sciendo DOI: 10.2478/aoj-1999-0005

Bond strengths of orthodontic brackets to restorative resin composite surfaces

Poon Y. Lai
BDSc(Qld), FRACDS, MDSc(Melb)
Private practice, Orthodontics, Brisbane, Australia.

Michael G. Woods
MDSc(Melb), FRACDS, FRACDS(Orth), DOrth RCS(Eng), CertOrth(Okla), DipAmBdOrthod
Associate Professor and Head of Orthodontics,

Martin J. Tyas
BDS, PhD, DDSc, GradDipHlthSc, AFCHSE, CHE, FRACDS. FADM, FICD, FPFA
Associate Professor and Reader in Dental Materials,
The University of Melbourne
Australia

In orthodontic practice, it is not uncommon to bond brackets to resin composite restorations. With this in mind, this study was designed to compare first the shear/peel strengths of metal, ceramic and polycarbonate brackets bonded to microfilled resin composite (RC), 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); and then to examine the effects of thermocycling on the shear/peel strengths of these systems. Four different brackets were used: two stainless steel (Victory and Optimesh), one ceramic (Transcend 6000) and one polycarbonate (Spirit MB) Seventy-two specimens of each bracket were divided into three groups for bonding with one of the three adhesives. Half the specimens from each group were also thermocycled. Mean shear/peel bond strengths were found to be significantly different for the four different brackets, although not influenced by the three adhesives used within each group. All groups were found to have clinically-acceptable mean bond strengths, except for Spirit MB-System 1+. After thermocycling, both Optimesh-Transbond XT and Victory-System 1+ groups showed superior mean bond strengths (26.8 and 24.4 MPa, respectively) when compared with all other groups ($p<0.05$).
Applying the Weibull survival analysis for groups utilising Victory, Transcend 6000 and Spirit MB brackets, those with 90 per cent or greater probabilities of survival included Victory-System 1+, Transcend 6000-Fuji Ortho LC, Victory-Fuji Ortho LC and Spirit MB-Transbond XT groups. In all groups, bond failure was mainly (64 per cent) cohesive within the RC restorative surface. The thermocycled Spirit MB-Transbond XT group had the highest frequency of undamaged RC failure interfaces. Despite the focus of this study being on bond strength and the potential for surface damage, it was noted that these properties should always be considered alongside other factors such as the strength of the bracket itself, friction within the bracket slot, patients' wishes, cost of the materiols and the presenting malocclusion.

Aust J Orthod 1999; 15 235–45

Received for publication: February 1998
Accepted December 1998

Introduction

Teeth that have been restored with resin composite (RC) are commonly encountered in any orthodontic practice, especially since adults now make up a significant proportion (about 25 per cent) of the total patient pool.[1-3] In addition, adults are more likely than younger patients to present with restorations.[4-7] When used as an aesthetic restorative material, RC usually replaces outer portions of teeth missing as a result of trauma, caries, erosion, abrasion, attrition, hypoplasia or other anomalies such as microdontia. RC is also used to mask intrinsic discolouration or staining such as that from tetracycline, excessive fluoride intake at a young age, and devitalised or endodontically-treated teeth. It is not uncommon, therefore, to find situations in which orthodontic brackets must be bonded to RC surfaces. In addition, there are certain instances in which patients with anterior restorations are more likely to present at orthodontic offices. These patients would include those with severely-protruding maxillary incisors that have been reported to be at considerable risk of fracture and thus requiring restoration.[8-10] It is interesting to note that, in an informal survey of patients being treated in 1997 by the six orthodontic graduate-students at The University of Melbourne, eighteen patients out of a total of three hundred and fifteen (5.7 per cent) required brackets to be bonded to anterior RC surfaces.

Despite the clinical need to bond to RC surfaces, there is not a great deal of information in the literature regarding the bonding of brackets to them. Newman *et al.*,[11] Kao *et al.*,[12] Schwartz *et al.*[13] and Chunhacheevachaloke and Tyas[14] have all investigated certain aspects of this topic. Schwartz *et al.*,[13] for instance, found that the tensile strengths for metal brackets bonded to microfilled and hybrid RC surfaces satisfied the 7.8 MPa clinical bond strength requirement recommended by both Lopez[15] and Wright and Power.[16] Chunhacheevachaloke and Tyas[14] reported mean shear/peel bond strengths for ceramic brackets bonded to RC in the range of

17.1 to 19.2 MPa. Neither of these experiments involved the thermocycling of specimens to simulate the effects of normal thermally-induced stresses within the oral cavity.[17] If such thermocycling had been used, the bond strengths found in their studies may in fact have been quite different. Finally, it should be noted that in the works of Kao *et al.*[12] and Chunhacheevachaloke and Tyas,[14] only ceramic brackets were tested, and different adhesive-material systems were not compared.

