MPa) showed statistically significant higher mean bond strengths when compared with the other groups. The bond strengths were not influenced by the various bonding systems used within each bracket variety. Lai, Woods and Tyas (1999) also found that resin composite restorative surfaces were damaged in most cases. Most of the groups were not affected by thermocycling.

2.5.2 Enamel

When ceramic brackets first became available, their bond strengths to enamel were often 40 MPa, and this led to lots of tooth damage during debonding. As a result, the manufacturers modified the brackets to reduce their bond strengths to the much lower values we find in today's ceramic brackets.

Many authors have evaluated bond strengths of orthodontic attachments to enamel. Bishara *et al.* (1999) studied the shear bond strength of two types of ceramic brackets (Clarity™, MXi®) bonded to etched enamel using Transbond™ XT adhesive. Clarity™ brackets (10.4 MPa) showed significantly higher bond strengths than MXi® (7.6 MPa) brackets, but both brackets exhibited forces that were acceptable for clinical use. Mundstock *et al.* (1999) also evaluated two types of ceramic brackets (Transcend 6000, 3-M Unitek and Clarity™, 3-M Unitek) bonded to etched enamel with Transbond™ XT. Mean bond strengths for Clarity™ and Transcend 6000 were 13.27 and 21.19 MPa respectively.

Bond strengths of ceramic brackets to enamel have been found to be higher than metal brackets (Ødegaard and Segner, 1988; Harris, Joseph and Rossouw, 1990; Joseph and Rossouw, 1990; Forsberg and Hagberg, 1992; Haydar, Sartkaya and Çehreli, 1999). Joseph and Rossouw (1990) evaluated bond strengths of two types of brackets (metal and ceramic) bonded to etched enamel using two different adhesives (one light-cured resin, Heliosit and one chemically cured resin, Concise) and found

significantly higher bond strengths with ceramic brackets with either the light-cured or chemically cured resin adhesives. The mean bond strengths for ceramic brackets using the light-cured and the chemically cured adhesives were 24.25 and 28.27 MPa respectively and the mean bond strengths for metal brackets were 17.80 and 17.34 MPa respectively. On the other hand, Lai, Woods and Tyas (1999) evaluated shear/peel strengths of metal and ceramic brackets to composite resins with different adhesives (light-cured composite resin adhesive, chemically-cured composite adhesive and resin-modified glass ionomer cements) and found that bond strengths with steel brackets were generally greater (0-50%) than those with ceramic brackets.

Haydar, Sartkaya and Çehreli (1999) evaluated the shear bond strengths of a light-cured composite resin (Transilluminate, Ortho Organizers Inc), a light-cured glass Ionomer (Fuji Ortho LC, GC Corp), and a light-cured compomer (Compoglass, Vivadent Dental) used with metal (Omni arch, GAC) and ceramic brackets (Allure IV, GAC). They found that ceramic brackets had significantly higher bond strengths than metal brackets with any of the adhesives types. The bond strengths range from 8.39 to 20.17 MPa for the ceramic brackets and from 4.32 to 7.06 MPa for the metal brackets.

Forsberg and Hagberg (1992) evaluated the shear bond strengths of two different types of ceramic brackets (Transcend and Trancend 2000, 3-M Unitek) and one type of metal bracket (Ormco, Foil-Mesh) bonded to etched enamel with a composite resin adhesive (Unite, 3-M Unitek). Both types of ceramic brackets showed significantly

higher shear bond strengths ranging from 17.8 to 22.3 MPa in comparison with the metal brackets, 8.4 MPa.

Some authors have shown that ceramic brackets with a chemical bond have significantly higher bond strengths than ceramic and metal brackets with a mechanical bond, but that there were no significant differences between the bond strengths of ceramic brackets with a mechanical bond and metal brackets (Viazis, Cavanaugh and Bevis, 1990; Wang, Meng and Tarng, 1997).

2.5.3 Porcelain

Bonding orthodontic attachments to dental porcelain surfaces has been investigated by many authors. Surface treatments to enhance mechanical retention include abrading with rotary instruments, acid etching, and air abrasion (Nebbe and Stein, 1996; Zachrisson, Zachrisson and Büyükyilmaz, 1996; Bourke and Rock, 1999; Chung *et al.*, 1999). Only one chemical method, priming the porcelain surface with silanes is currently used.

Deglazing is not necessary for adequate bond strengths (Nebbe and Stein, 1996; Bourke and Rock, 1999). Nebbe and Stein (1996) concluded that deglazing does not substantially increase micromechanical retention. According to Bourke and Rock (1999), the use of hydrofluoric acid prior to bonding was found to be unnecessary and that the best regime for orthodontic bonding to a glazed feldspathic porcelain was to

apply 37% phosphoric acid for 60 seconds on a glazed surface (to remove surface contaminants that would prevent the silane from bonding), and prime with silane prior to bonding. Repair of the damaged porcelain has been studied by Kao, Boltz and Johnston (1988) and by Smith, McInnes-Ledoux, Ledoux and Weinberg (1988).

Wood *et al.* (1986) found that roughening of the porcelain, adding porcelain primer, and using highly filled resins all increased the bond strengths but also produced greater porcelain damage on debonding. It was suggested that the use of a highly filled resin on an intact, glazed porcelain surface without using a porcelain primer might provide sufficient bond strength clinically.

In several studies, the use of a silane significantly increased the bond strength of orthodontic attachments to porcelain (Wood *et al.*, 1986; Whitlock III *et al.* 1994; Zachrisson, Zachrisson and Büyükyilmaz 1996; Bourke and Rock, 1999; Chung *et al.*, 1999). On the other hand, Cochran *et al.* (1997) concluded that the use of a silane was not necessary to achieve acceptable clinical bond strengths (6.5 MPa – 17.8 MPa) and that the incidence of porcelain damage was reduced.

2.5.4 Metal

Zachrisson, Büyükyilmaz and Zachrisson (1995) compared the *in vitro* tensile bond strength of orthodontic brackets bonded to a silver amalgam following two different surface treatments (diamond bur vs. sandblasting) with different adhesive systems.

The results showed significantly lower bond strengths of the brackets bonded to amalgam (3.4 to 6.4 MPa), when compared to the bond strength of orthodontic brackets bonded to enamel (13.2 MPa). Sandblasting was more effective than roughening with a diamond bur, but the difference was not statistically significant.

Gross, Foley and Mamandras (1997) tested the bond strengths of metal brackets bonded to amalgam with different resins systems (Concise, 3-M, and C&B Metabond, Parkell) and different surface preparations (sandblasting and sandblasting with Adlloy treatment). Adlloy is a gallium-tin liquid alloy that alters the surface of precious metal restorations to improve bonding with dental adhesives (Gross, Foley and Mamandras, 1997). Results showed no differences in bond strengths when using Concise with either surface preparation; bond strengths ranged from 4.15 to 4.53 MPa. Results showed significant differences when using C&B Metabond; the mean bond strength of brackets bonded with C&B Metabond on a sandblasted metal surface was 8.43 MPa and the mean bond strength of brackets bonded with C&B Metabond on a sandblasted metal surface treated with Adlloy was 13.19 MPa.

Büyükyılmaz, Zachrisson and Zachrisson (1995) studied the bond strengths of metal brackets to gold alloy using two types of adhesives and two types of surface preparations. The two types of adhesive were Concise (3-M Unitek) and Superbond C&B (Sun Medical Co.). The surface preparations consisted of either sandblasting, sandblasting plus tin electroplating or roughening with a diamond bur. Results showed that when using Concise adhesive, surface preparations made no significant

differences and bond strengths ranged from 3.0 to 5.4 MPa. When using Superbond C&B, bond strengths were significantly higher for the groups with the sandblasted surfaces (with or without tin electroplating). The bond strengths ranged from 17.1 to 19.6 MPa as compared to 9.6 MPa for the group that had surfaces roughened with a diamond bur.

Nollie, Foley and McConnell (1997) found that metal brackets bonded to sandblasted gold (3.36 MPa) or Adlloy-treated gold (6.86 MPa) had statistically significant lower bond strengths than metal brackets to etch enamel (11.18 MPa).

2.6 Ceramic Brackets

The first ceramic brackets were introduced into the market in the mid 1980's (Britton *et al.*, 1992; Gibbs, 1992). By 1987, most major orthodontic manufacturers could offer ceramic brackets to orthodontists (Birnie, 1990). This new material had only one major advantage: aesthetics. Their many disadvantages include brittleness, enamel damage during debonding and increased friction during sliding mechanics (Bishara and Fehr, 1997; Omana, Moore and Bagby, 1992).

Different types of ceramic brackets are now available. Some ceramic objects are formed by casting, or by milling. The most commonly used ceramic for orthodontic brackets is aluminum oxide (alumina, Al_2O_3). Zirconia (ZrO_2) is another type of ceramic that has been used. Alumina is strong and offers both good aesthetics and an

excellent chemical resistance. Disadvantages include lack of ductility, low fracture toughness, extreme hardness and a difficult and costly manufacturing process (Birnie, 1990).

2.6.1 Manufacturing process

Two basic types of ceramic brackets are available: These are polycrystalline ceramic and monocrystalline ceramic (Kusy, 1988; Birnie, 1990; Bishara and Fehr, 1997). Monocrystalline brackets are made from molten alumina (synthetic sapphire), which is cooled slowly under very carefully controlled conditions to produce a single crystal alumina. Brackets are then milled into shape from the single crystal. This manufacturing process is difficult and expensive because of the hardness of the material. Polycrystalline brackets are made of fused aluminum oxide particles. The first phase of the process is blending the particles with a binder to form a mixture. The mixture is molded into the required shape. The molded material is heated to allow the binder to burn out and to allow the alumina particles to fuse. This process is called sintering. The shaped material is milled into a bracket and is re-heated to remove surface imperfections and relieve stresses. The disadvantages of this molding process are the presence of structural imperfections and the incorporation of trace amounts of impurities, which can serve as foci for crack propagation under stress. An alternative method is injecting the molten alumina into a bracket mold to eliminate the machining step (Swartz, 1988; Omana, Moore and Bagby, 1992; Birnie, 1990; Bishara and Fehr, 1997).

2.6.2 Physical properties

Ceramic brackets have an extremely high hardness value (range of 2400 to 2450 KHN), which is almost nine times as hard as metal (stainless steel) brackets (approximately 280 KHN) or enamel (354-431 KHN) (Viazis *et al.*, 1990; Collys *et al.*, 1992). Because of their high values, ceramic brackets can cause damage to the teeth (Douglas, 1989; Winchester, 1992; Karamouzos, Athanasiou and Papadopoulos, 1997). Viazis, Cavanaugh and Bevis (1990) demonstrated *in vitro* that visible enamel abrasion from ceramic brackets against teeth can be obtained after only 15 chewing cycles. Because the hardness of the ceramics is so much higher than the metals, nicks can occur in the relatively softer metal arch wires, increasing friction (Bishara and Fehr, 1997).

One of the properties that improves a materials resistance to structural failure is tensile strength. Tensile strength is much greater in monocrystalline alumina than polycrystalline alumina. This property has been used to compare ceramic and metal brackets. According to Scott (1988), it is misleading and may misstate the relative advantages and disadvantages of ceramics and metals because this property should also be related to the surface characteristics of the ceramic. It has been shown that the surface conditions, such as a shallow scratch on the surface of a ceramic, may drastically decrease the load required for fracture (Scott, 1988; Viazis, Nakajima and Kleven, 1993; Karamouzos, Athanasiou and Papadopoulos, 1997). Kusy (1988)

demonstrated that the surface morphology influenced dramatically the fracture toughness, which is the ability of a material to resist fracture. Ceramics are very brittle; as shown in **Figure 2.5**, the elongation for ceramic at failure is less than 1% in contrast with approximately 20% for stainless steel (Scott, 1988). The tensile strength of monocrystalline brackets (1793 MPa) is higher than both polycrystalline (379 MPa) and metal brackets (207-276 MPa) (Birnie, 1990). The fracture toughness of metal brackets (80-95 MPa M) is much higher than monocrystalline (2-4.5 MPa M) and polycrystalline brackets (3-5 MPa M) (Scott, 1988; Birnie, 1990).

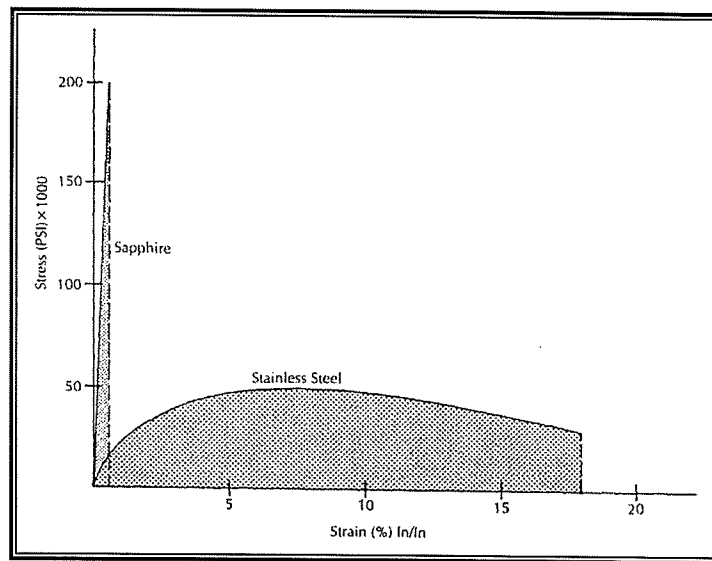


Figure 2.5. Stress-strain curve for sapphire and stainless steel. (From Scott, 1988)

The optical properties of ceramics provide the only advantage over metal brackets (Kusy, 1988; Scott, 1988). According to Bishara and Fehr, (1997), the crystal size of the ceramic influences its opacity. The larger the crystal structure, the more transparent the ceramic is. The impurities introduced during the manufacturing process also result in some degree of opacity.

Both monocrystalline and polycrystalline brackets resist staining and discoloration (Karamouzos, Athanasiou and Papadopoulos, 1997; Olsen, Bishara and Jakobsen, 1997).

2.6.3 Bracket base designs

Aluminum oxide is an inert material and bonding represents a challenge. Several methods of retention for ceramic brackets have been used and can be classified into three groups: mechanical retention, chemical retention using silane, and a combination of both (Bishara and Fehr, 1997; Willems, Carels and Verbeke, 1997). Methods of retention influence bonding properties of the brackets (Guess *et al.*, 1988; Gregory *et al.*, 1992; Bordeaux, Moore and Bagby, 1994; Olsen, Bishara and Jakobsen, 1997). Ceramic brackets can be modified to facilitate mechanical bonding by creating a fitting surface composed of either crystals of the bracket ceramic standing proud or of a surface coated with a layer of either imbedded silica crystals or silica glass beads. Chemical bonding can be achieved by a surface covered with a thin silica glass film and coated with silane, or to facilitate debonding, a surface that has a pad of polycarbonate bonded to it. The silane is used to link the alumina to organic polymers and create a chemical bond between the adhesive and the bracket.

2.6.4 Bonding properties of ceramic brackets

Numerous studies have been conducted on ceramic brackets regarding their bonding properties to different structures or materials, such as enamel (Forsberg and Hagberg, 1992; Bishara, Fehr and Jakobsen, 1993; Viazis, Nakajima and Kleven, 1993; Martin and Garcia-Godoy, 1994), composite resin (Kao *et al.*, 1995; Chunchacheevachaloke and Tyas, 1997; Lai, Woods and Tyas, 1999) and porcelain (Winchester, 1991; Nebbe and Stein, 1996; Bourke and Rock, 1999; Chung *et al.*, 1999). Studies have shown that bonding ceramic brackets to enamel, using a silane coupler, can produce bond strengths up to 29 MPa. Because of the high bond strengths, ceramic bracket debonding can produce some of the following adverse effects: enamel fracture, cracks, porcelain flaking, and pulp irritation (Ostertag *et al.*, 1991; Bishara, Fehr and Jacobsen, 1993; Takla and Shivapuja, 1995; Nebbe and Stein, 1996; Chung *et al.*, 1999; Bishara, 2000).

2.7 Restorative Composite Resins

2.7.1 Overview

Restorative composite resins are widely used in dentistry today. They are used to replace missing tooth structure and modify tooth colour and structure. They are also used in an effort to achieve an “invisible” repair of teeth, replacing unaesthetic metal restorations such as gold or amalgam. Mercury toxicity and environmental concerns

have also led the manufacturers to develop composites as alternatives to amalgam restorations (Craig, 1993).

Historically, silicate restoratives were the first direct aesthetic restorative materials. They were introduced in 1871 and were prepared from an alumina-silica glass powder and a phosphoric acid liquid. The main advantages were aesthetics, albeit for a relatively short period of time, and fluoride release to provide an anticariogenic feature. Disadvantages included a poor biological response, extremely high sensitivity to moisture, dissolution in oral fluids, lack of adequate mechanical properties and loss of translucency (Craig, 1993).

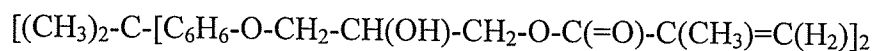
Acrylic restorative resins were introduced shortly after the Second World War. They consisted of unfilled and low molecular weight polymers. Advantages over the silicate materials included lower solubility in oral fluids, lower susceptibility to fracture and higher colour stability. Disadvantages in general were a low resistance to abrasion and a poor dimensional stability resulting in leakage, recurrent carious lesions and discolorations (Craig, 1993).

To improve properties such as a higher resistance to abrasion, a lower coefficient of expansion and a lower dimensional change on wetting, filled resin restorative materials or composites were developed (Craig, 1993). A composite material is defined as a combination of two or more materials, which is designed to have better

properties than the individual components. The dental material “composite” is made of a polymer-ceramic composite (Combe, Burke and Douglas, 1999).

2.7.2 Constituents

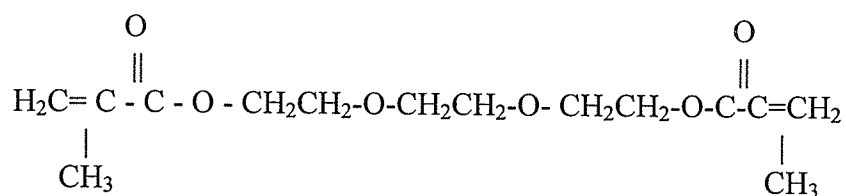
The basic ingredients in composite restorative materials include: Monomers, inorganic fillers, silane coupling agents, polymerization inhibitors, initiator/activator components and ultra violet stabilizers. (Bowen, 1979; Combe, Burke and Douglas, 1999). A widely used monomer, the reaction product of bisphenol-A and glycidyl methacrylate, is called Bis-GMA or Bowen’s resin (developed by Dr. R.L. Bowen) (Combe, Burke and Douglas, 1999). UDMA, urethane dimethacrylate is also used as a monomer (Craig, 1993). To reduce and control the viscosity of the composite, low molecular weight compounds such as triethylene glycol dimethacrylate (TEGMA), are added by the manufacturer (Craig, 1993).