With these things in mind, this study was designed first to compare the shear/peel bond strengths of metal, ceramic and polycarbonate brackets when bonded to microfilled RC, using either a chemically-cured composite adhesive, a light-cured composite adhesive, or a resin-modified glass ionomer cement; and then to investigate the effects of thermocycling on the shear/peel bond strengths of these systems.

Materials and methods

Two hundred and eighty-eight specimens of a microfilled RC restorative material,[*] consisting of BIS-GMA with TEGDMA, colloidal silica filler of ~0.04 µm at 52 per cent mass to volume were prepared using a plastic mould measuring 6 mm internal diameter 6 mm high. The RC was injected into the mould in 2 mm increments and cured by means of a light-curing unit[†] for 20 s for each increment. Following final curing, specimens were stored in water at 37° C for one week. The 288 cylinders were randomly divided into 24 groups of 12 specimens as illustrated in Figure 1. Brackets made from three different materials were used in this study: two stainless steel Siamese-type brackets,[‡] a ceramic Siamese-type bracket,[§] and a polycarbonate Siamese-type bracket,[||] as shown in Table I. Seventy-two brackets of each of the four varieties were used. For each bracket variety, three adhesive systems were tested (Table II): a light-cured resin-modified glass ionomer,[¶] a light-cured composite[**] and a chemical-cured composite.[††]

Each RC surface for bracket attachment was cleaned using a pumice and water slurry in a rubber cup attached to a revolving slow speed handpiece. The RC surface was roughened with a fine disc,[‡‡] etched with 37 per cent phosphoric acid for 30 seconds, rinsed with water and dried with oil-free compressed air. The manufacturers' instructions for further treatment of the surface and bonding of brackets were followed. Half the specimens were thermocycled 50015 times[12,18] between 5° C and 6° C with 20 s in each bath and 20 s between baths. The other half served as controls, stored in water at 37° C.

Shear/peel testing was performed using a universal test[§§] at a cross-head speed of 1 mm/min[17,19] and a 100 kg load cell, with a shear/peel jig.[||||] Each specimen was selected randomly and inserted snugly into an epoxy-resin prefabricated mount (contained in a PVC ring 24 mm diameter and 10 mm deep, with an aperture 6 mm in diameter) for testing. During insertion, each bracket was orien ted with its side facing the blade in order to achieve even contact of the guillotine blade with the bonded test bracket. The inner surface of the blade was set parallel to and at a distance of 1 mm from the RC surface (Figure 2).

Bond strength (BS) in megapascals (MPa) for each specimen was calculated using the formula:

$$BS = 9.807\,\frac{F}{A}$$

where F = the failure force (kg)
A = the surface area of the bracket base (mm²)

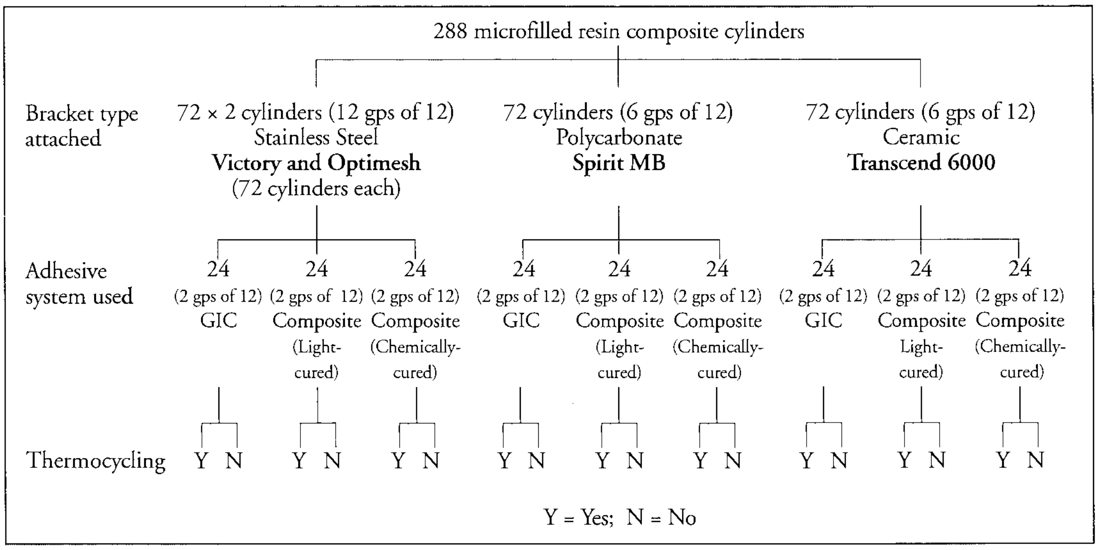

Figure 1. Allocation of the resin composite cylinders.

[*] Silux Plus: 3M,USA. Batch no.19960807, 6BN; Shade Dy.
[†] Optilux, Ormco, USA.
[‡] Victory: 3M, Monrovia, CA, USA & Optimesh; Ormco, Glendora, CA, USA.
[§] Transend 6000: 3M Monrovia, CA, USA.
[||] Spirit: Ormco, Glendora, CA, USA.
[¶] Fuji Ortho LC: GC, Tokyo, Japan.
[**] Transbond XT: 3M, Monrovia, CA, USA.
[††] System 1+: Ormco, Glendora, CA, USA.
[‡‡] Soflex: 3M, St.Paul, USA.
[§§] Shimadzu Autograph IS-5000, Serial #67617, Seisakusho Ltd, Kyoto, Japan.
[||||] Bencor: Danville Enginee ring Inc., San Ramon, CA, USA.

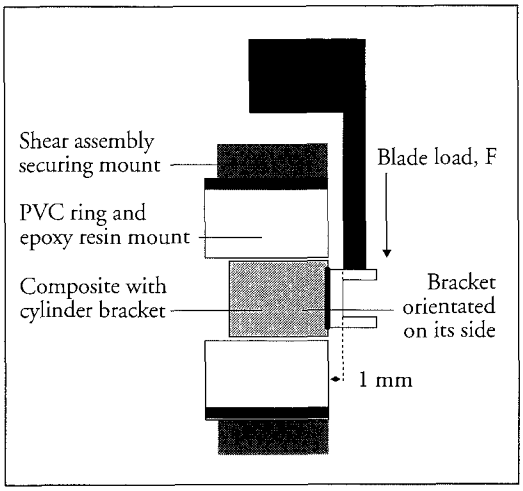

Figure 2. Cross-section of jig with mount and specimen.

The surface areas of the brackets were obtained from the manufacturers and verified using digital callipers.

After shearing, the bracket base and the corresponding RC disc were examined under a stereomicroscope at x 20 magnification. This enabled the determination of the failure interface and the use of the Adhesive Remnant Index (ARI; Carty and Tyas[20]).

The failure interface of each specimen was allocated to one of the following categories:

1. A/B: Adhesive/Bracket interface, where no adhesive remained on the bracket surface.
2. A/R: Adhesive/RC interface, where no adhesive remained on the RC surface.
3. COMB: Combination failure, where the adhesive failed and remained on both the bracket and the RC surface.
4. SC: Surface cracks or incomplete fracture observed on the intact RC surface.
5. RC#: Cohesive composite fracture, where the RC surface no longer remained intact, with or without involvement of Categories 2, 3 and 4.

The ARI for assessing the amount of adhesive remaining on the RC surface, was applicable only to specimens in Categories 1, 2 and 3 of the failure interface. A score from (i) to (v) was used: (i) a continuous layer of adhesive was present on the RC surface; (ii) greater than 90 per cent of the bonded RC surface was covered with adhesive; (iii) 10 to 90 per cent of the bonded RC surface was covered with adhesive; (iv) less than 10 per cent of the bonded RC surface was covered with adhesive, and (v) no adhesive remained on the RC, corresponding to Category 2, above.

The data were collected by one author (PYL) to eliminate inter-examiner variability. Intra-examiner reliability was tested by repeating all scoring and categorisation once, for both failure interface and ARI assessments, leading to 100 and 96.9 per cent agreements, respectively. When the first and second assessments were found to be different, each of the specimens concerned was re-examined to determine the final categorisation or scoring to be used.