Bis-GMA: 2,2-bis[4(2-hydroxy-3-methacryloyloxy-propyloxy)-phenyl] propane

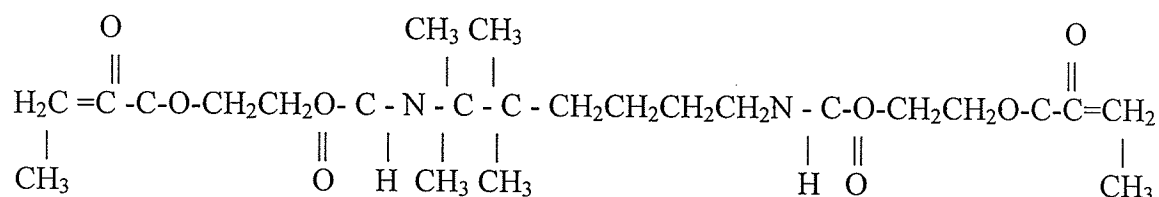
or Bis-GMA or Bowen's resin.

(After Ferracane, 1995)



TEGMA: Triethylene glycol dimethacrylate

(After Combe, Burke and Douglas, 1999)



UDMA: Urethane dimethacrylate

(After Combe, Burke and Douglas, 1999)

Figure 2.6. Chemical Structure of Monomers Used in Dental Composites

Inorganic fillers increase dimensional stability (Bowen, 1979) and vary in types, size and quantity. Fillers may be made of lithium aluminosilicates, crystalline quartz, strontium or zinc glass, barium aluminium silicate, or colloidal silica (Craig, 1993; Combe, Burke and Douglas, 1999). Resin composite materials can be classified by

the particle size: macrofilled, microfilled and hybrid filled. Macrofilled resin composites have particle sizes of 1-35 μm . They are more difficult to polish than the other two types and their surface becomes rougher in service due to the preferential abrasion of the resin matrix. Microfilled resin composites have particle sizes of about 0.04 μm and they have a smoother surface following polishing and wear, weaker mechanical properties and poorer wear resistance than macrofills. Hybrid filled resin composites have particle sizes of 0.5-2 μm and also 0.04 μm to improved polishability, as compared to macrofilled resin composites and they have better wear resistance than microfilled resin composites (Combe, Burke and Douglas, 1999).

For a composite resin to have successful properties, a good bond must form between the inorganic filler and the monomer. To achieve this, the filler is usually treated with a silane, such as γ -methacryoxypropyl trimethoxysilane (Craig, 1993; Combe, Burke and Douglas, 1999). The silane coupling agent mediates the filler-resin adhesion (Bowen, 1979).

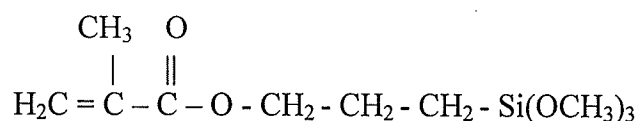


Figure 2.7. Vinyl silane compound (γ -methacryoxypropyl trimethoxysilane).

Polymerization inhibitors such as monomethyl ether of hydroquinone are used to prevent polymerisation on storage (Bowen, 1979; Combe, Burke and Douglas, 1999). Polymerization of composites is achieved by chemical or visible light activation, or a combination of both. Chemical activation can be accomplished by a benzoyl peroxide initiator reacting with a tertiary amine activator (such as N,N-dihydroxyethyl-*p*-toluidine) to form free radicals (Combe, Burke and Douglas, 1999). Light activation is accomplished by irradiating the camphoroquinone initiator with blue light of wavelength 460-485 nm to form free radicals. The free radicals then initiate polymerization and the reaction is accelerated by an amine. (Craig, 1993; Combe, Burke and Douglas, 1999).

Ultra violet stabilizers are incorporated to prevent discoloration of composites in service (Bowen, 1979; Combe, Burke and Douglas, 1999). This improves colour stability. An example of ultra violet stabilizers would be 2-hydroxy-4-methoxybenzophenone (Combe, Burke and Douglas, 1999).

2.7.3 Composite repairs

Bonding fresh resin composite to an “aged” composite has been evaluated in several studies. An “aged” composite refers to an old, previously polymerized and contaminated composite. Composite repairs may be considered for surface discoloration or wear of existing restorations, small areas of recurrent decay along the margins of an “aged” composites and also when complete removal of a very large

composite restoration would jeopardize the health of a tooth (Boushlicher, Reinhardt and Vargas, 1997). Bond strengths of indirect composite restorations to an existing composite can also be evaluated as a composite repair.

Bonding an orthodontic attachment to an “aged” composite can represent a similar challenge. Investigators have shown that bond strengths of a repaired composite can be significantly reduced when interfaces involve an “aged” composite (Boyer, Chan and Reinhardt, 1984; Shiau *et al.*, 1993; Brosh *et al.*, 1997).

A variety of surface treatments have been evaluated in order to achieve satisfactory bond strengths: sanding, air-abrasion, silanization, hydrofluoric acid or phosphoric acid conditioning, low-pressure silicate ceramic deposition, or a combination of these techniques (Shiau *et al.*, 1993; Stokes, Tay and Pereira, 1993; Tate, DeSchepper and Cody, 1992; Boushlicher, Reinhardt and Vargas, 1997). The surface condition of a cured composite significantly affects the bond strength of composite bonded to the surface (Stokes, Tay and Pereira, 1993; Kupiec and Barkmeier, 1996; Brosh *et al.*, 1997). Composite surfaces treated with air-abrasion (50 μ m aluminum oxide) provided high, consistent and reliable bond strengths (Swift *et al.*, 1992; Turner and Meiers, 1993; Latta and Barkmeier, 1994; Brosh *et al.*, 1997).

2.7.4 Water solubility and sorption

The leaching of components from composites resins has a potential impact on the structural stability (Ferracane, 1994), mechanical properties (Pearson, 1979; Söderholm, 1983; Øysæd and Ruyter, 1986; Söderholm, 1990) and the biocompatibility of the material (Thompson, Miller and Bowles, 1982; Ferracane, 1994). Research has shown that cured orthodontic bonding resins are far from being an inert material and considerable quantities of unpolymerized components are leached out by various aqua solution from the cured product, when immerse in water, saliva or 5% ethanol solution (Thompson, Miller and Bowles, 1982). Ferracane (1994) stated that virtually all of the components in dental composites might be leached into solution. Such components include zinc, silicon, barium, strontium and sodium (Söderholm, 1981; Øysæd and Ruyter, 1986; Ferracane, 1994). It has also been shown that monomers (Bis-GMA and/or TEGMA) are eluted from composite when stored in aqueous solution (Inoue and Hayashi, 1982; Thompson, Miller and Bowles, 1982; Pham and Ferracane, 1989; Rathburn *et al.*, 1991; Tanaka *et al.*, 1991).

Solubility of composite resins has been shown to be rapid during the initial period of soaking and slows substantially within hours (Pearson, 1979; Inoue and Hayashi, 1982; Ferracane, 1994). Ferracane and Condon (1990) found that 75% of the elutable species were extracted within several hours. The quantity of the components eluted has been studied by different authors. Weight losses of up to 2% of the mass of the composite have been reported under certain conditions (Ferracane and Condon,

1990). On the other hand, Inoue and Hayashi (1982) determined that only 0.05-0.12% of the original composite weight could be eluted into water over a 14 day period. Pearson and Longman (1989) recorded value of 0.25-0.85% of the initial weight of the composite.

Cattani-Lorente *et al.* (1999) evaluated the effect of water on the physical properties of resin-modified glass ionomer (RMGIC). They tested the physical properties of five commercial RMGIC's and three conventional GIC's stored in either a dry environment, immersed in water or in a humid environment. RMGIC absorbed large amounts of water (114-172 mg/cm³) during the first 24 hours compared to the conventional GIC (30-63 mg/cm³). Water also provoked an expansion in volume of the immersed specimens, ranging from 3.4 to 11.3% after 24 hours. They concluded that RMGIC's were very sensitive to water sorption and that samples kept in contact with water, either in a humid atmosphere or completely immersed, are characterized by a decrease in their physical properties, such as lower flexural strength (20-80%), lower elastic modulus (50 to 80%) and softer surfaces (\approx 50%), as compared to dry samples.

From the preceding, it is apparent that water can alter the properties of both resins and resin-modified glass ionomer materials. Due to the presence of saliva and the ingestion of fluids, water sorption needs to be taken into account when considering orthodontic bonding to composite resins using either a resin or a resin-modified glass ionomer material.

From this review of the literature, it appears that using ceramic brackets is a good esthetic alternative to metal brackets, provided they bond to the teeth and also provided they do not damaged the adherend surfaces. Some of the variables which affect bonding include the type of attachment and adhesive and the nature of the surfaces onto which attachments are bonded.

3. MATERIALS AND METHODS

3.1 Materials used in this study

The materials used in this study, and their manufacturers and batch numbers are shown in Table 3.1.

Materials	Manufacturer	Batch Number
Clarity™ brackets	3M Unitek Monrovia, CA, USA	0194841000
MXi® brackets	TP Orthodontics LaPorte, IN, USA	Unknown
Allure® brackets	GAC Central Islip, NY, USA	0400
Victory Series™ brackets	3M Unitek Monrovia, CA, USA	Unknown
Transbond™ XT light- cured adhesive paste and primer	3M Unitek Monrovia, CA, USA	OEH/OAA
Fuji ORTHO™ LC adhesive	GC America Alsip, IL, USA	9907131
Z100™ composite Shade CG	3M Dental Products St. Paul, MN, USA	20000113

Table 3.1. Materials; manufacturers and batch number

3.1.1 Brackets

Four types of upper central incisor brackets were used in this study. These brackets were chosen because of their relatively flat bonding surfaces, which would adapt well to the flat composite surfaces.

Clarity™ brackets

The Clarity™ bracket (Figure 3.1) is a polycrystalline ceramic bracket made of a brand of aluminum oxide called “Transtar”. The bracket is injection molded and the wire slot is machined out. The base is made of a layer of aluminum oxide particles, which are fused to the base, creating a mechanical retentive layer into which the adhesive can flow. The fracture propagates through this layer when debonding the bracket (Bergstrand, 2001).

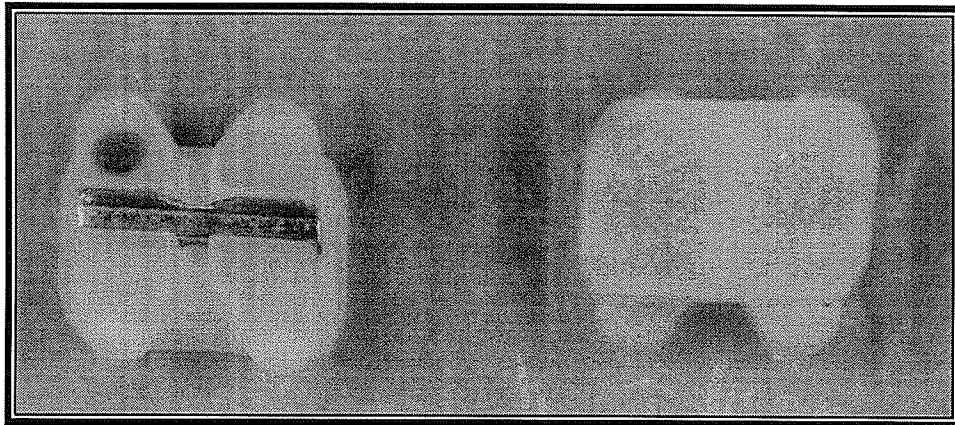


Figure 3.1. Clarity™ brackets

MXi® brackets

The MXi[®] bracket (Figure 3.2) is a polycrystalline ceramic bracket made of 99.9% pure aluminum oxide (Al₂O₃). It is injection molded and sintered. Particles of various sizes are selected to achieve the maximum density and to obtain a high degree of surface smoothness. The manufacturer claims that the MXi[®] bracket achieves superior bond strength through a mechanical interlock (molded mesh backing) and a chemical bond (which has excellent bond strength to adhesives, according to the manufacturer). The MXi[®] bracket base is cast *in situ* from a flexible epoxy resin system, which undergoes plastic deformation during debonding which, according to the manufacturer, generates lower tensile forces. The epoxy base is bonded to the alumina through a porous amorphous glass layer, which is formed integrally on the smooth ceramic surface through a high-temperature sintering process (Devanathan, 1997; Devanathan, 1998; Devanathan, Storer and Schalek, 1998). Figure 3.3 illustrates the bracket structure.

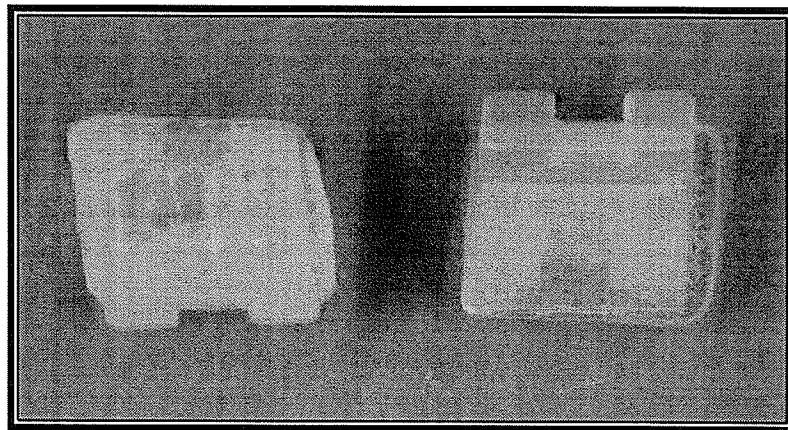


Figure 3.2. MXi[®] brackets

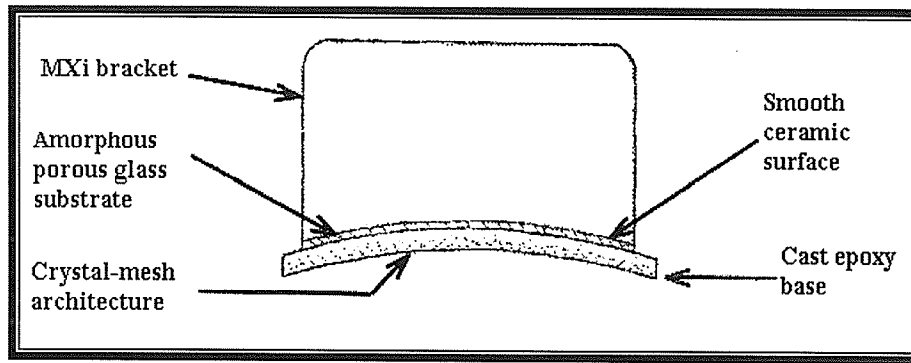


Figure 3.3. Description of the MXi[®] bracket (After Devanathan, 1998)

Allure[®] brackets

The Allure[®] bracket (Figure 3.4) is made of 99.5% Aluminum Oxide (Al₂O₃). The base is treated with silane to provide a chemical bond only. According to the manufacturer, a thermoset acrylic is coated on the bracket base after the silane has been applied to decrease the bond strength, which would be too high otherwise (GAC International, 2001). This thermoset acrylic is inert and heavily cross-linked alleviating bonding. It is important to note that the thermocet acrylic only partially covers the base, shown on the Figure 3.4 as the square more opaque areas.

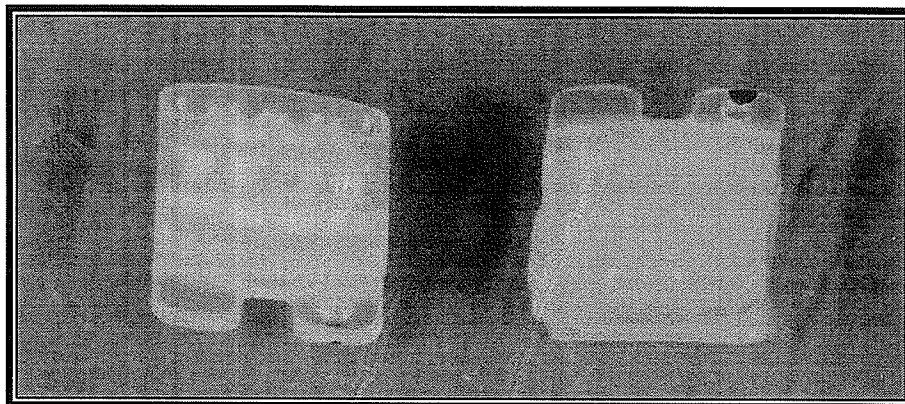


Figure 3.4. Allure[®] brackets
Victory Series™ brackets

The Victory Series™ bracket (Figure 3.5) was used as the control and is a stainless steel bracket with a mesh-foil base providing only mechanical locks.

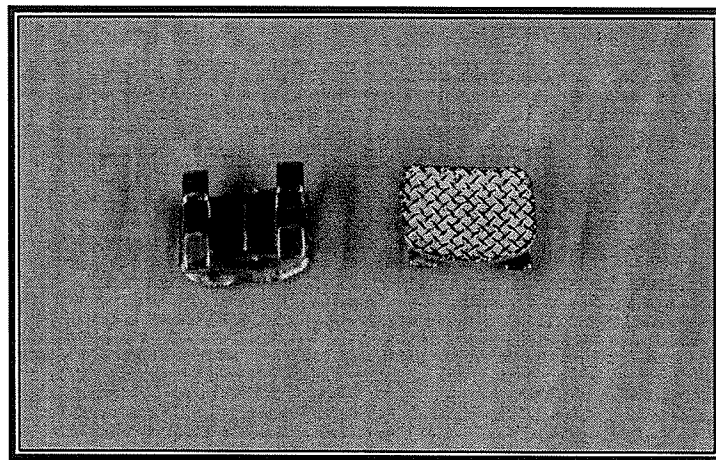


Figure 3.5. Victory Series™ stainless steel brackets

3.1.2 Adhesive systems

The adhesive systems used in this study are shown in Table 3.1

Composite Orthodontic Adhesive System

Transbond™ XT light-cured adhesive paste is a hybrid composite resin. The average particle size is 3 microns, the filler loading is approximately 82 % by weight and the resin base is bisphenol A glycidyl methacrylate (Bis-GMA) and triethyleneglycoldimethacrylate (TEGDMA) in a ratio of 1:1 (Bradburn and Pender, 1992; Material Safety Data Sheets 11938, 1993). The primer is an unfilled resin

composed of 44-54% Bis-GMA and 45-55% TEGDMA (Material Safety Data Sheets 11939, 1993; Lai Woods and Tyas, 1999).