A spreadsheet¶¶ was used to obtain basic descriptive statistics. All other analyses were performed using Minitab.*** These analyses included a three-way analysis of variance (ANOVA) at the 5 per cent level of significance, a customised macro used for the 270 multiple pairwise comparisons of the differences in mean bond strengths for the 24 groups, and the Weibull survival analysis (a log linear regression developed to assess differences in the distribution of failure interfaces amongst the specimens).

Results

The mean shear/peel bond strengths and other descriptive statistics for the 24 groups using the three adhesives with the four different brackets, thermocycled (T) and non-thermocycled (NT), are shown in Table III and Figure 3.

The three-way ANOVA indicated no significant differences in the mean bond strengths of the three adhesive systems within each bonded bracket variety except for the Spirit MB brackets; for those brackets, multiple pairwise comparisons indicated that bond strengths using Fuji Ortho LC (T, 10.9 MPa, NT, 9.72 MPa) and Transbond XT (T and NT, 10.9 MPa) were significantly greater than System 1+ (T, 4.09 MPa, NT, 3.06 MPa; $p<0.05$).

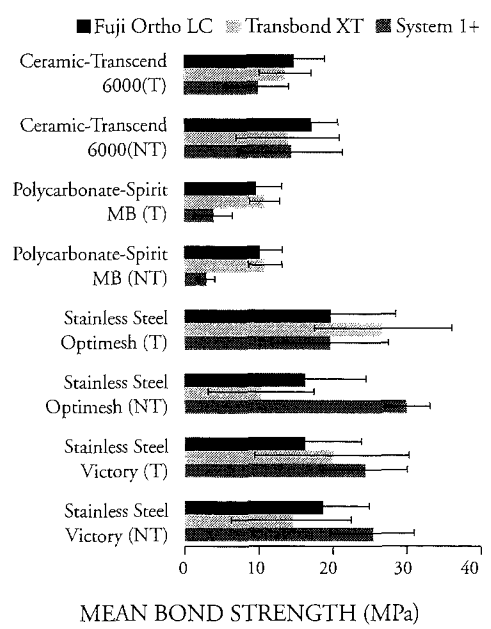

Figure 3. Bond strength of bracket adhesive combinations thermocycled (T) and non-thermocycled (NT).

¶¶ Excel: Microsoft Corp. Redmond, USA.

*** Minitab Inc, Reading, USA.

Table I. Brackets used.

Proprietary Name(Code)	Type	Area of base (mm^2)	Method of retention	Specification	Batch No.	Manufacturer
Victory Series (SS-VIC)	Stainless steel	11.3	Mechanical (80 gauge)	Upper centrals 0.22 slot 0*Torque, 0* Angulation	32408,9603	Unitek/3M Monrovia CA, USA
Mini Diamond **Optimesh** (SS-OPTI)	Stainless steel	12.8	Mechanical (100 gauge, roughened mesh) and Chemical (Silanated)	Upper centrals 0.22 slot +14* Torque, +5* Angulation	6H447H	Ormco Glendora CA, USA
Spirit MB (POLY)	Polycarbonate	11.6	Mechanical	Upper centrals 0.22 slot 0* Torque, +5* Angulation	6D31	Ormco Glendora CA, USA
Transcend 6000 (CERAM)	Ceramic (polycrystalline)	11.9	Mechanical	Upper centrals 0.22 slot 0* Torque, 0* Angulation	32403,1190	Unitek/3M Monrovia CA, USA

Table II. Adhesive systems used.

Proprietary Name	Type	Composition	Batch No.	Manufacturer
Transbond XT	Light-cured composite adhesive (no-mix paste-liquid)	Paste: ~18% BIS-GMA/TEGDMA monomers and ~82% hybrid filler of submicron silica, microfine composite of 3 μm average particle size. Adiketone and an organic amine as photoinitiators. Liquid: BIS-GMA combined with a urethane oligomer	092096, 426A Paste: 6BT Liquid:6BR	Unitek/3M Monrovia CA, USA
System 1+	Chemical-cured composite adhesive (no-mix paste-liquid)	Paste: ~60% BIS-GMA/Triethylene-glycol-dimethacrylate (TEGDMA) monomers and ~40% hybrid fill (~29% of 6μm and ~11% of 0.03μm average particle size, silane-treated quartz particles). Benzoyl peroxide catalyst (=1.0%) Liquid: BIS-GMA combined with a urethane oligomer	Paste: 6G1, 10/96 Liquid: 6G1, 8/96	Ormco Glendora CA, USA
Fuji Ortho LC	Light-cured resin-modified glass ionomer (Powder-liquid, hand mixing required)	Powder: Fluoroaluminosilicate glass Liquid: HEMA, water, copolymer of acrylic and maleic acids, activator and camphorquinone (photoinitiator) Powder/liquid ratio of 3 g to 1 g	Powder: 250851 Liquid: 210851	GC Corp Itabashi-ku Tokyo, Japan