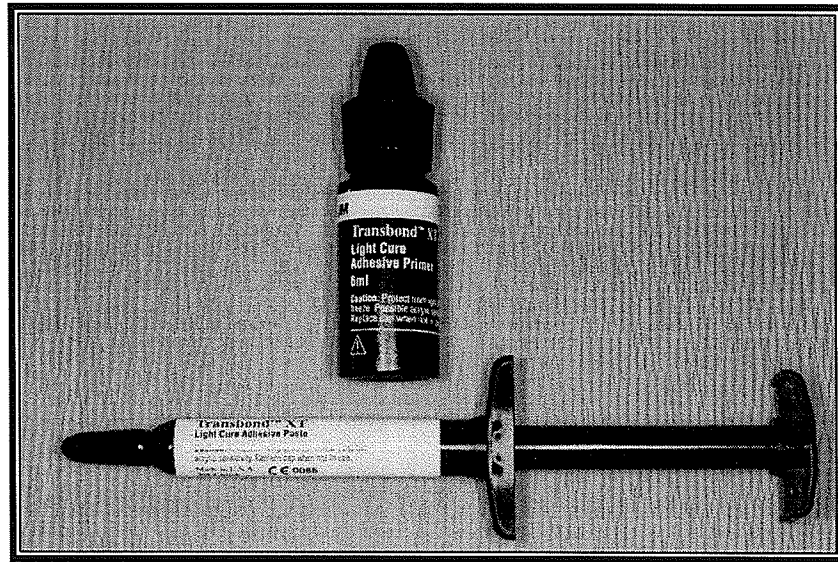


Figure 3.6. Transbond™ XT

Resin Modified Glass Ionomer Cement Adhesive System

Fuji ORTHO™ LC is a light-cured resin-modified glass ionomer cement. Fuji ORTHO™ LC powder is made of 100% alumino-silicate glass (Material Safety Data Sheets 439421, 1997). Fuji ORTHO™ LC liquid is made of polyacrylic acid (20-22%), 2-hydroxyethyl methacrylate (35-40%), 2,2,4, trimethyl hexamethylene dicarbonate (5-7%) and TEGMA (4-6%) (Material Safety Data Sheets 439409, 1997). An example of the Fuji ORTHO LC capsule is shown in Figure 3.7.



Figure 3.7. Fuji ORTHO™ LC

3.1.3 Restorative Resin Composite

Z100™ (Table 3.1 and Figure 3.8) is a light-cured hybrid restorative composite resin. Z100™ composite utilizes Bis-GMA/TEGMA resins, which accounts for 15% of the weight (Ferracane, 1994). Z100™ is heavily filled with zirconia silica fillers in a wide distribution of very small sizes (average particles size = 0.5-0.7 μ m and largest particles = 4 μ m). Z100™ composite is very dense, with fillers accounting for 65-70% by volume of the product (Ferracane, 1995).

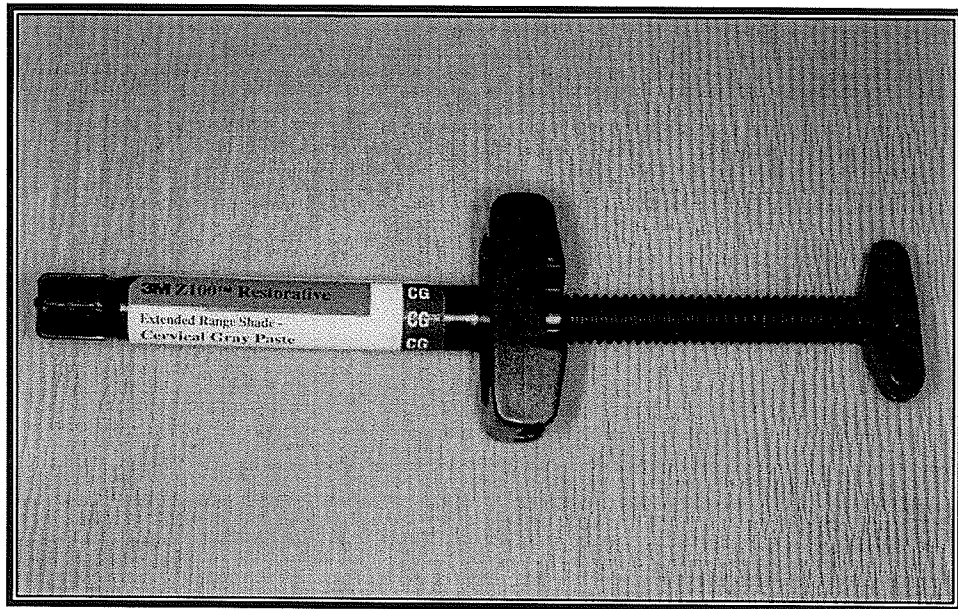


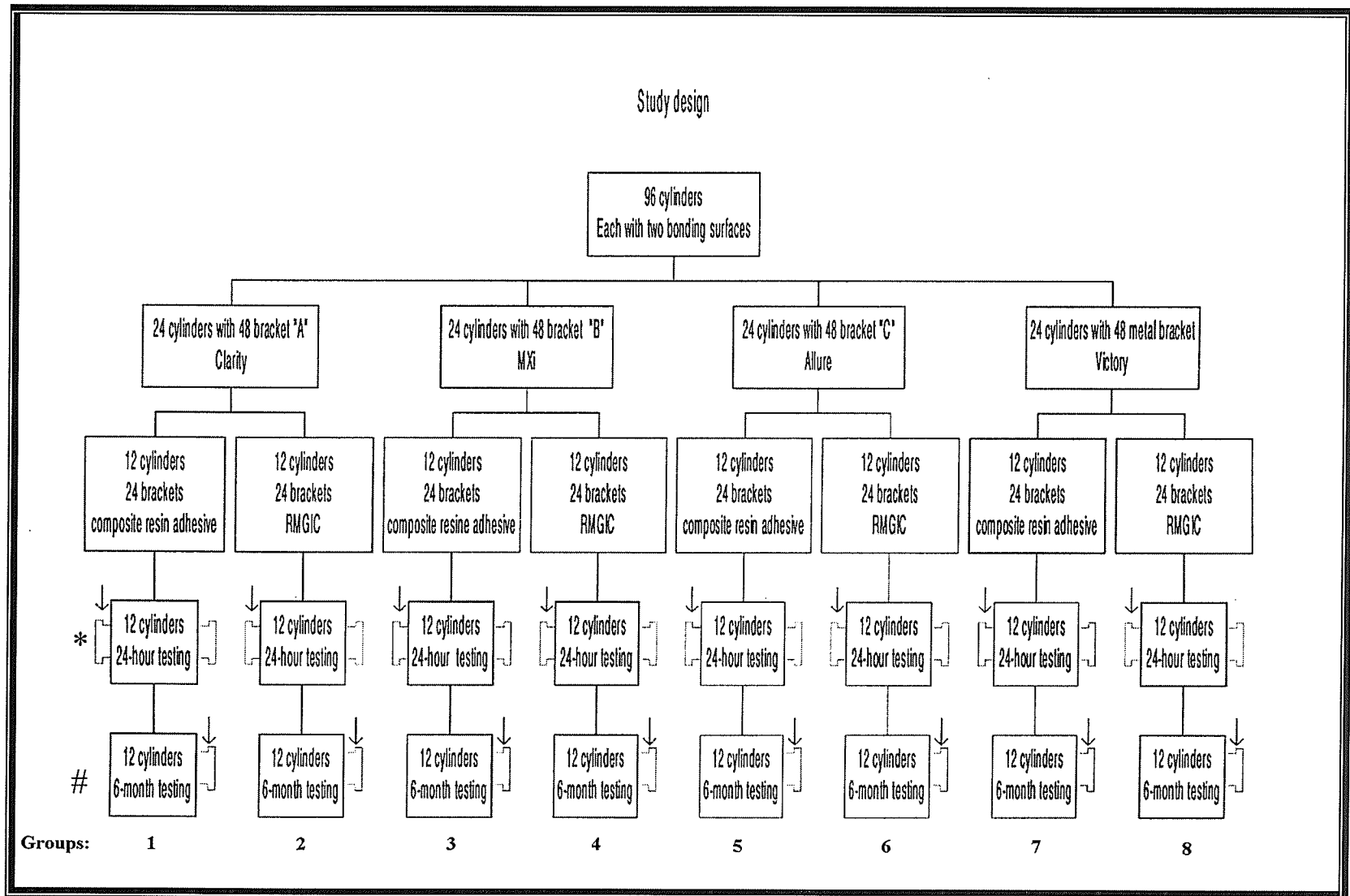
Figure 3.8. Z100™

3.2 Experimental method

3.2.1 Experimental design outline

Figure 3.9 on the following page illustrates an overview of the experimental design.

Figure 3.9. Study design



* Shear-peel testing on one bracket only (at 24 hours)

Shear-peel testing on the remaining bracket (at six months)

3.2.2 Preparation of the composite specimens

The barrel of a disposable 3cc syringe (3mm in diameter) was used as a mould to fabricate composite resin blanks (Figure 3.10). The mould was filled by packing the Z100 composite resin from its dispensing tube directly into the barrel. Care was taken to begin packing at the bottom of the barrel to prevent developing voids in the samples.

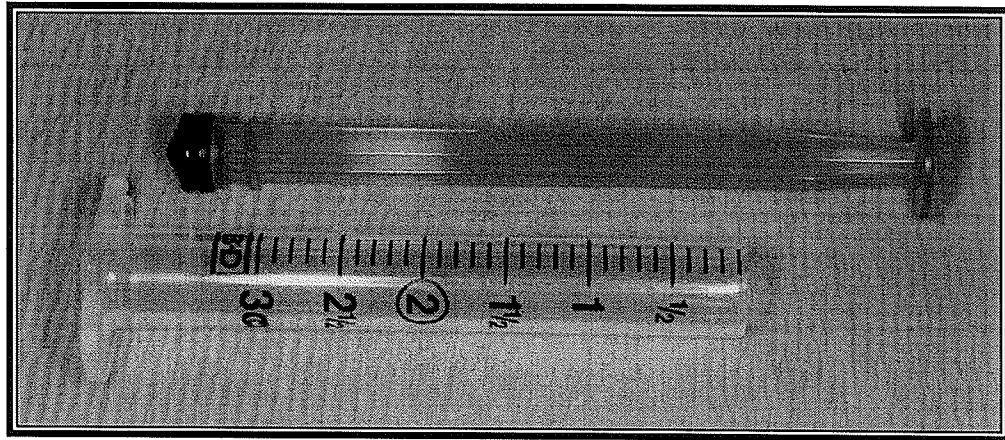


Figure 3.10. Composite resin sample mould

The blanks were light cured with an OrtholuxTM XT (3M Dental Products, St. Paul, MN) light-curing unit as follows: The wand tip was placed in contact with and at right angles to the side of the barrel and the light turned on. The wand tip was slid back and forth at a uniform speed along the entire length of the syringe barrel for 40 seconds. This process was repeated 3 more times, with the barrel rotated $\frac{1}{4}$ turn each time. After removal from the mould, all blanks were light cured in a TriadTM Lightcuring Unit (Dentsply International, York, PA) for an additional 5 minutes to

ensure complete polymerization. The blanks were sliced to form ninety-six (96) cylinders 7mm long (average) samples using a diamond saw blade (Pro-slicer[®], Crystalite Corporation, CA).

Final surface treatment was done by abrading both ends of the composite cylinder with 50 μ m aluminum oxide particles, using an air abrasion device (Microetcher[™], Engineering Inc, Danville, CA) at 80 psi air pressure, at a distance of 5mm and at right angles to the composite surface (Bouschlicher, Reinhardt and Vargas, 1997). Composite surfaces treated with air-abrasion (50 μ m aluminum oxide) provide high, consistent and reliable bond strengths (Swift *et al.*, 1992; Turner and Meiers, 1993; Latta and Barkmeier, 1994; Brosh *et al.*, 1997). The samples were stored in distilled water, at 37°C in an incubator (Thelco, Precision Scientific Co., Chicago, IL), for seven days before starting the bonding procedure to saturate the substrate with water (ISO, 1988).

3.2.3 Surface area of the brackets

The surface areas of 12 randomly selected brackets of each type of brackets were scanned (Duoscan T 1200, Agfa) and saved as picture files on a computer. Using a scientific digital image analysis software (SigmaScan Pro[®], SPSS Inc., Chicago, IL), the surface area of each type of brackets was outlined, calculated and averaged. The surface area was used to calculate the shear-peel bond strength in MPa at bond failure.

3.2.4 Bonding procedures

The ninety-six composite resin cylinders fabricated according to the method described in paragraph 3.2.2 were randomly divided into eight groups of twelve as shown in Figure 3.9. The groups were as follows:

Group #1: Clarity™ brackets bonded to the composite cylinders with Transbond™ XT

Group #2: Clarity™ brackets bonded to the composite cylinders with Fuji ORTHO™ LC

Group #3: MXi® brackets bonded to the composite cylinders with Transbond™ XT

Group #4: MXi® brackets bonded to the composite cylinders with Fuji ORTHO™ LC

Group #5: Allure® brackets bonded to the composite cylinders with Transbond™ XT

Group #6: Allure® brackets bonded to the composite cylinders Fuji ORTHO™ LC

Group #7: Victory Series™ brackets bonded to the composite cylinders with Transbond™ XT (control group)

Group #8: Victory Series™ brackets bonded to the composite cylinders with Fuji ORTHO™ LC (control group)

Each cylinder had one bracket bonded to each end. One bracket was used for the 24-hour evaluation and the other for the 6-month evaluation. This completed sample is shown in Figure 3.14.

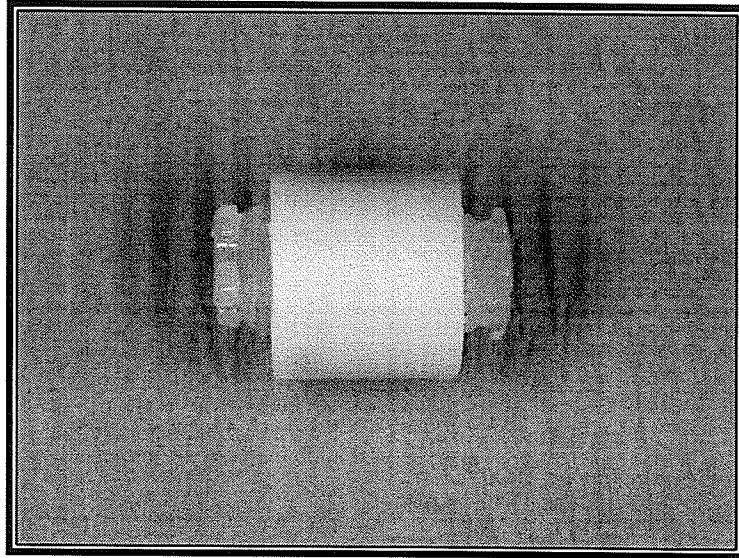


Figure 3.14. Composite resin sample with two brackets

Brackets were bonded to the composite resin cylinders according to the manufacturer's instructions as follows:

Transbond™ XT adhesive: Transbond™ XT Light Cured Adhesive Primer was applied to the dried, sand blasted composite surface, air blown with an air-water syringe to obtain a thin layer, and light-cured for 20 seconds with an Ortholux™ XT (3M Dental Products, St. Paul, MN) light-curing unit. The adhesive was applied to the entire base surface and the bracket was positioned onto the end of the composite

cylinder. Using a periodontal probe in the centre of the bracket, a firm pressure was applied until all excess material was expressed from underneath the bracket. A reported method (Driesen *et al.*, 1989) of seating the attachment on the sample, which consist applying a uniform 500g force measured with a Bencor™ Multi-T testing device to ensure consistency could not be used in this study because of the bracket wing design. If the Bencor device was used, the bracket was displaced laterally because the bracket wings were not perpendicular to the Bencor™ Multi-T testing device when applying the pressure. The method used in this study is justified because it reflected the clinical situation. All excess was thoroughly removed using an explorer under close visual inspection. The specimen was light cured for 40 seconds at right-angles to the bracket.

Fuji ORTHO™ LC capsule: Capsules were used for more consistent mixing results, as recommended by the manufacturer. A new capsule was used for every bracket bonded to the resin composite cylinder. The capsule was tapped on its side 2-3 times on a hard surface (counter top) to loosen the powder. The capsule was then squeezed to allow contact between the powder and the liquid and placed into an amalgamator (Vari-Mix® III, Caulk, Milford, DE) for 10 seconds at high speed. The mixed adhesive was then applied to the entire base surface and the bracket was positioned onto the end of the composite

cylinder and using a periodontal probe in the centre of the bracket, a firm pressure was applied until all excess material expressed from underneath the bracket. The manufacturer's recommendation that no conditioner or primer is to be used on the resin composite surface was followed. All excess adhesive was thoroughly removed using an explorer under close visual inspection. The specimen was light cured with a Visible Light Curing Unit (Ortholux™ XT; 3M Dental Products, St. Paul, MN) for 40 seconds directed at right-angles to the bracket.



Figure 3.15. Ortholux™ XT

3.2.5 Storage conditions

Specimens were stored in distilled water at 37° in an incubator (Thelco, Precision Scientific Co., Chicago, Il,) for 24 hours (ISO, 1994). After the 24-hour storage period, one of the brackets was articulated in the test set-up for testing. Following testing, the samples were stored at 37° for 6 months (minus one day), at which time the 6-month testing on the remaining bracket was performed (ISO, 1994).

3.2.6 Shear-peel bond strength testing

The samples were mounted horizontally in a metal jig (Figure 3.13) and secured with a stabilizing screw. The jig was then mounted in a Bencor™ Multi-T testing apparatus (Danville Engineering, San Ramon, CA) (Figure 3.14-3.15) in a Zwick Universal Testing Machine Model #1445 (Zwick GmbH & Co., Ulm, Germany)(Figure 3.16). The bracket was tested to failure with a straight edge chisel using a 10 Kilo Newton load cell and a 0,5 mm/min crosshead speed (ISO, 1994).

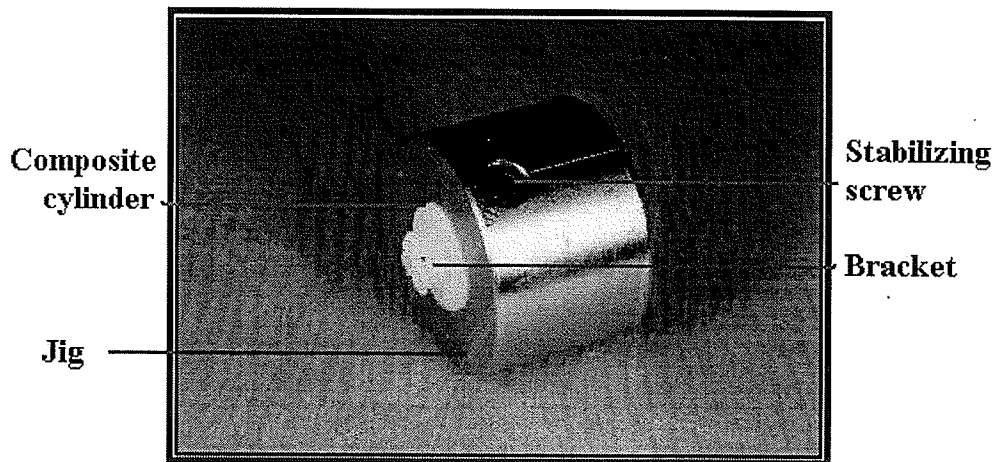


Figure 3.13. Jig

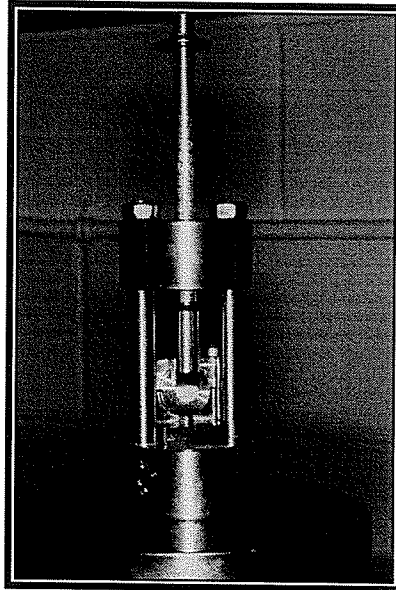


Figure 3.14. Bencor™ Multi-T testing apparatus

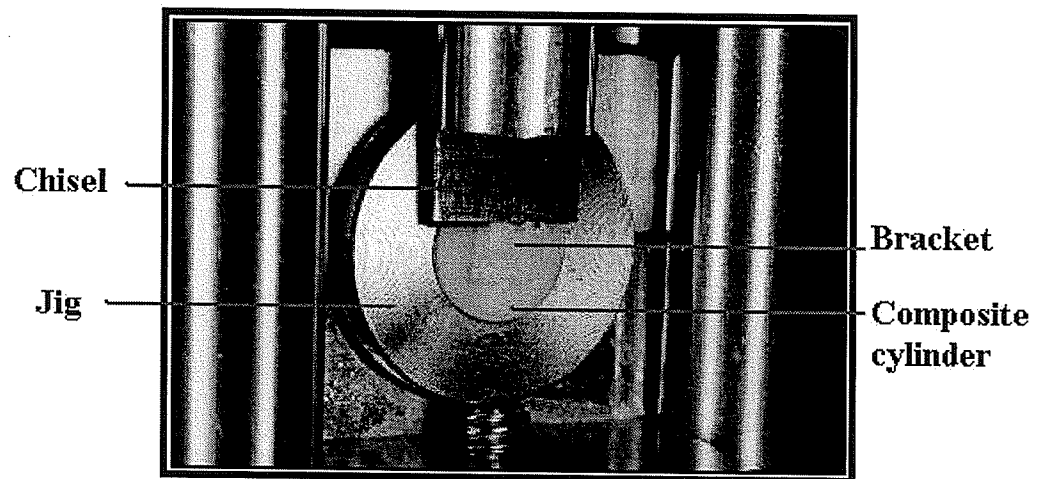


Figure 3.15. Bencor™ Multi-T testing apparatus (close-up)

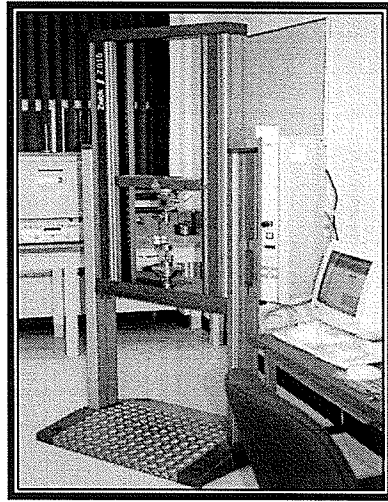


Figure 3.16. Zwick Universal Testing Machine attached to a computer

3.2.7 Site failure evaluation

The composite surfaces and the bracket bases were examined under a binocular microscope at 10x magnification to assess the location of the failure of the fractured interfaces. The site of failure was classified using a modified Adhesive Remnant Index (Årtun and Bergland, 1984) as follows:

Score 0: No adhesive left on composite surface

Score 1: Less than half of the adhesive left on the composite surface

Score 2: More than half of the adhesive left on the composite surface

Score 3: All of the adhesive left on the composite surface with distinct impression of bracket mesh

Score 4: Cohesive fracture of composite resin and no adhesive left on the composite sample

Score 5: Cohesive fracture of composite resin and some adhesive left on the composite sample

A second evaluator randomly examined 20% of the samples to detect possible operator bias or errors.

3.3 Statistical analysis

A Split Unit Analysis of Variance was used to analyse the shear-peel bond strength as a function of bracket type, adhesive type and storage time at a 5% level of significance. A Duncan's multiple comparison test was used to determine where statistically significant differences existed among the different bracket types, adhesive types and storage time (Hassard, 1991). The incidence of composite fracture of the different bracket/adhesive/storage time groups were compared using a Fisher's Exact Test at 0.05 level of significance.

4. RESULTS

4.1 Surface area of the brackets

The surface area of each bracket type was calculated as described in 3.2.3 and the results are shown in Table 4.1.

Bracket type	Mean surface area
Clarity™	14.15 mm ²
MXi®	18.06 mm ²
Allure®	12.38 mm ²
Victory Series™	10.90 mm ²

Table 4.1. Surface area of the brackets

4.2 Shear-peel bond strengths

4.2.1 Twenty-four-hour bond strengths

Individual shear-peel bond strengths of each sample, as well as mean shear-peel bond strengths, maximums, minimums, standard deviations and standard errors for each group are listed in **Tables 4.2-4.9**.

The comparative data for the twenty-four hour mean shear-peel bond strengths and standard deviations are listed in **Table 4.10** and shown graphically in **Figure 4.1**.

The overall highest mean bond strength was obtained by the control group, Victory Series™ stainless steel brackets bonded with Transbond™ XT (23.99 ± 1.82 MPa). No statistically differences could be found between the Victory™/Transbond™ XT group, the Clarity™/Transbond™ XT group (22.71 ± 5.80 MPa) or the Clarity™/Fuji™ ORTHO LC group (20.26 ± 5.99 MPa) at the 5% level of confidence ($p > 0.05$).

The highest mean bond strengths for ceramic brackets were obtained with Clarity™ brackets bonded with either Transbond™ XT (22.71 ± 5.80 MPa) or Fuji ORTHO™ LC (20.26 ± 5.99 MPa). No statistically significant differences could be found between these two groups at the 5% level of confidence ($p > 0.05$).

The lowest mean bond strengths were obtained with MXi® brackets bonded with either Transbond™ XT (6.41 ± 0.82 MPa) or Fuji ORTHO™ LC (12.98 ± 2.91 MPa). The mean bond strength of the MXi®/Transbond™ XT group (6.41 ± 0.82 MPa) was significantly lower than the MXi®/Fuji ORTHO™ LC group (12.98 ± 2.91 MPa) ($p < 0.05$). Mean bond strengths of both groups were statistically lower than any other bracket/adhesive combination at the 5% confidence level ($p < 0.05$).

Allure® brackets bonded with either Transbond™ XT (18.97 ± 4.32 MPa) or Fuji ORTHO™ LC (17.33 ± 4.05 MPa), Victory™ brackets bonded with Fuji ORTHO™ LC (18.31 ± 3.79 MPa) and Clarity™ brackets bonded with Fuji ORTHO™ LC

(20.26 ± 5.99 MPa) had mean bond strengths that were similar in magnitude. No statistically significant differences could be found between these different bracket/adhesive groups at the 5% level of confidence ($p > 0.05$).

No statistically significant differences could be found between the Allure[®]/Transbond[™] group (18.97 ± 4.32 MPa), the Clarity[™]/Fuji[™] group (20.26 ± 5.99 MPa) or the Clarity[™]/Transbond[™] XT group (22.71 ± 5.80 MPa) at the 5% level of confidence ($p > 0.05$).

When the shear-peel bond strengths were analysed as a function of adhesive type, the Transbond[™] XT group (18.02 ± 7.91 MPa) and the Fuji ORTHO[™] LC group (17.22 ± 4.98 MPa) had similar mean bond strength magnitudes. No statistically significant differences could be found between these two groups at 5% level of confidence ($p = 0.34$).

24-hour ClarityTM/TransbondTM Sample #	Shear-Peel Bond Strength in MPa
1	15.62
2	21.77
3	18.46
4	15.26
5	16.19
6	26.38
7	18.29
8	28.67
9	25.80
10	31.28
11	29.27
12	25.58
Minimum	15.26
Maximum	31.28
Mean	22.71
Standard Deviation	5.80
Standard Error	1.67

Table 4.2. 24-hour Shear-Peel Bond Strengths of ClarityTM Brackets Bonded with TransbondTM XT

24-hour Clarity™/Fuji ORTHO™ LC Sample #	Shear-Peel Bond Strength in MPa
1	16.58
2	18.30
3	16.51
4	19.07
5	25.52
6	19.70
7	9.94
8	19.07
9	29.84
10	15.05
11	23.51
12	30.06
Minimum	9.94
Maximum	30.06
Mean	20.26
Standard Deviation	5.99
Standard Error	1.73

Table 4.3. 24-hour Shear-Peel Bond Strengths of Clarity™ Brackets Bonded with Fuji ORTHO™ LC

24-hour MXi[®]/Transbond[™] XT Sample #	Shear-Peel Bond Strength in MPa
1	6.41
2	5.60
3	6.35
4	5.90
5	7.08
6	5.75
7	5.74
8	8.26
9	6.96
10	6.32
11	7.10
12	5.43
Minimum	5.43
Maximum	8.26
Mean	6.41
Standard Deviation	0.82
Standard Error	0.24

Table 4.4. 24-hour Shear-Peel Bond Strengths of MXi[®] Brackets Bonded with Transbond[™] XT

24-hour MXi[®]/Fuji ORTHO[™] LC Sample #	Shear-Peel Bond Strength in MPa
1	13.57
2	14.46
3	12.49
4	12.80
5	15.28
6	6.13
7	15.34
8	12.75
9	12.97
10	12.99
11	17.50
12	9.48
Minimum	6.13
Maximum	17.50
Mean	12.98
Standard Deviation	2.91
Standard Error	0.84

Table 4.5. 24-hour Shear-Peel Bond Strengths of MXi[®] Brackets Bonded with Fuji ORTHO[™] LC

24-hour Allure[®]/Transbond[™] XT Sample #	Shear-Peel Bond Strength in MPa
1	23.63
2	18.8
3	20.67
4	16.5
5	9.95
6	16.88
7	18.69
8	23.42
9	21.41
10	12.75
11	22.52
12	22.44
Minimum	9.95
Maximum	23.63
Mean	18.97
Standard Deviation	4.32
Standard Error	1.25

Table 4.6. 24-hour Shear-Peel Bond Strengths of Allure[®] Brackets Bonded with Transbond[™] XT

24-hour Allure[®]/Fuji ORTHO[™] LC Sample #	Shear-Peel Bond Strength in MPa
1	21.29
2	20.14
3	18.73
4	13.11
5	10.22
6	18.81
7	15.97
8	25.46
9	17.16
10	14.23
11	18.43
12	14.85
Minimum	10.22
Maximum	25.46
Mean	17.33
Standard Deviation	4.05
Standard Error	1.17

Table 4.7. 24-hour Shear-Peel Bond Strengths of Allure[®] Brackets Bonded with Fuji ORTHO[™] LC

24-hour Victory™/Transbond™ XT Sample #	Shear-Peel Bond Strength in MPa
1	25.92
2	24.65
3	26.19
4	22.14
5	23.42
6	23.25
7	24.87
8	20.65
9	23.70
10	25.86
11	25.50
12	21.69
Minimum	20.65
Maximum	26.19
Mean	23.99
Standard Deviation	1.82
Standard Error	0.52

Table 4.8. 24-hour Shear-Peel Bond Strengths of Victory Series™ Brackets Bonded with Transbond™ XT

24-hour Victory™/Fuji ORTHO™ LC Sample #	Shear-Peel Bond Strength in MPa
1	18.31
2	11.38
3	19.30
4	20.59
5	17.53
6	18.01
7	18.30
8	24.92
9	11.50
10	21.52
11	20.06
12	18.32
Minimum	11.38
Maximum	24.92
Mean	18.31
Standard Deviation	3.79
Standard Error	1.10

Table 4.9. 24-hour Shear-Peel Bond Strengths of Victory Series™ Brackets Bonded with Fuji ORTHO™ LC

Bracket/Adhesive group	Shear-Peel Bond Strength (MPa)	Standard Deviation (MPa)	Standard Error
MXi [®] /Transbond [™] XT	6.41	0.82	0.24
MXi [®] /Fuji ORTHO [™] LC	12.98	2.91	0.84
Allure [®] /Fuji ORTHO [™] LC	17.33 ● *	4.05	1.17
Victory [™] /Fuji ORTHO [™] LC	18.31	3.79	1.10
Allure [®] /Transbond [™] XT	18.97 ● *	4.32	1.25
Clarity [™] /Fuji ORTHO [™] LC	20.26 ● *	5.99	1.73
Clarity [™] /Transbond [™] XT	22.71 ● *	5.80	1.67
Victory [™] /Transbond [™] XT	23.99 ● *	1.82	0.52

* Groups joined by a vertical line showed no statistical differences in their mean bond strengths at 95% confidence level

Table 4.10. Comparative Data for 24-Hour Bond Strengths

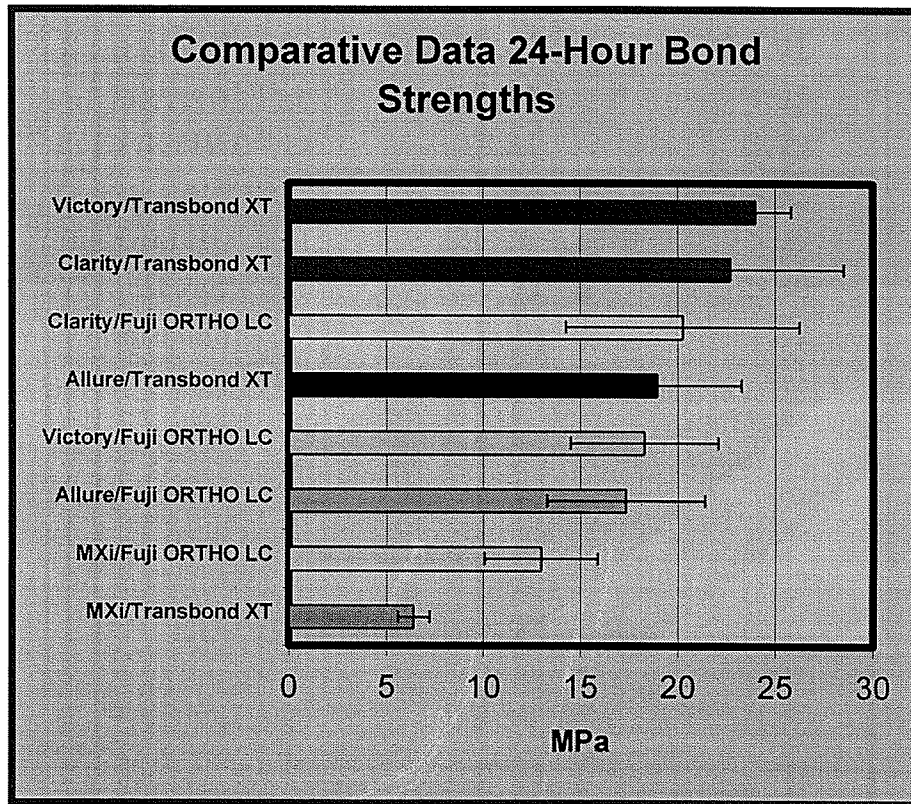


Figure 4.1. Comparative Data for 24-Hour Bond Strengths

4.2.2 Six-month bond strengths

Individual shear-peel bond strengths of each sample, as well as mean shear-peel bond strengths, maximums, minimums, standard deviations and standard errors for each group are listed in **Tables 4.11-4.18**. The comparative data for the 6-month mean shear-peel bond strengths and standard deviations are listed in **Table 4.19** and shown graphically in **Figure 4.2**.

The overall highest mean bond strength was obtained by the control group, Victory Series™ stainless steel brackets bonded with Transbond™ XT (26.42 ± 2.4 MPa). The mean bond strength of the Victory™/Transbond™ XT group was significantly greater than all other bracket/adhesive groups, at 5% level of confidence ($p < 0.001$).

The highest mean bond strengths for ceramic brackets were obtained with Clarity™ brackets bonded with Transbond™ XT (20.42 ± 4.63 MPa). The mean bond strength of the Clarity™/Transbond™ XT group was significantly greater than all other ceramic bracket/adhesive groups, at 5% level of confidence ($p < 0.001$).

The lowest mean bond strengths were obtained with MXi® brackets bonded with Transbond™ XT (6.42 ± 2.32 MPa) and with Allure® brackets bonded with Fuji ORTHO™ LC (6.73 ± 3.33 MPa). No statistically differences could be found between these two bracket/adhesive groups at 5% level of confidence ($p > 0.05$).

MXi[®] brackets bonded with Fuji ORTHO[™] LC (13.32 ± 1.47 MPa), Allure[®] brackets bonded with Transbond[™] XT (14.01 ± 6.43 MPa) and Clarity[™] brackets bonded with Fuji ORTHO[™] LC (14.91 ± 7.10 MPa) had mean bond strengths that were similar in magnitude. No statistically significant differences could be found between these different bracket/adhesive groups at 5% level of confidence ($p > 0.05$).

When the shear-peel bond strengths were analysed as a function of adhesive type, the highest mean bond strengths was obtained in the Transbond[™] XT group (16.82 ± 8.59 MPa). The mean bond strengths of the Transbond[™] XT group was significantly greater than the Fuji ORTHO[™] LC group (13.81 ± 6.36 MPa) at 5% level of confidence ($p < 0.05$), although their magnitudes were similar.