The ANOVA also showed significant differences ($p<0.01$) in mean shear/peel bond strengths for the different bracket varieties. Bond strengths with steel brackets (Optimesh and Victory) were generally greater than those with ceramic (Transcend 6000) and polycarbonate (Spirit MB) brackets (Table III). Optimesh, Victory, Transcend 6000 and Spirit MB brackets had mean bond strength ranges of 10.4 to 30.1 MPa, 14.5 to 25.4 MPa, 10.0 to 17.2 MPa, and 3.1 to 10.9 MPa, respectively.

Thermocycling significantly affected only the Optimesh steel brackets bonded with Transbond XT or System 1+ ($p<0.001$; Table III). The mean bond strength was enhanced by 157 per cent (10.4 MPa to 26.8 MPa) for those brackets bonded with Transbond XT, whereas those bonded with System 1+ were weakened by 34 per cent (30.1 MPa to 19.8 MPa), when compared with NT control groups.

Table III. Descriptive statistics of shear/peel bond strengths.

Adhesive	Bracket	Thermocycled	Mean (MPa)	T-test (p)	Maximum (MPa)	Minimum (MPa)	S.D. (MPa)
Transbond XT	SS-VIC	Yes	20.0*	n.s	37.8	6.29	10.5
(Light-cured		No	14.5		26.3	3.91	8.16
composite)	SS-OPTI	Yes	26.8	0.0001	39.8	7.85	9.29
		No	10.4		25.1	2.30	7.15
	POLY	Yes	10.9	n.s	14.4	7.61	1.99
		No	10.9*		15.9	7.82	2.28
	CERAM	Yes	13.6*	n.s	19.4	8.65	3.64
		No	14.0		29. 7	6.39	6.89
System 1+	SS-VIC	Yes	24.4	n.s	32.6	12.2	5.76
(Chemical-cured		No	25.4		34.9	15.4	5.66
composite)	SS-OPTI	Yes	19.8	0.001	31.8	5.94	7.90
		No	30.1		35.2	24.9	2.99
	POLY	Yes	4.09	n.s	8.88	1.27	2.60
		No	3.06		5.28	1.06	1.09
	CERAM	Yes	10.0	n.s	22.3	5.77	4.27
		No	14.6		29.9	5.97	6.88
Fuji Ortho LC	SS-VIC	Yes	16.2	n.s	28.4	5.21	7.74
(Light-cured resin-	No	18.6		29.7	8.46	6.34	
modified glass-ionomer)	SS-OPTI	Yes	19.8	n.s	31.0	4.60	8.77
		No	16.2		28.4	4.60	8.35
	POLY	Yes	9.72	n.s	15.2	5.07	3.47
		No	10.3		15.4	6.13	2.93
	CERAM	Yes	15.0	n.s	22.7	7.42	4.21
		No	17.2		27.0	11.1	4.82

*11 samples: one failed prior to testing n.s = non-significant (p<0.05) S.D.= Standard deviation

Table IV. Weibull analysis and probability of survival for the various brackets using different bonding systems.

Adhesive	Bracket	N	Mean Strength (MPa)	Weibull Modulus	Normalizing paramere (chararcteristic srrength)	Probability of survival at stress of		Stress for 99%, 95% and 5% probabilities of survival (MPa)		
					(MPa)	7.8 MPa	10.0 MPa	99%	95%	5%
Transbond XT	SS-VIC	23	17.2	1.88	19.34	83%	75%	1.67	3.98	34.7
(Light-cured	POLY	23	10.9	5.58	11.77	90%	67%	5.16	6.91	14.3
composite)	CERAM	23	13.8	2.67	15.56	85%	74%	2.77	5.11	23.5
System 1+	SS-VIC	24	24.9	5.39	27.05	100%	100%	11.5	15.6	33.2
(chemical-cured	POLY	24	3.58	1.94	4.06	3%	0%	0.38	0.88	7.13
composite)	CERAM	24	12.3	2.21	13.96	76%	62%	1.74	3.64	23.0
Fuji Ortho LC	SS-VIC	24	17.4	2.83	19.57	93%	86%	3.84	6.84	28.9
(Resin-modified	POLY	24	10.0	3.61	11.15	76%	51%	3.12	4.89	15.1
glass-ionomer)	CERAM	24	16.1	3.83	17.76	96%	90%	5.34	8.18	23.7