6-month ClarityTM/TransbondTM Sample #	Shear-Peel Bond Strength in MPa
1	19.06
2	24.37
3	20.63
4	17.45
5	21.97
6	16.00
7	20.64
8	16.88
9	28.93
10	12.63
11	19.60
12	26.87
Minimum	12.63
Maximum	28.93
Mean	20.42
Standard Deviation	4.63
Standard Error	1.34

Table 4.11. 6-month Shear-Peel Bond Strengths of ClarityTM Brackets Bonded with TransbondTM XT

6-month Clarity™/Fuji ORTHO™ LC Sample #	Shear-Peel Bond Strength in MPa
1	13.33
2	18.00
3	7.24
4	24.68
5	22.18
6	12.99
7	9.39
8	12.51
9	28.16
10	11.51
11	14.41
12	4.53
Minimum	4.53
Maximum	28.16
Mean	14.91
Standard Deviation	7.10
Standard Error	2.05

Table 4.12. 6-month Shear-Peel Bond Strengths of Clarity™ Brackets Bonded with Fuji ORTHO™ LC

6-month MXi[®]/Transbond[™] XT Sample #	Shear-Peel Bond Strength in MPa
1	5.36
2	4.23
3	9.21
4	5.90
5	8.46
6	11.60
7	7.21
8	4.05
9	5.31
10	4.37
11	4.86
12	6.46
Minimum	4.05
Maximum	11.60
Mean	6.42
Standard Deviation	2.32
Standard Error	0.67

Table 4.13. 6-month Shear-Peel Bond Strengths of MXi[®] Brackets Bonded with Transbond[™] XT

6-month MXi[®]/Fuji ORTHO[™] Sample #	Shear-Peel Bond Strength in MPa
1	14.51
2	11.86
3	13.10
4	13.84
5	11.50
6	15.30
7	14.28
8	15.13
9	11.32
10	14.26
11	13.36
12	11.39
Minimum	11.32
Maximum	15.30
Mean	13.32
Standard Deviation	1.47
Standard Error	0.43

Table 4.14. 6-month Shear-Peel Bond Strengths of MXi[®] Brackets Bonded with Fuji ORTHO[™] LC

6-month Allure[®]/Transbond[™] Sample #	Shear-Peel Bond Strength in MPa
1	10.96
2	18.18
3	9.79
4	8.46
5	2.50
6	16.71
7	12.70
8	18.25
9	15.49
10	17.13
11	10.06
12	27.87
Minimum	2.50
Maximum	27.87
Mean	14.01
Standard Deviation	6.43
Standard Error	1.86

Table 4.15. 6-month Shear-Peel Bond Strengths of Allure[®] Brackets Bonded with Transbond[™] XT

6-month Allure[®]/Fuji ORTHO[™] LC Sample #	Shear-Peel Bond Strength in MPa
1	5.39
2	10.65
3	12.70
4	10.60
5	6.16
6	6.07
7	3.78
8	4.58
9	4.44
10	3.11
11	3.29
12	9.93
Minimum	3.11
Maximum	12.70
Mean	6.73
Standard Deviation	3.33
Standard Error	0.96

Table 4.16. 6-month Shear-Peel Bond Strengths of Allure[®] Brackets Bonded with Fuji ORTHO[™] LC

6-month Victory™/Transbond™ XT Sample #	Shear-Peel Bond Strength in MPa
1	23.25
2	28.72
3	25.87
4	24.10
5	25.56
6	26.30
7	28.05
8	27.58
9	26.04
10	30.62
11	28.42
12	22.47
Minimum	22.47
Maximum	30.62
Mean	26.42
Standard Deviation	2.40
Standard Error	0.69

Table 4.17. 6-month Shear-Peel Bond Strengths of Victory Series™ Brackets Bonded with Transbond™ XT

6-month Victory™/Fuji ORTHO™ LC Sample #	Shear-Peel Bond Strength in MPa
1	21.27
2	21.15
3	26.88
4	19.15
5	17.71
6	22.88
7	21.43
8	19.17
9	18.28
10	19.10
11	19.16
12	17.19
Minimum	17.19
Maximum	26.88
Mean	20.28
Standard Deviation	2.67
Standard Error	0.77

Table 4.18. 6-month Shear-Peel Bond Strengths of Victory Series™ Brackets Bonded with Fuji ORTHO™ LC

Bracket/Adhesive Group	Shear-Peel Bond Strength (MPa)	Standard Deviation (MPa)	Standard Error
MXi [®] /Transbond [™] XT	6.42 ● *	2.32	0.67
Allure [®] /Fuji ORTHO [™] LC	6.73 ●	3.33	0.96
MXi [®] /Fuji ORTHO [™] LC	13.32 ● *	1.47	0.43
Allure [®] /Transbond [™] XT	14.01 ●	6.43	1.86
Clarity [™] /Fuji ORTHO [™] LC	14.91 ●	7.10	2.05
Victory [™] /Fuji ORTHO [™] LC	20.28 ● *	2.67	0.77
Clarity [™] /Transbond [™] XT	20.42 ●	4.63	1.34
Victory [™] /Transbond [™] XT	26.42	2.40	0.69

* Groups joined by a vertical line showed no statistical differences in their mean bond strengths at the 95% confidence level

Table 4.19. Comparative Data for 6-month Bond Strengths

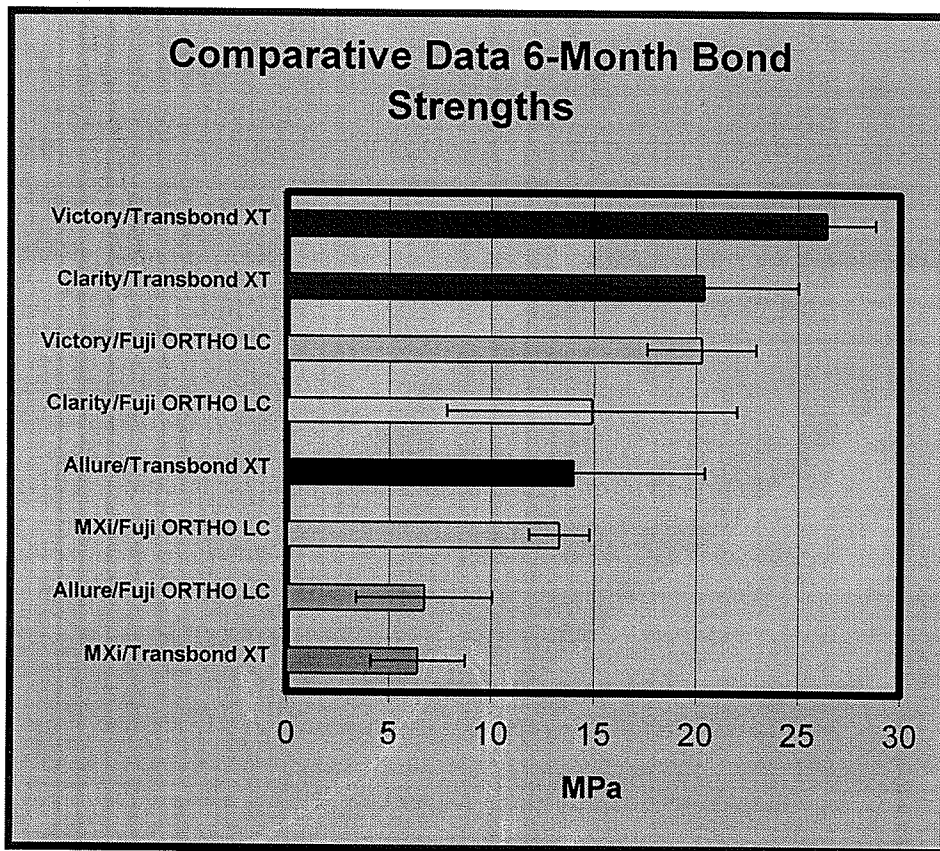


Figure 4.2. Comparative Data for 6-month Bond Strengths

4.2.3 Twenty-four-hour vs. six-month bond strengths

The comparative data for the 24-hour and 6-month mean shear-peel bond strengths and standard deviations are listed in **Table 4.20-4.21** and are graphically shown in **Figure 4.3**. Mean shear-peel bond strengths, standard deviations and standard errors for each bracket type group are listed in **Tables 4.22-4.25**.

The mean bond strengths decreased over time by 61.1% for the Allure[®] brackets bonded with Fuji ORTHO[™] LC (17.33 ± 4.05 MPa vs. 6.73 ± 3.33 MPa), by 26.4% for the Clarity[™] brackets bonded with Fuji ORTHO[™] LC (20.26 ± 5.99 MPa vs. 14.91 ± 7.10 MPa), by 26.1% for the Allure[®] brackets bonded with Transbond[™] XT (18.97 ± 4.32 MPa vs. 14.01 ± 6.43 MPa), and by 10.1% for the Clarity[™] brackets bonded with Transbond[™] XT (22.71 ± 5.80 MPa vs. 20.42 ± 4.63 MPa).

The mean bond strengths increased over time by 0.2% for the MXi[®] brackets bonded with Transbond[™] XT (6.41 ± 0.82 MPa vs. 6.42 ± 2.32 MPa), by 2.6% for the MXi[®] brackets bonded with Fuji ORTHO[™] LC (12.98 ± 2.91 MPa vs. 13.32 ± 1.47 MPa), by 10.1% for the Victory Series[™] brackets bonded with Transbond[™] XT (23.99 ± 1.82 MPa vs. 26.42 ± 2.40 MPa) and by 10.8% for the Victory Series[™] brackets bonded with Fuji ORTHO[™] LC (18.31 ± 3.79 MPa vs. 20.28 ± 2.67 MPa).

The bond strengths measured at 24 hours and 6 months were found to be significantly different ($p < 0.05$) for the Allure[®] brackets bonded with Fuji ORTHO[™] LC (17.33 ± 4.05 MPa vs. 6.73 ± 3.33 MPa), the Clarity[™] brackets bonded with Fuji ORTHO[™] LC (20.26 ± 5.99 MPa vs. 14.91 ± 7.10 MPa), the Allure[®] brackets bonded with Transbond[™] XT (18.97 ± 4.32 MPa vs. 14.01 ± 6.43 MPa), and the Victory Series[™] brackets bonded with Transbond[™] XT (23.99 ± 1.82 MPa vs. 26.42 ± 2.40 MPa).

When the bond strengths were analysed as a function of the adhesive type, the 6-month mean bond strengths of the brackets bonded with Fuji ORTHO[™] LC (13.81 ± 6.36 MPa) were significantly lower than the 6-month mean bond strengths of the brackets bonded with Transbond[™] XT (16.82 ± 8.59 MPa), the 24-hour mean bond strengths of the brackets bonded with Fuji ORTHO[™] LC (17.22 ± 4.98 MPa) or the 24-hour mean bond strengths of the brackets bonded with Transbond[™] XT (18.02 ± 7.91 MPa) ($p < 0.05$). However, the mean bond strengths of the Transbond[™] XT/6-month group, the Fuji ORTHO[™] LC/24-hour group and the Transbond[™] XT/24-hour group were not statistically different ($p > 0.05$).

Bond strengths were also analysed for the different bracket types.

MXi[®] brackets

The mean bond strengths of the MXi[®] brackets bonded with Transbond[™] XT at either 24 hours (6.41 ± 0.82 MPa) or 6 months (6.42 ± 2.32 MPa) was significantly lower than the mean bond strengths of the MXi[®] brackets bonded with Fuji

ORTHO™ LC at either 24 hours (12.98 ± 2.91 MPa) or 6 months (13.32 ± 1.47 MPa) ($p < 0.05$). The mean bond strengths of the MXi® brackets bonded with Transbond™ XT at either 24 hours (6.41 ± 0.82 MPa) or 6 months (6.42 ± 2.32 MPa) showed no significant differences ($p > 0.05$). The mean bond strengths of the MXi® brackets bonded with Fuji ORTHO™ LC at 24 hours (12.98 ± 2.91 MPa) were significantly lower than the mean bond strengths of the MXi® brackets bonded with Fuji ORTHO™ LC at 6 months (13.32 ± 1.47 MPa) ($p < 0.05$).

Allure brackets

The mean bond strengths of the Allure® brackets bonded with Fuji ORTHO™ LC at 6 months (6.73 ± 3.33 MPa) were significantly lower than the Allure® brackets bonded with Transbond™ XT at 6 months (14.01 ± 6.43 MPa), the Allure® brackets bonded with Fuji ORTHO™ LC at 24 hours (17.33 ± 4.05 MPa) and Allure brackets bonded with Transbond™ XT at 24 hours (18.97 ± 4.32 MPa) ($p < 0.05$). The highest mean bond strengths were obtained with the Allure brackets bonded with Transbond™ XT at 24 hours (18.97 ± 4.32 MPa). However, there were no significant differences between the mean bond strengths of the Allure® brackets bonded with Transbond™ XT at 24 hours (18.97 ± 4.32 MPa) and the Allure® brackets bonded with Fuji ORTHO™ LC at 24 hours (17.33 ± 4.05 MPa) ($p > 0.05$).

Clarity™

The mean bond strengths of the Clarity™ brackets bonded with Fuji ORTHO™ LC at 6 months (14.91 ± 7.10 MPa) were significantly lower than the Clarity™ brackets

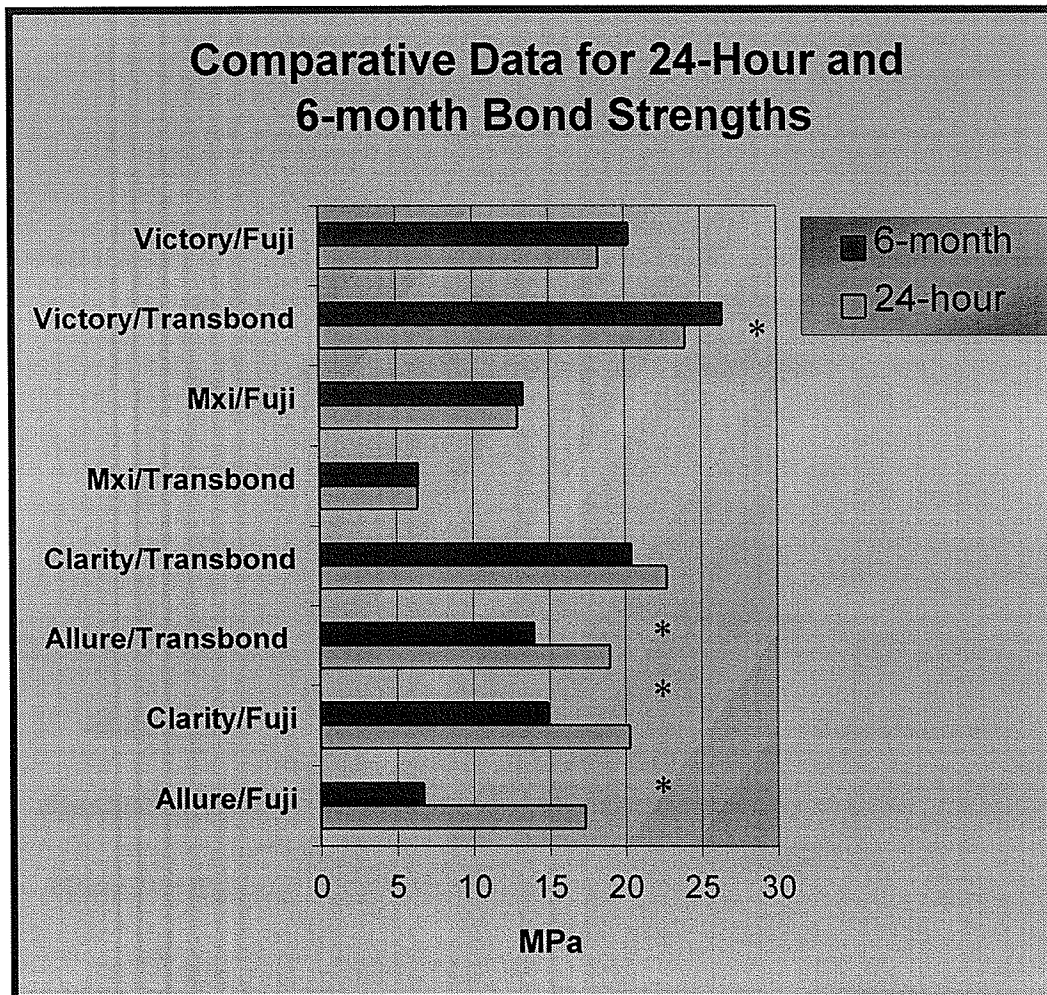
bonded with Fuji ORTHO™ LC at 24 hours (20.26 ± 5.99 MPa), the Clarity™ brackets bonded with Transbond™ XT at either 24 hours (22.71 ± 5.80 MPa) or 6 months (20.42 ± 4.63 MPa). However, there were no significant differences in the mean bond strengths of the Clarity™ brackets bonded with Fuji ORTHO™ LC at 24 hours, the Clarity™ brackets bonded with Transbond™ XT at either 24 hours or 6 months ($p > 0.05$).

Victory Series™

The mean bond strengths of the Victory Series™ brackets bonded with Fuji ORTHO™ LC at either 24 hours (18.31 ± 3.79 MPa) or 6 months (20.28 ± 2.67 MPa) were significantly lower than the Victory Series™ brackets bonded with Transbond™ XT at either 24 hours (23.99 ± 1.82 MPa) or 6 months (26.42 ± 2.40 MPa). However, there were no significant differences in the mean bond strengths of the Victory Series™ brackets bonded with Fuji ORTHO™ LC at either 24 hours or 6 months. On the other hand, the mean bond strengths of the Victory Series™ brackets bonded with Transbond™ XT at 24 hours were significantly lower than the Victory Series™ brackets bonded with Transbond™ XT at 6 months ($p < 0.05$).

Bracket/Adhesive Group	Time	Shear/peel bond strengths in MPa	Standard deviation	% change
Allure[®]/Fuji ORTHO[™] LC	24-hour	17.33	4.05	
	6-month	6.73	3.33	-61.1%
Clarity[™]/Fuji ORTHO[™] LC	24-hour	20.26	5.99	
	6-month	14.91	7.10	-26.4%
Allure[®]/Transbond[™] XT	24-hour	18.97	4.32	
	6-month	14.01	6.43	-26.1%
Clarity[™]/Transbond[™] XT	24-hour	22.71	5.80	
	6-month	20.42	4.63	-10.1%
MXi[®]/Transbond[™] XT	24-hour	6.41	0.82	
	6-month	6.42	2.32	+0.2%
MXi[®]/Fuji ORTHO[™] LC	24-hour	12.98	2.91	
	6-month	13.32	1.47	+2.6%
Victory[™]/Transbond[™] XT	24-hour	23.99	1.82	
	6-month	26.42	2.40	+10.1%
Victory[™]/Fuji ORTHO[™] LC	24-hour	18.31	3.79	
	6-month	20.28	2.67	+10.8%

Table 4.20. Comparative Data for 24-hour and 6-month Bond Strengths



* Groups that showed statistical significant differences in their mean bond strengths between 24-hour and 6-month testing ($p < 0.05$).

Figure 4.3. Comparative Data for 24-hour and 6-month Bond Strengths

Adhesive/Time group	Shear-Peel Bond Strength (MPa)	Standard Deviation (MPa)	Standard Error
Fuji ORTHO™ LC/6-month	13.81	6.36	0.92
Transbond™ XT/6-month	16.82 ● *	8.59	1.24
Fuji ORTHO™ LC/24-hour	17.22	4.98	0.72
Transbond™ XT/24-hour	18.02 ●	7.91	1.14

* Groups joined by a vertical line showed no statistical differences in their mean bond strengths at 95% confidence level

Table 4.21. Comparative data as a function of Adhesive type/Time of debonding

MXi® bracket Adhesive/Time group	Shear-Peel Bond Strength (MPa)	Standard Deviation (MPa)	Standard Error
Transbond™ XT/24-hour	6.41 ● *	0.82	0.02
Transbond™ XT/6-month	6.42 ●	2.32	0.67
Fuji ORTHO™ LC/6-month	12.98 ● *	2.91	0.84
Fuji ORTHO™ LC/24-hour	13.32 ●	1.47	0.43

* Groups joined by a vertical line showed no statistical differences in their mean bond strengths at 95% confidence level

Table 4.22. Comparative data for the MXi® brackets group

Allure® bracket Adhesive/Time group	Shear-Peel Bond Strength (MPa)	Standard Deviation (MPa)	Standard Error
Fuji ORTHO™ LC/6-month	6.73	3.33	0.96
Transbond™ XT/6-month	14.01 ● *	6.43	1.86
Fuji ORTHO™ LC/24-hour	17.33 ● ● *	4.05	1.17
Transbond™ XT/24-hour	18.97 ●	4.32	1.25

* Groups joined by a vertical line showed no statistical differences in their mean bond strengths at 95% confidence level

Table 4.23. Comparative data for the Allure brackets group

Clarity™ bracket Adhesive/Time group	Shear-Peel Bond Strength (MPa)	Standard Deviation (MPa)	Standard Error
Fuji ORTHO™ LC/6-month	14.91	7.10	2.05
Fuji ORTHO™ LC/24-hour	20.26 ● *	5.99	1.73
Transbond™ XT/6-month	20.42	4.63	1.34
Transbond™ XT/24-hour	22.71 ●	5.80	1.67

* Groups joined by a vertical line showed no statistical differences in their mean bond strengths at 95% confidence level

Table 4.24. Comparative data for the Clarity™ brackets group

Victory Series™ Adhesive/Time group	Shear-Peel Bond Strength (MPa)	Standard Deviation (MPa)	Standard Error
Fuji ORTHO™ LC/24-hour	18.31 ● *	3.79	1.10
Fuji ORTHO™ LC/6-month	20.28 ●	2.67	0.77
Transbond™ XT/24-hour	23.99	1.82	0.52
Transbond™ XT/6-month	26.42	2.40	0.69

* Groups joined by a vertical line showed no statistical differences in their mean bond strengths at 95% confidence level

Table 4.25. Comparative data for the Victory Series™ brackets group

4.2.4 Adhesive Remnant Index (ARI) Scores – modified

The adhesive remnant index scores calculated for each bracket/adhesive group at 24 hour and six month are listed in **Tables 4.26-4.29**. Typical debonds at the composite resin /adhesive junction are shown in **Figure 4.4-4.7**.

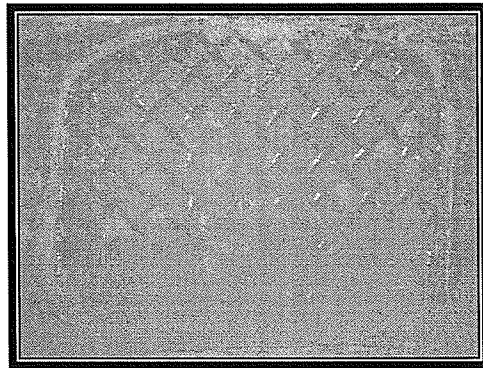


Figure 4.4. Typical debond at the resin composite/adhesive junction with an ARI score of 2 (More than half of the adhesive remained on the composite resin surface).

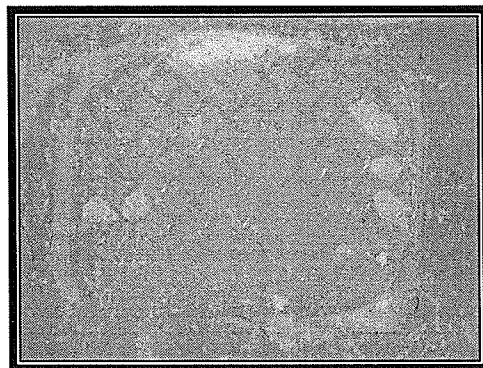


Figure 4.5. Typical debond at the resin composite/adhesive junction with an ARI score of 3 (100% of the composite remained on the composite resin surface with distinct impression of bracket mesh).

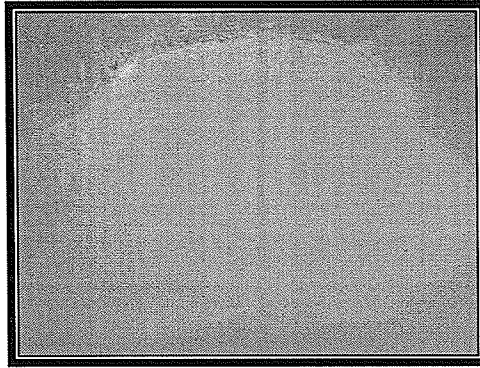


Figure 4.6. Typical debond at the resin composite/adhesive junction with an ARI score of 4 (Cohesive fracture of composite resin and no adhesive left on the composite surface).

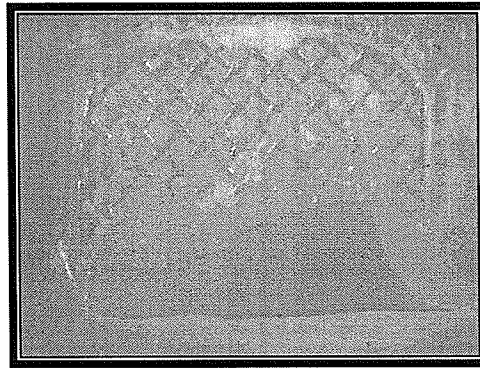


Figure 4.7. Typical debond at the resin composite/adhesive junction with an ARI score of 5 (Cohesive fracture of composite resin and some adhesive left on the composite surface).

Overall, the most common type of debond was score 3, in which all the adhesive remained on the composite resin surface. This occurred in 141 of the 192 tested samples (73.4%). The second most common type of debond was score 2, in which more than 50% and less than 100% of the adhesive remained on the composite resin surface. This occurred in 30 samples (15.6%). The third most common type of debond was a score 5, in which composite resin fracture was noted but with some adhesive remaining on the composite surface. This occurred in 16 samples (8.3%) and

all but four (4) occurred when the Victory brackets were used (eleven (11) at six months and one (1) at 24 hours). The least common type of debond was score 4, in which composite resin fracture was noted without any adhesive left on the composite resin sample. This type of failure occurred in five samples (2.6%). Results are listed in **Table 4.30** and **Figure 4.8**.

At the 24-hour testing, 68 of the 96 tested sample were given a score of 3 (70.8%), 26 samples were given a score of 2 (27.1%) and two samples were given a score of 5 (2.1%). Only two composite resin fractures were noted in the 24-hour testing, a Victory Series™ bracket bonded with Fuji ORTHO™ LC and an Allure® bracket bonded with Fuji ORTHO™ LC. Results are listed in **Table 4.31** and graphically shown in **Figure 4.9**.

At the 6-month testing, 73 of the 96 tested samples were given a score of 3 (76.0%), 14 samples were given a score of 5 (14.6%), five samples were given a score of 4 (5.2%) and four samples were given a score of 2 (4.2%). Results are listed in **Table 4.31** and graphically shown in **Figure 4.9**.

The Fisher's exact test was used to compare composite fracture incidence between the groups at six months at 5% level of confidence. The Victory Series™ brackets debonded at 6 months (13 samples with composite resin fracture) showed a statistically higher incidence of composite resin fracture than all the other groups

together (6 samples with composite resin fracture) ($p < 0.0001$). Results are listed in **Table 4.32-4.33.**

Clarity™ Transbond™ XT			Clarity™ Fuji ORTHO™ LC		
Sample #	ARI scores		Sample #	ARI scores	
	24-hour	6-month		24-hour	6-month
1	3	3	1	3	3
2	3	3	2	3	3
3	3	3	3	3	3
4	3	3	4	3	3
5	3	3	5	3	3
6	3	3	6	3	3
7	3	3	7	3	3
8	3	3	8	3	3
9	3	3	9	3	3
10	3	3	10	3	3
11	3	3	11	3	3
12	3	3	12	3	3

Table 4.26. Modified Adhesive Remnant Index for Clarity™ brackets

MXi® Transbond™ XT			MXi® Fuji ORTHO™ LC		
Sample #	ARI scores		Sample #	ARI scores	
	24-hour	6-month		24-hour	6-month
1	2	3	1	3	2
2	3	3	2	3	2
3	3	3	3	3	3
4	3	3	4	2	2
5	3	3	5	3	3
6	3	5	6	3	4
7	3	3	7	3	4
8	3	3	8	3	3
9	3	3	9	3	3
10	3	3	10	3	3
11	3	2	11	3	3
12	3	3	12	3	3

Table 4.27. Modified Adhesive Remnant Index for MXi® brackets

Allure [®] Transbond [™] XT Sample #	ARI scores		Allure [®] Fuji ORTHO [™] LC Sample #	ARI scores	
	24-hour	6-month		24-hour	6-month
1	2	3	1	3	3
2	3	3	2	3	3
3	3	3	3	2	3
4	3	3	4	2	3
5	3	3	5	3	3
6	2	5	6	2	3
7	3	3	7	2	3
8	2	4	8	5	3
9	3	3	9	2	3
10	3	3	10	3	3
11	3	5	11	2	3
12	3	3	12	2	3

Table 4.28. Modified Adhesive Remnant Index for Allure[®] brackets

Victory Series [™] Transbond [™] XT Sample #	ARI scores		Victory Series [™] Fuji ORTHO [™] LC Sample #	ARI scores	
	24-hour	6-month		24-hour	6-month
1	2	3	1	2	5
2	2	3	2	3	3
3	2	5	3	2	5
4	3	5	4	3	4
5	3	5	5	2	5
6	2	3	6	3	5
7	2	5	7	2	5
8	2	3	8	3	3
9	2	4	9	2	3
10	2	3	10	2	3
11	3	3	11	5	5
12	3	3	12	2	5

Table 4.29. Modified Adhesive Remnant Index for Victory Series[™] brackets

ARI score	# of samples	%
0	0	0
1	0	0
2	30	15.63
3	141	73.44
4	5	2.60
5	16	8.33

Table 4.30. Overall Modified Adhesive Remnant Index Scores

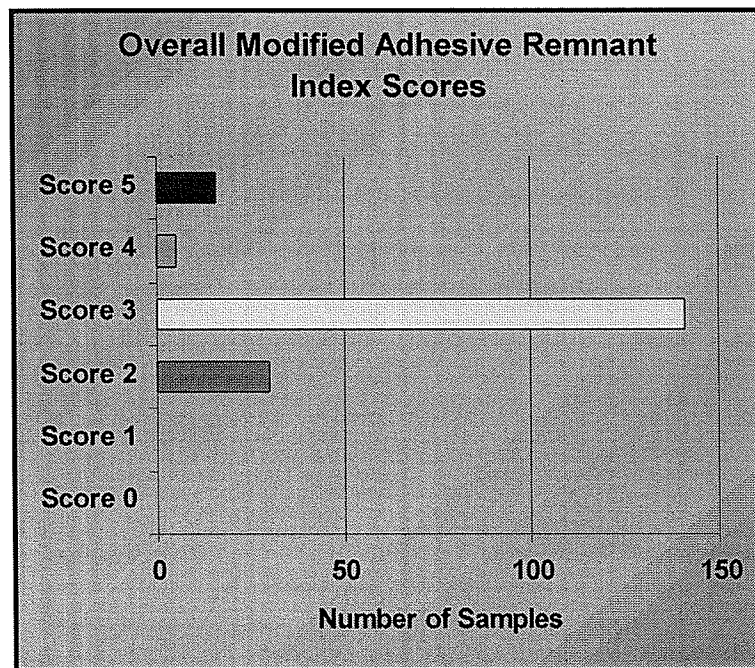


Figure 4.8. Overall Modified Adhesive Remnant Index Scores

ARI score	# of samples 24 hour	%	# of samples 6 month	%
0	0	0%	0	0%
1	0	0%	0	0%
2	26	27.08%	4	4.17%
3	68	70.83%	73	76.04%
4	0	0%	5	5.21%
5	2	2.08%	14	14.58%

Table 4.31. Comparative Adhesive Remnant Index Scores at 24 hours and 6 months

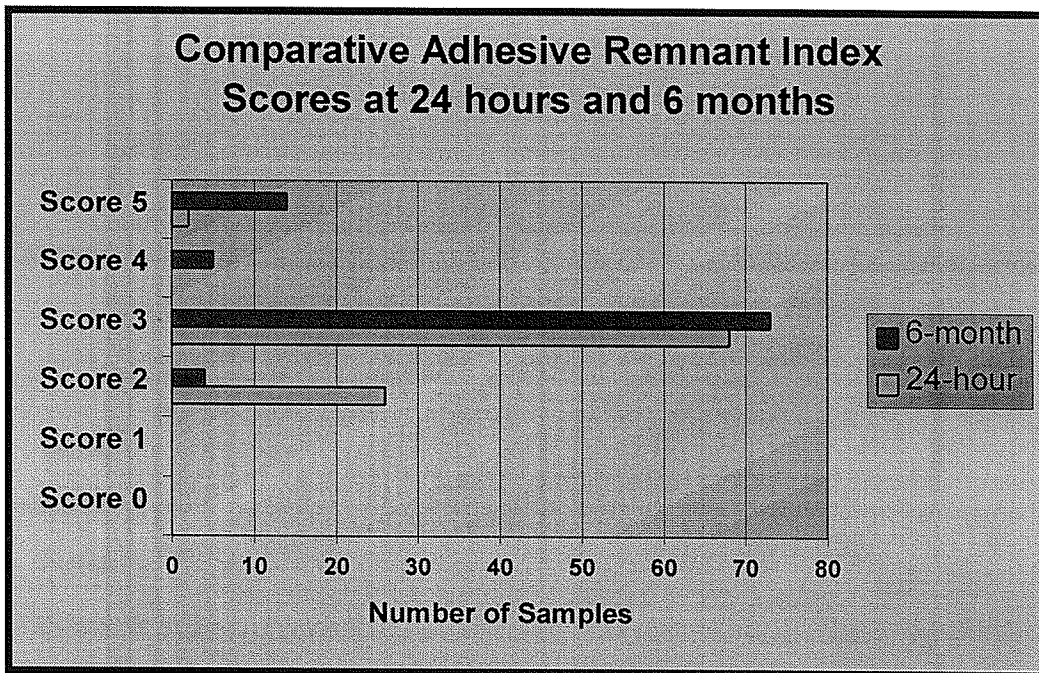


Figure 4.9. Comparative Adhesive Remnant Index Scores at 24 hours and 6 months

Bracket/Adhesive	Nb of Composite resin fracture	
	Yes	No
MXi [®] /Transbond [™] XT	0	12
MXi [®] /Fuji ORTHO [™] LC	0	12
Allure [®] /Transbond [™] XT	0	12
Allure [®] /Fuji ORTHO [™] LC	1	11
Clarity [™] /Transbond [™] XT	0	12
Clarity [™] /Fuji ORTHO [™] LC	0	12
Victory [™] /Transbond [™] XT	0	12
Victory [™] /Fuji ORTHO [™] LC	1	11
Total	2	94

Table 4.32. Comparative Data for the 24-hour Composite Resin Fracture Incidence

Bracket/Adhesive	Nb of Composite resin fracture	
	Yes	No
MXi [®] /Transbond [™] XT	1	11
MXi [®] /Fuji ORTHO [™] LC	2	10
Allure [®] /Transbond [™] XT	3	9
Allure [®] /Fuji ORTHO [™] LC	0	12
Clarity [™] /Transbond [™] XT	0	12
Clarity [™] /Fuji ORTHO [™] LC	0	12
Victory [™] /Transbond [™] XT	5	7
Victory [™] /Fuji ORTHO [™] LC	8	4
Total	19	77

Table 4.33. Comparative Data for the 6-month Composite Resin Fracture Incidence

5. DISCUSSION

5.1 Shear-peel Bond Strengths

5.1.1 Clinical versus laboratory findings

Results from *in vitro* studies should be interpreted with caution since they often differ from *in vivo* studies. Zachrisson (2000) listed three reasons for this: (1) the continually increasing tensile or shear loads applied to bonded brackets in the laboratory are not representative of the force applications that occur clinically. Clinically, the load applied to brackets is not constant. It is usually of a short duration and the force level could range from very low to very high; (2) the type of debonding force developed in testing machines is not the same as the force applied in clinical debonding. In the present study, a shear-peel load was applied as close as possible to the interface of the adhesive and the base of the brackets. Clinically, the load is usually a combination of shear-peel and torsional loads (Katona, 1997), which is usually applied to the tie-wings. This places it at some distance from the bracket base/adhesive interface; and (3) the complex variations in temperature, stresses, humidity, acidity, and plaque that are present in the oral environment are not reproducible in the laboratory. Although laboratory studies, which cannot always be extrapolated to the clinical situation, are very helpful in comparing different biomaterials, clinical studies should always follow laboratory studies to validate the results.

5.1.2 Variables affecting inter-study comparison

Comparisons with other studies can be difficult because of discrepancies in the variables involved in the experiments and also because there is no recognized standardized protocol for bond strength testing in orthodontics (Fox, McCabe and Buckley, 1994; Katona and Moore, 1994; Eliades and Brantley, 2000). As discussed earlier in section 2.4.1, different modes of load application can be utilized, which makes inter-study comparisons problematic, if not impossible. Misalignment of the load application and variations in cement thickness both across the body interface and between brackets may provide other sources of error, as shown in a recent finite element model analysis (Katona and Moore, 1994). The crosshead speed should also be taken into consideration. Eliades and Brantley (2000) stated that viscoelastic behavior of the adhesive is important when using low crosshead speeds. Viscoelastic behavior is largely absent at the much higher impact velocities typically present in *in vivo* debonding incidents. In the present study, the crosshead speed which was set at 0.5mm/min (ISO, 1994) provided a slow rate of loading conducive to viscoelastic deformation. In other studies using composite as a substrate, Chunhacheevachaloke and Tyas (1997) used 5mm/min., Kao *et al.* (1995) and Lai, Woods and Tyas (1999) used 1mm/min., Newman, Dressler, and Granadier (1984) used 0.508mm/min. Schwartz, Tyas and West (1990) did not state their crosshead speed.