When considering both T and NT groups, multiple pairwise comparisons showed that the Victory-System 1+ combination had the greatest mean bond strength which was also unaffected by thermocycling (T, 24.4 MPa ; NT, 25.4 MPa) (p<0.01). When considering only T groups, both the Optimesh-Transbond XT and Victory-System 1+ combinations had similar mean bond strengths (26.8 and 24.4 MPa, respectively). These were greater than all other combinations (p<0.05).

The Weibull analysis was applied to the pooled T and NT groups that were unaffected by thermocycling. These involved the Victory, Transcend 6000 and Spirit MB brackets. Table IV shows the results of the Weibull analysis including the Weibull modulus and characteristic strength, together with the probabilities for survival under stresses of 7.8 and 10.0 Mpa; the bond strengths considered to be clinically acceptable for most orthodontic needs by Reynolds[21] and Maijer and Smith,[22] respectively.

Table V. Failure interface for the various adhesive-bracket combinations.

Adhesive	Bracket	Thermocycled	Failure interface (Category)				
			A/B(1)	A/R(2)	COMB(3)	SC(4)	RC# (5)
Transbond XT	SS-VIC	No	0	4	0	2	6
(Light-cured		Yes	0	0	0	2	10
composite)	SS-OPTI	No	0	5	0	4	3
		Yes	0	0	0	0	12
	POLY	No	1	0	8	1	2
		Yes	2	0	9	0	1
	CERAM	No	0	0	5	2	5
		Yes	0	0	6	2	4
System 1+	SS-VIC	No	0	0	0	0	12
(Chemical-cured		Yes	0	0	0	1	11
composite)	SS-OPTI	No	0	0	0	0	12
		Yes	0	0	0	0	12
	POLY	No	0	0	8	2	2
		Yes	0	0	7	2	3
	CERAM	No	0	0	3	1	8
		Yes	0	0	7	1	4
Fuji Ortho LC	SS-VIC	No	0	0	0	1	11
(Light-cured resin-		Yes	0	0	2	0	10
modified glass	SS-OPTI	No	0	0	0	0	12
ionomer)		Yes	0	0	0	1	11
	POLY	No	0	0	4	0	8
		Yes	0	0	4	2	6
	CERAM	No	0	0	1	0	11
		Yes	0	0	2	2	8
			3	9	66	26	184
							N = 288

Table VI. Failure interface pooled into "Undamaged" RC and "Damaged" RC categories.

Adhesive	Bracket	Thermocycled	Fracrure interface Undamaged RC	Damaged RC
Transbond XT	SS-VIC	No	4	8
(Light-cured		Yes	0	12
composite)	SS-OPTI	No	5	7
		Yes	0	12
	POLY	No	9	3
		Yes	11	1
	CERAM	No	5	7
		Yes	6	6
System 1+	SS-VIC	No	0	12
(Chemical-cured		Yes	0	12
composite)	SS-OPTI	No	0	12
		Yes	0	12
	POLY	No	8	4
		Yes	7	5
	CERAM	No	3	9
		Yes	7	5
Fuji Ortho LC	SS-VIC	No	0	12
(Light-cured resin-		Yes	2	10
modified glass-	SS-OPTI	No	0	12
ionomer)		Yes	0	12
	POLY	No	4	8
		Yes	4	8
	CERAM	No	1	11
		Yes	2	10
			78	210
				N = 288