The different types of orthodontic attachments such as brackets and buttons used in research protocols also affect the comparability of the results. Differences include bracket material (metal, ceramic or plastic), bracket base design and method of retention (mechanical, chemical or both). In the present study, three types of ceramic brackets were used. Even though they are all polycrystalline brackets, the base design and materials used are dissimilar. Another source of error is the surface area of the bracket. Because results are usually reported in MPa, which is the shear-peel force at failure (in Newtons) divided by the surface area of the bracket base (in mm), the use of an accurate value for area is important. Multiplying the width of the bracket base by its height, as used by Chunchacheevachaloke and Tyas (1997), and Lai, Woods and Tyas (1999), will not reflect the actual surface area because bracket bases are not perfectly rectangular. In the present study, to ensure greater accuracy, the surface areas of the brackets were calculated using scientific digital image analysis software described in section 3.2.3.

Another variable is the substrate used in bonding studies. Enamel, porcelain, amalgam and composite resin have been utilized. In the present study, a hybrid resin was used. Kao *et al.* (1995), Chunchacheevachaloke and Tyas (1997), and Lai, Woods and Tyas (1999) used a microfilled resin. Schwartz, Tyas and West (1990) used both microfilled and hybrid resins. Surface preparations (such as abraded, sandblasted or untouched), filler material and physical properties of the substrate differ between the various studies and this would probably affect the bond strength values.

Storage time and media could also influence the study outcome. Schwartz, Tyas and West (1990) did not report their storage time and media, Kao *et al.* (1995) thermocycled their samples 500 times between 4° and 55° then stored them in water at 37° for 7 days, Chunchacheevachaloke and Tyas (1997) placed their samples in distilled water for 24 hours and Lai, Woods and Tyas (1999) thermocycled half of their specimens and the other half were stored in water at 37° for an unstated duration. In the present study, half of the specimens were stored in distilled water for 24 hours and the other half for six months before debonding.

In an attempt to reveal some common trends, the present study will be compared to studies that have similar materials and methods.

5.1.3 Twenty-four-hour bond strengths

All bracket/adhesive combinations had mean bond strengths after 24 hours above the 6-8 MPa range, recommended by Reynolds (1975) as being minimum values for clinical acceptability. The highest mean bond strengths for ceramic brackets were obtained with Clarity™ brackets with either Transbond™ XT or Fuji ORTHO™ LC. The lowest mean bond strengths were obtained with MXi® brackets with Transbond™ XT, followed by MXi® brackets bonded with Fuji ORTHO™ LC. Both MXi® groups were statistically lower than all other groups tested at 24-hours. When the shear-peel bond strengths were analysed as a function of adhesive type, both Transbond XT and Fuji ORTHO™ LC groups had similar mean bond strengths.

Chunhacheevachaloke and Tyas (1997) evaluated the shear bond strength of ceramic brackets (Transcend™ Series 6000/ 3M Unitek) bonded to smooth and roughened (obtained by using a coarse Soflex (3M Dental products) disc) microfilled composite resin using Transbond™ (3M Unitek). Transcend™ Series 6000 brackets have identical base design and composition as Clarity™ brackets. The mean shear bond strength of the Transcend™ brackets to roughened composite was $19.2\text{MPa} \pm 6.75$ ranging from 13.6MPa to 36.1MPa . In the present study, a comparable value with Clarity™ brackets was found but with a slightly tighter distribution: The mean was $22.7\text{MPa} \pm 5.80$ ranging from 15.26MPa to 31.28MPa . These values are well in excess of the 6-8 MPa minimum bracket bond strength mentioned by Reynold (1975).

Lai, Woods and Tyas (1999) also evaluated the shear-peel bond strengths of Transcend™ Series 6000 brackets bonded to a microfilled composite resin using Transbond™ XT (3M Unitek) and Fuji ORTHO™ LC (GC America). The surface was roughened by using a fine Soflex (3M Dental products) abrasive disc. The mean shear-peel bond strength of the Transcend brackets to roughened composite using Transbond™ XT was $14.0\text{MPa} \pm 6.89$ ranging from 6.4MPa to 29.7MPa . The values are much lower than those reported in the present study ($22.7\text{MPa} \pm 5.80$ ranging from 15.26MPa to 31.28MPa). Different variables could have affected the differences in values: (1) the composite resin used (microfilled vs. hybrid); (2) the resin composite surface treatment (Soflex abrasive disc vs. air abrasion); (3) the crosshead speed (1mm/min. vs. 0.5mm/min.). The mean shear-peel bond strength of the

Transcend brackets to roughened composite using Fuji ORTHO™ LC was 17.2MPa \pm 4.82 ranging from 11.1MPa to 27.0MPa (Lai, Woods and Tyas, 1999). These values were comparable to those found in the present study (20.26MPa \pm 5.99 ranging from 9.94MPa to 30.06MPa).

A search of the literature failed to reveal studies using Allure® or MXi® brackets bonded to resin composite. In this present study, MXi® brackets were found to have the lowest shear-peel bond strengths and both groups (Transbond™ XT and Fuji ORTHO™ LC) were statistically lower than any other bracket group. MXi® brackets have an epoxy base bonded to the alumina and during the experiment, some samples displayed a detachment of this epoxy layer from the base on debonding.

When the shear-peel bond strengths were analysed as a function of adhesive type, Lai, Woods and Tyas (1999) concluded that there were no significant differences between the Transbond™ XT groups and the Fuji ORTHO™ LC groups. These findings correlate with those in the present study at 24 hours.

5.1.4 Six-month bond strengths

During the testing that was conducted at 6 months, the highest mean bond strengths were again obtained with Clarity brackets bonded with Transbond™ XT and was significantly greater than all other ceramic bracket/adhesive groups. The lowest mean bond strengths were obtained with MXi® brackets bonded with Transbond™ XT and

with Allure[®] brackets bonded with Fuji ORTHO[™] LC and no statistical differences could be found between these two groups.

A search of the literature failed to report studies investigating the long-term bond strengths of ceramic brackets to composite resin.

The mean bond strengths at 6 months reduced significantly for only three ceramic bracket groups: Allure[®] brackets bonded with either Transbond[™] XT or Fuji ORTHO[™] LC and Clarity[™] brackets bonded with Fuji ORTHO[™] LC. The method of bonding of the Allure[®] brackets, which is only chemical, could be a significant factor in the bond strength decrease following long-term water storage. No explanation could be found for the decrease in bond strengths of Clarity[™] brackets bonded with Fuji ORTHO[™] LC. Long-term storage in water did not affect the bond strengths of the following ceramic bracket/adhesive combinations: Clarity[™] brackets bonded with Transbond[™] XT and MXi[®] brackets bonded with either Transbond[™] XT or Fuji ORTHO[™] LC.

When analysing the bond strengths as a function of the adhesive types, water storage affected Fuji ORTHO[™] LC more than Transbond[™] XT. The bond strengths of the Fuji ORTHO[™] LC groups at six months were significantly lower than at 24 hours. No other studies could be found in the literature comparing long-term bond strengths of ceramic brackets bonded to composite.

In an attempt to understand the long-term effect of water storage on the adhesive used in this study, other studies using similar bonding materials will be reported. Cattani-Lorente (1999) showed that RMGIC were very sensitive to water sorption and a correlation was established between the decrease in their physical properties and the water uptake. Iwami *et al.* (1998) also demonstrated significant water sorption with light-cured glass-ionomer cement compared to resin composites (at least three times as much but no exact values were given), which affected their physical properties. Attin *et al.* (1995) studied the curing shrinkage and volumetric changes of resin-modified glass ionomer and reported shrinkage of the material within 5 minutes after polymerization, which increased over a period of at least 24 hours. They showed that immersion of resin-modified glass ionomer in water for 28 days resulted in expansion of the material, affecting its physical properties. In the present study, the sensitivity to water sorption could have resulted in a decrease in bond strengths. This contradicts the study of Czochrowsky *et al.* (1999) who found that long-term storage of RMGIC did not decrease the bond strengths of orthodontic brackets bonded with Fuji ORTHO™ LC. Choo, Ireland and Sherriff (2001) investigated the long-term bond strengths of metal brackets bonded to teeth using Fuji ORTHO LC or Transbond at one hour, one week, one month and one year. They concluded that there were no significant changes in bond strengths for both Transbond and Fuji ORTHO LC. Unlike Transbond, Fuji ORTHO LC underwent marked surface changes. According to Choo, Ireland and Sherriff (2001) since the material is only exposed at the margins of the joint in orthodontic bonding, this effect may not be of any consequence. The studies by Czochrowsky *et al.* (1999) and Choo, Ireland and Sherriff (2001),

however, involved metal brackets bonded to teeth, so inter-study comparison is difficult.

5.2 ARI Scores

Composite fractures were seen in samples with a score of 4 or 5. A score of 4 was given for a cohesive fracture of the composite resin with no adhesive left on the composite sample, whereas a score of 5 was given for a cohesive fracture of the composite resin with some adhesive left on the composite sample. Only two samples out of 96 (2.08%) showed a composite fracture at 24 hours, which is not significant. At six months, 19 of 96 (19.79%) composite samples showed a cohesive fracture (14 of 96 (14.58%) with a score of 4 and 5 of 96 (5.21%) samples with a score of 5). 13 of 24 (54.17%) composite fractures occurred when using the control Victory™ Series metal bracket, which was the only significant group. Three fractures occurred with Allure® brackets bonded with Transbond™ XT, two with MXi® brackets bonded with Fuji ORTHO™ LC and one with a MXi® bracket bonded with Transbond™ XT. In the present study, composite fracture was not significant with ceramic brackets bonded to resin composite. This contradicts the work of Chunchacheevachaloke and Tyas (1997) and Lai, Woods and Tyas (1999), who found that the resin composite was damaged in most cases.

As stated previously, the Victory Series™ metal bracket groups showed the most composite fractures. An explanation for this fact could be that the adhesive is capable

of bonding strongly with the metal bracket. The base design (metal mesh) of the Victory Series™ metal bracket promotes a better interlocking mechanism for the adhesive, as compared with any of the other ceramic brackets. For a substrate fracture to happen, the bracket/adhesive bond strength must be stronger than the adhesive/substrate bond strength. In the ceramic bracket groups, most of the fractures occurred between the adhesive and the substrate, suggesting that the bracket/base bond strength is weaker than the adhesive/substrate bond strength. Both Transbond™XT and Fuji ORTHO™ LC must be stronger than the composite resin used as a substrate in order to get a cohesive fracture of the substrate.

The clinical relevance of ARI Scores could not be assessed completely with an *in vitro* study because of the number of variables present as discussed under sections 5.1.1 and 5.1.2. These scores can, however, establish a baseline for comparison with other studies. Unfortunately, there is no standardized protocol for the scoring system. Different scoring systems have been used in the literature (Årtun and Bergland, 1984; Chunchacheevachaloke and Tyas, 1997; Lai, Wood and Tyas, 1999). The profession has not decided which failure mode is clinically the most desirable. Clinically, the risk of surface damage is diminished if most of the adhesive is left on the composite surface. On the other hand, when the adhesive remains on the bracket, less time is consumed for the adhesive clean up. A weaker adhesive, while safer for the tooth or restorative surface, probably means a higher rate of bond failure during the course of a treatment, and an increase in treatment time and a decrease in efficiency. The best

adhesive would be one that stays on the bracket when debonding without any significant risk of restoration surface damage.

Is stronger always better? According to Kusy (1994), bracket cements have undergone an evolution from being too weak to being too strong. Early scientists were trying to bond dissimilar materials and enhancing the bond strength was the main goal. But when does bond strength get strong enough without being excessive? No exact answer can be given. Kusy (1994) stated that a product should not be overdesigned (bond strength too high). In today's orthodontics, more than just the usual laboratory bond strength comparison is needed. Clinical optimization studies should be done to evaluate different aspects of the bonding and debonding procedures in order to fully evaluate a bonding material (Kusy, 1994).

5.3 Evaluation of the null hypotheses

From the results of this study, the null hypothesis which states that there are no statistical differences between shear-peel bond strengths of the different types of attachments bonded to a popular composite resin restorative material (Z100™) is rejected ($p < 0.05$).

The null hypothesis which states that there are no statistical differences in shear-peel bond strengths using either a composite resin adhesive (Transbond™ XT) or a resin-

modified glass ionomer cement (Fuji ORTHO™ LC) is accepted for the 24-hour testing ($p>0.05$) but rejected for the six-month testing ($p<0.05$).

The null hypothesis which states that there are no statistical differences in shear bond strength between the 24-hour and the 6-month evaluations is rejected for the following groups: Allure® brackets bonded with Fuji ORTHO™ LC, the Clarity™ brackets bonded with Fuji ORTHO™ LC, the Allure® brackets bonded with Transbond™ XT ($p<0.05$). This null hypothesis is accepted for the following groups: MXi® brackets bonded with either Transbond™ XT or Fuji ORTHO™ LC and Clarity™ brackets bonded with Transbond XT ($p>0.05$).

6. Conclusions and Recommendations

6.1 Conclusions

From this study, the following conclusions can be made:

1. Ceramic brackets can be successfully bonded to resin composite *in vitro*.
2. At 24 hours, the highest mean bond strengths for ceramic brackets were obtained with Clarity™ brackets with either Transbond™ XT or Fuji ORTHO™ LC and the lowest mean bond strengths were obtained in MXi® brackets with Transbond™ XT followed by MXi® brackets bonded with Fuji ORTHO™ LC.
3. At 24 hours, there were no significant differences between the two adhesives used: Transbond™ XT and Fuji ORTHO™ LC.
4. Long-term storage in water at 37° significantly reduced the bond strengths of the following groups: Allure® brackets bonded with either Transbond™ XT or Fuji ORTHO™ LC and Clarity™ brackets bonded with Fuji ORTHO™ LC.
5. Long-term storage in water at 37° did not affect the bond strengths of the following groups: Clarity™ brackets bonded with Transbond™ XT and MXi® brackets bonded with either Transbond™ XT or Fuji ORTHO™ LC.
6. Long-term storage in water at 37° significantly reduced the bond strengths when using Fuji ORTHO™ LC.

7. Minimal composite resin surface damage occurred at either 24 hours or six months of debonding ceramic brackets.
8. A high incidence of composite resin surface damage occurred at the six month debonding interval when using Victory Series™ brackets bonded with Transbond™ XT or Fuji ORTHO™ LC
9. The *in vitro* data from this study may not accurately reflect the clinical situation and should be interpreted with caution.
10. The results of the various materials tested for this study showed material specificity, making generalizations difficult.

6.2 Recommendations

Judging from this *in vitro* results:

1. Bonding ceramic brackets to resin composite: The use of Transbond™ XT and Fuji ORTHO™ LC are suitable bonding materials as they provide adequate shear-peel bond strengths (as recommended by Reynolds, 1975) and cause minimal resin composite damage on debonding.
2. Further investigations should be made in the bonding protocol for Victory Series™ brackets bonded to resin composite since many composite samples were damaged on debonding at six months.
3. Future efforts should be made to standardize *in vitro* studies in order to improve inter-study comparisons.

4. *In vitro* studies should always include a sample group that is stored long-term in water to better simulate the clinical situation. Six months storage in water could give some important information but consideration should be given to include a sample stored in water for at least 18 months, which is usually the minimum duration of clinical orthodontic cases.
5. The appropriate finishing, polishing, and repair techniques for composite resin surfaces damaged during the debonding or clean-up procedures requires further investigation.

REFERENCES

- Årtun J, Bergland S. *Clinical trials with crystal growth conditioning as an alternative to acid-etch enamel pre-treatment*. American Journal of Orthodontics and Dentofacial Orthopedics 1984;85:333-340.
- Attin T, Buchalla W, Kielbassa AM, Hellwig E. *Curing shrinkage and volumetric changes of resin-modified glass ionomer restorative materials*. Dental Materials 1995;11:359-362.
- Bergstrand F. *Personal conversation*. 3M/Unitek, Monrovia, CA 2001.
- Birnie D. *Orthodontic Materials Update*. British Journal of Orthodontics 1990;17:71-75.
- Bishara SE. *Ceramic brackets and the need to develop national standards*. American Journal of Orthodontics and Dentofacial Orthopedics 2000;117:595-597.
- Bishara SE, Fehr DE. *Ceramic Brackets. Something Old, Something New, A Review*. Seminars in Orthodontics 1997;3:178-188.
- Bishara SE, Fehr DE, Jakobsen JR. *A comparative study of the debonding strengths of different ceramic brackets, enamel conditioners, and adhesives*. American Journal of Orthodontics and Dentofacial Orthopedics 1993;104:170-179.
- Bishara SE, Olsen M, Von Wald L. *Comparison of shear bond strength of precoated and uncoated brackets*. American Journal of Orthodontics and Dentofacial Orthopedics 1997;112:617-621.
- Bishara SE, Olsen M, Von Wald L. *Evaluation of debonding characteristics of a new collapsible ceramic bracket*. American Journal of Orthodontics and Dentofacial Orthopedics 1997;112:552-559.
- Bishara SE, Olsen M, Von Wald L, Jakobson B. *Comparison of the debonding characteristics of two innovative ceramic bracket designs*. American Journal of Orthodontics and Dentofacial Orthopedics 1999;116:86-92.
- Bordeaux JM, Moore RN, Bagby MD. *Comparative evaluation of ceramic bracket base designs*. American Journal of Orthodontics and Dentofacial Orthopedics 1994;105:552-60.
- Bourke BM, Rock WP. *Factors affecting the shear bond strength of orthodontic brackets to porcelain*. British Journal of Orthodontics 1999;26:285-290.

Bouschlicher MR, Reinhardt JW, Vargas MA. *Surface treatment techniques for resin composite repair*. American Journal of Orthodontics and Dentofacial Orthopedics 1997;10:279-283.

Bowen RL. *Compatibility of various materials with oral tissues. I: The components in composite restorations*. Journal of Dental Research 1979;58:1493-1503.

Boyer DB, Chan KC, Reinhardt JW. *Build-up and Repair of Light-Cured Composites: Bond Strength*. Journal of Dental Research 1984;63:1241-1244.

Bradburn G, Pender N. *An in vitro study of the bond strength of two light-cured composites used in the direct bonding of orthodontic brackets to molars*. American Journal of Orthodontics and Dentofacial Orthopedics 1992;102:418-426.

Britton JC, McInnes P, Weinberg R, Ledoux W, Retief D. *Shear bond strength of ceramic orthodontic brackets to enamel*. American Journal of Orthodontics and Dentofacial Orthopedics 1992;98: 348-353.

Brosh T, Pilo R, Bichacho N, Blutstein R. *Effect of combinations of surface treatments and bonding agents on the bond strength of repaired composites*. Journal of Prosthetic Dentistry 1997;77:122-126.

Buonocore MG. *A simple method of increasing the adhesion of acrylic filling materials to enamel surfaces*. Journal of Dental Research 1955;34:382-391.

Buonocore MG. *The use of adhesives in dentistry*. Springfield: Thomas Publisher, 1975:3-18.

Büyükyılmaz T, Zachrisson Y, Zachrisson BU. *Improving orthodontic bonding to gold alloy*. American Journal of Orthodontics and Dentofacial Orthopedics 1995;108:510-518.

Cattani-Lorente M-A, Dupuis V, Payan J, Moya F, Meyer J-M. *Effect of water on the physical properties of resin-modified glass ionomer cements*. Dental Materials 1999;15:71-78.

Chaconas SJ, Caputo A, Niu GSL. *Bond strength of ceramic brackets with various bonding systems*. The Angle Orthodontist 1991;61:34-42.

Choo SC, Ireland AJ, Sherriff M. *An in vitro investigation into the use of resin-modified glass poly (alkenoate) cements as orthodontic bonding agents*. European Journal of Orthodontics 2001;23:243-252.

Chung C-H, Brendlinger EJ, Brendlinger DL, Bernal V, Mante FK. *Shear bond strengths of two resin-modified glass ionomer cements to porcelain*. American Journal of Orthodontics and Dentofacial Orthopedics 1999;115: 533-535.

Chung C-H, Cuozzo PT, Mante FK. *Shear bond strength of a resin-reinforced glass ionomer cement: An in vitro comparative study*. American Journal of Orthodontics and Dentofacial Orthopedics 1999;115:52-54.

Chunhacheevachaloke E, Tyas MJ. *Shear bond strength of ceramic brackets to resin-composite surfaces*. Australian Journal of Orthodontics 1997;15:10-15.

Cochran D, O'Keefe KL, Turner DT, Powers JM. *Bond strength of orthodontic composite cement to treated porcelain*. American Journal of Orthodontics and Dentofacial Orthopedics 1997;111:297-300.

Collys K, Slop D, Cleymaet R, Coomans D, Michotte Y. *Load dependency and reliability of microhardness measurements on acid-etched enamel surfaces*. Dental Materials 1992;8:332-335.

Combe EC, Burke FJT, Douglas WH. *Dental Biomaterials*. Boston: Kluwer Academic Publishers, 1999:89,144-145,158-159,222-223,227-230,233-240,249-250.

Cook PA, Luther F, Youngson CC. *An in vitro study of the bond strength of light-cured glass ionomer cement in the bonding of orthodontic brackets*. European Journal of Orthodontics 1996;18:199-204.

Craig RB. *Restorative dental materials*. 9th ed. St-Louis: CV Mosby, 1993:248-252.

Darvell BW. *Materials science for dentistry*. 5th ed. Hong Kong: BW Darvell, 1998:175-179.

Devanathan D. *Design and development of an advanced ceramic bracket*. TP Orthodontics Manufacturer Publications 1997:1-4.

Devanathan D. *Technical brief debonding mechanics of the MXi[®] bracket*. TP Orthodontics Manufacturer Publications 1998:1-2.

Devanathan D, Storer C, Schalek R. *Effect of surface defects on the failure characteristics of ceramic brackets*. TP Orthodontics Manufacturer Publications 1998:1-3.

Douglass JB. *Enamel wear caused by ceramic brackets*. American Journal of Orthodontics. 1989;95:96-98.

Eliades T., Brantley W.A. *The inappropriateness of conventional orthodontic bond strength assessment protocols*. European Journal of Orthodontics 2000;22:13-23.

- Ferracane JL. *Elution of leachable components from composites*. Journal of Oral Rehabilitation 1994;21:441-452.
- Ferracane JL, Condon JR. *Rate of elution of leachable components from composite*. Dental Materials 1990;6:282-287.
- Forsberg C-M, Hagberg C. *Shear bond strength of ceramic brackets with chemical or mechanical retention*. British Journal of Orthodontics 1992;19: 183-189.
- Fox NA, McCabe JF, Buckley JG. *A Critique of Bond Strength Testing in Orthodontics*. British Journal of Orthodontics 1994;21:33-43.
- GAC International. *Personal conversation with Mark Katz and Mark Manny*. Central Islip, NY 2001.
- Gibbs SL. *Clinical Performance of Ceramic Brackets: A survey of British orthodontists'*. British Journal of Orthodontists 1992;19:191-197.
- Gottlieb EL, Vogels DS. *1983 JCO Orthodontic Practice Study*. Journal of Clinical Orthodontics 1984;18:247-253.
- Gregory W, Berry S, Duke E, Dennison JB. *Physical properties and repair bond strength of direct and indirect composite resins*. Journal of Prosthetic Dentistry 1992;68:406-411.
- Gross MW, Foley TF, Mamandras AH. *Direct bonding to Adlloy-treated amalgam*. American Journal of Orthodontics and Dentofacial Orthopedics 1997;112:252-258.
- Guess MB, Watanabe LG, Beck FM, Crall MG. *The Effect of Silane Coupling Agents on the Bond Strength of a Polycrystalline Ceramic Bracket*. Journal of Clinical Orthodontics 1988;22:788-792.
- Harris AMP, Joseph VP, Rossouw E. *Comparison of Shear Bond Strengths of Orthodontic Resins to Ceramic and Metal Brackets*. Journal of Clinical Orthodontics 1990;24:725-728.
- Hassard TH. *Understanding biostatistics*. Mosby-Year Book, St-Louis, 1991.
- Haydar B, Sartkaya S, Çehreli ZC. *Comparison of shear bond strength of three bonding agents with metal and ceramic brackets*. The Angle Orthodontist 1999;69:457-462.
- Inoue K, Hayashi I. *Residual monomer (Bis-GMA) of composite resins*. Journal of Oral Rehabilitation 1982;9:493-497.

International Organization for Standardization. *ISO 4049 Resin-based filling materials*. Geneva, Switzerland: WHO, 1988.

International Organization for Standardization. *ISO/TR 11405 Dental materials - guidance on testing of adhesion to tooth structure*. Geneva, Switzerland: WHO, 1994.

Iwami Y, Yamamoto H, Sato W, Kawai K, Torii M, Ebisu S. *Weight change of various light-cured restorative materials after water immersion*. Operative Dentistry 1998;23:132-137.

Joseph VP, Rossouw E. *The shear bond strengths of stainless steel and ceramic brackets used with chemically and light-activated composite resins*. American Journal of Orthodontics and Dentofacial Orthopedics 1990;97:121-125.

Kao EC, Eliades T, Rezvan E, Johnston M. *Torsional bond strength and failure pattern of ceramic brackets bonded to composite resin laminate veneers*. European Journal of Orthodontics 1995;17:533-540.

Karamouzos A, Athanasiou AE, Papadopoulos MA. *Clinical characteristics and properties of ceramic brackets: A comprehensive review*. American Journal of Orthodontics and Dentofacial Orthopedics 1997;112:34-40.

Kao EC, Boltz KC, Johnston WM. *Direct bonding of orthodontic brackets to porcelain laminate veneers*. American Journal of Orthodontics and Dentofacial Orthopedics 1988;94:458-468.

Katona TR. *A comparison of the stresses developed in tension, shear peel, and torsion strength testing of direct bonded orthodontic brackets*. American Journal of Orthodontics and Dentofacial Orthopedics 1997;112:244-251.

Katona TR. *The effects of load location and misalignment on shear/peel testing of direct bonded orthodontic brackets: a finite element model*. American Journal of Orthodontics and Dentofacial Orthopedics 1994;106:395-402.

Katona TR, Moore BK. *The effects of load misalignment on tensile load testing of direct bonded orthodontic brackets- a finite element model*. American Journal of Orthodontics and Dentofacial Orthopedics 1994;105:543-551.

Kupiec KA, Barkmeier WW. *Laboratory Evaluation of Surface Treatments for Composite Repair*. Operative Dentistry 1996;21:59-62.

Kuzy RP. *Commentary on Dr. Wiltshire's article: When is stronger better?* American Journal of Orthodontics and Dentofacial Orthopedics 1994;106:17A.

Kusy RP. *Morphology of Polycrystalline Alumina Brackets and its Relationship to Fracture Toughness and Strength*. The Angle Orthodontist 1988;58:197-203.

Lai PY, Woods MG, Tyas MJ. *Bond strengths of orthodontic brackets to restorative resin composite surfaces*. Australian Journal of Orthodontics 1999;15:235-245.

Latta MA, Barkmeier WW. *Bond strength of a resin cement to a cured composite inlay material*. Journal of Prosthetic Dentistry 1994;72:189-193.

Martin S, Garcia-Godoy F. *Shear bond strength of orthodontic brackets cemented with a zinc oxide-polyvinyl cement*. American Journal of Orthodontics and Dentofacial Orthopedics 1994;106: 615-620.

Material Safety Data Sheet. 11938. Transbond XT adhesive paste. 3M General Offices, St.Paul, MN, 1993.

Material Safety Data Sheet. 11939. Transbond XT primer. 3M General Offices, St.Paul, MN, 1993.

Material Safety Data Sheet. 439409. Fuji ORTHO LC liquid. GC America, Alsip, IL, 1997.

Material Safety Data Sheet. 439421. Fuji ORTHO LC powder. GC America, Alsip, IL, 1997.

Meehan MP, Foley TF, Mamandras AH. *A comparison of the shear bond strengths of two glass ionomer cements*. American Journal of Orthodontics and Dentofacial Orthopedics 1999;115:125-132.

Miguel JAM, Almeida MA, Chevitarase O. *Clinical comparison between a glass Ionomer cement and a composite for direct bonding of orthodontic brackets*. American Journal of Orthodontics and Dentofacial Orthopedics 1995;107:484-487.

Mundstock KS, Sadowsky PL, Lacefield W, Bae S. *An in vitro evaluation of a metal reinforced orthodontic ceramic bracket*. American Journal of Orthodontics and Dentofacial Orthopedics 1999;116:635-641.

Nebbe B, Stein E. *Orthodontic brackets bonded to glazed and deglazed porcelain surfaces*. 1996;109(4): 431-436.

Newman SM, Dressler KB, Genadier MR. *Direct bonding of orthodontic brackets to aesthetic restorative materials using a silane*. American Journal of Orthodontics and Dentofacial Orthopedics 1984;86:503-506

Nollie G, Foley TF, McConnell RJ. *Orthodontic bonding to Adlloy-treated type IV gold*. The Angle Orthodontist 1997;3:183-188.

Odegaard J, Segner D. *Shear bond strength of metal brackets compared with a new ceramic bracket.* American Journal of Orthodontics and Dentofacial Orthopedics 1988;94:201-206.

Olsen ME, Bishara SE, Jakobsen BA. *Evaluation of the shear bond strength of different ceramic bracket base designs.* The Angle Orthodontist 1997;67:179-182.

Omana HM, Moore RN, Bagby MD. *Frictional Properties of Metal and Ceramic Brackets.* Journal of Clinical Orthodontics 1992;26:425-432.

Ostertag AJ, Dhuru VB, Ferguson DJ, Meyer RA Jr. *Shear, torsional, and tensile bond strengths of ceramic brackets using three adhesive filler concentrations.* American Journal of Orthodontics and Dentofacial Orthopedics 1991;100:251-258.

Øysæd H, Ruyter IE. *Composites for use in posterior teeth: Mechanical properties tested under dry and wet conditions.* Journal of Biomedical Material Research 1986;20:261-271.

Øysæd H, Ruyter IE. *Water sorption and filler characteristics of composites for use in posterior teeth.* Journal of Dental Research 1986;65:1315-1318.

Pearson GJ. *Long term water sorption and solubility of composite filling materials.* Journal of Dentistry 1979;7:64-68.

Pearson GJ, Longman CM. *Water sorption and solubility of resin-based materials following inadequate polymerization by a visible -light curing system.* Journal of Oral Rehabilitation 1989;16:57-61.

Powers JM, Kim HB, Turner DS. *Orthodontic Adhesives and Bond Strength Testing.* Seminars in Orthodontics 1997;3:147-156.

Pham DC, Ferracane JL. *Early elution of uncured components from light-activated composites.* Journal of Dental Research 1989;68:207.

Proffit WR. Contemporary Orthodontics. 3rd ed. St.Louis: CV Mosby, 1999:397.

Rathburn MA, Craig RG, Hanks CT, Filisko FE. *Cytotoxicity of a Bis-GMA dental composite before and after leaching in organic solvents.* Journal of Biomedical Materials Research 1991;25:443-457.

Retief DH. *Failure at the dental adhesive-etched enamel interface.* Journal of Oral Rehabilitation 1974;1:265-284.

Retief DH. *Standardizing laboratory adhesion tests.* American Journal of Dentistry 1991;4:231-236.

Rezk-Lega F, Øgaard B. *Tensile bond force of glass Ionomer cements in direct bonding of orthodontic brackets: An in vitro comparative study.* American Journal of Orthodontics and Dentofacial Orthopedics 1991;100:357-361.

Reynolds, I.R. *A review of direct orthodontic bonding.* British Journal of Orthodontics 1975;2: 171-178.

Scott GE. *Fracture toughness and surface cracks - The Key to Understanding Ceramic Brackets.* The Angle Orthodontist 1988;1:5-8.

Shiau JY, Rasmussen ST, Phelps AE, Enlow DH, Wolf GR. *Analysis of the shear bond strength of pretreated aged composites used in some indirect bonding techniques.* Journal of Dental Research 1993;72:1291-1297.

Smith GA, McInnes-Ledoux P, Ledoux WR, Weinberg R. *Orthodontic bonding to porcelain-bond strength and refinishing.* American Journal of Orthodontics and Dentofacial Orthopedics 1988;94:245-252.

Söderholm K-JM. *Degradation of glass filler in experimental composites.* Journal of Dental Research 1981;60:1867-1875.

Söderholm K-JM. *Filler leachability during water storage of six composite materials.* Scandinavia Journal of Dental Research 1990;98:82-88.

Söderholm K-JM. *Leaking of fillers in dental composites.* Journal of Dental Reseach 1983;62:126-130.

Stokes AN, Tay WM, Pereira BP. *Shear bond of resin cement to post-cured hybrid composites.* Dental Materials 1993;9:370-374.

Swartz ML. *Ceramic brackets.* Journal of Clinical Orthodontics 1988;22:82-88,

Swift EJ Jr, Brodeur C, Cvitko E, Pires JAF. *Treatment of composite surfaces for indirect bonding.* Dental Materials 1992;8:193-196.

Swift EJ, LeValley BD, Boyer DB. *Evaluation of new methods for composite repair.* Dental Materials 1992;8:362-365.

Takla PM, Shivapuja PK. *Pulpal response in electrothermal debonding.* American Journal of Orthodontics and Dentofacial Orthopedics 1995;108:623-629.

Tanaka K, Taira M, Shintani H, Wakasa K, Yamaki M. *Residual monomers (TEGMA and Bis-GMA) of a set visible-light-cured dental composite resin when immersed in water.* Journal of Oral Rehabilitation 1991;18:353-362.

Tate WH, DeSchepper EJ, Cody T. *Quantitative analysis of six composite polishing techniques on a hybrid composite material.* Journal of Aesthetic Dentistry 1992;4(suppl):30-31.

Tavas MA, Salem NS. *Glass ionomers for direct bonding : an in vitro assessment.* British Journal of Orthodontics 1990;17:223-228.

Thomas RI, de Rijk WG, Evans CA. *Tensile and shear stresses in the orthodontic attachment adhesive layer with 3D finite element analysis.* American Journal of Orthodontics and Dentofacial Orthopedics 1999;116:530-532.

Thompson LR, Miller EG, Bowles WH. *Leaching of unpolymerized materials from orthodontic bonding resin.* Journal of Dental Research 1982;61:989-992.

Turner CW, Meiers JC. *Repair of an Aged, Contaminated Indirect Composite Resin with a Direct, Visible-Light-cured Composite Resin.* Operative Dentistry 1993;18:187-194.

Viazis AD, Cavanaugh G, Bevis RR. *Bond strength of ceramic brackets under shear stress: An in vitro report.* American Journal of Orthodontics and Dentofacial Orthopedics 1990;98:214-221.

Viazis AD, DeLong R, Bevis RR, Rudney JD, Pintado MR. *Enamel abrasion from ceramic brackets.* American Journal of Orthodontics and Dentofacial Orthopedics 1990;98:103 – 109.

Viazis AD, Nakajima H, Kleven JS. *Shear bond strengths of three new ceramic brackets.* Journal of Clinical Orthodontics 1993;27: 539-542.

Wang WN, Meng CL, Tarng TH. *Bond strength: A comparison between chemical coated and mechanical interlock bases of ceramic and metal brackets.* American Journal of Orthodontics and Dentofacial Orthopedics 1997;111:374-381.

Watson WG. *Future shock and adult orthodontics.* American Journal of Orthodontics 1979;76:577-580.

White LW. *Glass ionomer cement.* Journal of Clinical Orthodontics 1986;20:387-391.

Whitlock III BO, Eick JD, Ackerman RJ Jr, Glaros AG, Chappell RP. *Shear strength of ceramic brackets bonded to porcelain.* American Journal of Orthodontics and Dentofacial Orthopedics 1994;106:358-364.

Willems G, Carels CEL, Verbeke G. *In vitro peel/shear bond strength evaluation of orthodontic bracket base design.* Journal of Dentistry 1997;25:271-278.

Willems G, Carels CEL, Verbeke G. *In vitro peel/shear bond strength of orthodontic adhesives*. Journal of Dentistry 1997;25:263-270.

Wilson AD, Kent BW. *A new translucent cement for dentistry*. British Dental Journal 1972;132:133-135.

Wilson AD, McLean JW. *Glass Ionomer Cement*. Chicago: Quintessence Publishing Co, 1988:25.

Wiltshire WA. *Shear bond strengths of a glass ionomer for direct bonding in orthodontics*. American Journal of Orthodontics and Dentofacial Orthopedics 1994;106:127-130.

Winchester LJ. *A comparison between the old Transcend and the new Transcend series 2000 bracket*. British Journal of Orthodontics 1992;19:109-116.

Wood DP, Jordan RE, Way DC, Gali KA. *Bonding to porcelain and gold*. American Journal of Orthodontics and Dentofacial Orthopedics 1986;89:194-205.

Zachrisson BU, Büyükyilmaz T, Zachrisson YO. *Improving orthodontic bonding to silver amalgam*. The Angle Orthodontist 1995;1:35-42.

Zachrisson YO, Zachrisson BU, Büyükyilmaz T. *Surface preparation for orthodontic bonding to porcelain*. American Journal of Orthodontics and Dentofacial Orthopedics 1996;109:420-430.

Zachrisson BU. *Orthodontic bonding to artificial tooth surfaces: Clinical versus laboratory findings*. American Journal of Orthodontics and Dentofacial Orthopedics 2000;117:592-594.