Table VII. Adhesive Remnant Index

Adhesive	Bracket	Thermocycled	Distribution of the Adhesive Remnant Index				
			(i)	(ii)	(iii)	(iv)	(v)
Transbond XT	SS-VIC	No	0	0	0	0	4
(Light-cured		Yes	0	0	0	0	0
composite)	SS-OPTI	No	0	0	0	0	5
		Yes	0	0	0	0	0
	POLY	No	1	8	0	0	0
		Yes	2	8	1	0	0
	CERAM	No	0	5	0	0	0
		Yes	0	5	1	0	0
System 1+	SS-VIC	No	0	0	0	0	0
(Chemical-cured		Yes	0	0	0	0	0
composite)	SS-OPTI	No	0	0	0	0	0
		Yes	0	0	0	0	0
	POLY	No	0	1	7	0	0
		Yes	0	2	5	0	0
	CERAM	No	0	2	1	0	0
		Yes	0	4	3	0	0
Fuji Ortho LC	SS-VIC	No	0	0	0	0	0
(Light-cured resin-		Yes	0	1	0	1	0
modified glass	SS-OPTI	No	0	0	0	0	0
ionomer)		Yes	0	0	0	0	0
	POLY	No	0	1	3	0	0
		Yes	0	2	2	0	0
	CERAM	No	0	0	1	0	0
		Yes	0	2	0	0	0
			3	41	24	1	9
							N = 78

The combinations with the three highest Weibull moduli were Spirit MB-Transbond XT, Victory-System 1+ and Transcend 6000-Fuji Ortho LC. Combinations with the three highest characteristic strengths were Victory-System 1+, Victory-Fuji Ortho LC and Victory-Transbond XT.

The probabilities of survival at a stress level of 7.8 MPa for Victory steel brackets using Transbond XT, System 1+ and Fuji Ortho LC were 83, 100 and 93 per cent, respectively. Similarly, the probabilities of survival for Spirit MB polycarbonate brackets using the three adhesives were 90, 3 and 76 per cent, respectively, and those for bonded Transcend 6000 ceramic brackets were 85, 76 and 96 per cent, respectively.

The stress levels required for 99, 95 and 5 per cent probabilities of survival for each adhesive and bracket combination are also given in Table IV. Based on the Weibull analysis, the maximum stress levels with a 99 per cent probability of survival for Victory steel brackets bonded using Transbond XT, System 1+ and Fuji Ortho LC were 1.67, 11.5 and 3.84 MPa, respectively (Table IV).

Table V lists the failure interface in the five categories. The predominant (64 per cent) bond failure interface was a cohesive RC fracture (Category 5). Categories were pooled (Table VI) for analysis, as either "Damaged" RC (Categories 1, 2 and 3) or "Undamaged" RC (Categories 4 and 5) since many cells in Table V have fewer than five observations.

A log linear regression on these two pooled categories revealed significant differences in the failure interface for specific adhesive-bracket groups ($p<0.001$). Steel brackets (Victory and Optimesh) bonded using System 1+ and Fuji Ortho LC had significantly higher frequencies of "Damaged" RC failure interfaces compared with polycarbonate brackets (Spirit MB) using Transbond XT and Fuji Ortho LC ($p<0.001$). Thermocycling generally did not influence failure interface outcomes of the bonds within each bracket variety ($p>0.95$), but did so for the different bracket materials ($p<0.05$).

Based on failure-interface outcomes, polycarbonate brackets (Spirit MB) and ceramic brackets (Transcend 6000) bonded with light or chemical-cured composite adhesives resulted in more "Undamaged" RC failure interfaces, as shown in Table VI, than did steel brackets (Victory and Optimesh), especially following thermocycling.

The Adhesive Remnant Index (ARI) was only applicable to the 27 per cent (78 out of 288) of specimens that had been categorised into the "Undamaged" RC failure interface group (Table VI). Of these 78 specimens, 44 had a score of (i) or (ii) (Table VII). There were only ten specimens that had either a score of (iv) or (v).

Discussion

This experiment incorporated different adhesive and bracket combinations so that comparisons could be made directly amongst these systems without having to rely on data from other studies. It should also be noted that since the torque and angulation of Optimesh and Spirit MB prescription brackets are built into their slots rather than into their bases, it is unlikely that the orientation of the brackets relative to the shear blade would have had any effect on the results. This would validate the comparison of prescription brackets with the standard non-prescription brackets used in this study.

No significant differences were found in the mean bond strengths for the three adhesive systems tested, except when polycarbonate brackets were used. The weakest combination occurred when polycarbonate brackets were bonded using the no-mix chemical-cured composite adhesive (Spirit MB-System 1+ groups). This finding would be supported by prior investigations of bonding to enamel, because bonds with two-paste chemical-cured composite adhesives have generally been found to be stronger than those with the no-mix chemical-cured composite adhesives,[19,23-5] and bonds with light-cured no-mix composite adhesives have been shown to be as strong as those with two-paste chemical-cured composite adhesives.[26-29] All these previous studies have implied therefore that the no-mix chemical-cured composite adhesives are weaker than the no-mix light-cured composite adhesives. This was certainly found to be the case in the present study.

The fact that low strengths were found for the bonded polycarbonate brackets might suggest the need for the use of plastic-bracket primers, which were developed to improve bonding of diacrylate adhesives to plastic.[19-31] When Spirit MB polycarbonate brackets were used, the manufacturer's recommendation not to use such primers was adhered to in this study. Furthermore, although these polycarbonate brackets are reinforced with glass fillers and metal slots,[32-35] they are more likely to deform under shear/peel loading than either ceramic or metal brackets, thus accentuating the peel component, in turn, leading to lower bond strengths.[32,33]

It is interesting to note that thermocycling only affected the groups with Optimesh steel brackets. The lower mean strength found after thermocycling for these steel brackets bonded with chemical-cured composite adhesive would be supported by the findings of Klockowski *et al.*[36] and Millet and McCabe,[37] in studies involving steel brackets bonded to enamel. In contrast, an increase was found in the mean bond strength after thermocycling for the same Optimesh brackets, this time bonded with light-cured composite adhesive. Unfortunately, this difference could not be confirmed with reference to available studies,[11,12,17,19,36,38] none of which have involved any comparison of thermocycled and non-thermocycled bracket specimens when using light-cured composite adhesives.

If mean bond strength only is used as a reflection of likely clinical performance, the Victory steel brackets bonded with chemical-cured composite adhesive would be recommended, because they showed the highest mean strength, regardless of thermocycling ($p<0.01$). If, however, the effects of experimental thermocycling to mimic the thermal stresses in the oral environment are also taken into account, both Optimesh brackets bonded with light-cured composite adhesive (Transbond XT) and Victory steel brackets bonded with chemical-cured composite adhesive (System 1+) would be recommended, with thermocycling, both these combinations showed superior mean strengths when compared with all other tested combinations ($p<0.05$). It must be said, however, that all tested bracket-adhesive combinations, except for the polycarbonate brackets (Spirit MB) bonded with chemical-cured composite adhesive (System 1+), attained clinically-acceptable mean bond strengths, even according to the 8 to 10 MPa recommendation of Maijer and Smith,[22] which itself exceeds the commonly-recommended 5.9 to 7.8 MPa range of Reynolds.[21]

The study by Chunhacheevachaloke and Tyas[14] reported mean shear bond strengths in the range of 19.2 (± 6.8) MPa for ceramic brackets bonded to RC with chemical-cured composite adhesive, and not subjected to thermocycling. This range is comparable to that found in the present study for such non-thermocycled ceramic bracket specimens bonded with chemical-cured composite adhesive (14.0 ± 6.9 Mpa). Newman *et al.*[11] examined the bonding of steel brackets to RC[‡‡‡] surfaces using a two-paste composite adhesive[§§§] and subjected to thermocycling, reporting a mean bond strength of 9.0 (± 0.5) MPa. This is lower than the mean bond strength following thermocycling found in the present study for steel brackets (Victory and Optimesh) similarly bonded with chemical-cured composite adhesive 24.4 (± 5.8) and 19.8 (± 8.0), respectively. The considerably greater ranges found in this study may at least be partly explained by improvements that have recently been made in both bracket design and adhesive formulation.

The Weibull survival analysis was used in this study, since it has previously been shown to provide a reasonable indication of the likely clinical performances of various bracket-adhesive combinations, focusing on the probability of bond survival or failure rather than simply on mean bond strength.[39-44] The

‡‡‡Isosit; Vivadent Corp., NY, USA.

§§§Concise: 3M, St Paul,MN, USA.

Weibull analysis requires the use of as many specimens within each subgroup as possible (at least 20) for a reliable prediction to be made. "Unaffected" corresponding thermocycled and non-thermocycled groups were therefore pooled to increase the sample size of each group. This was only possible for bracket-adhesive combinations involving Victory, Transcend 6000 and Spirit MB brackets. Comparing these three bracket varieties and all adhesives, using the Weibull analysis and Reynolds' recommendation[21] of 7.8 MPa as the minimum clinically acceptable bond strength, combinations with probabilities of bond survival of greater than 90 per cent were: Victory-System 1+, Transcend 6000-Fuji Ortho LC, Victory-Fuji Ortho LC, and Spirit MB-Transbond XT. In addition, the reliability of the bond is a function of both the Weibull modulus and its characteristic strength; a high modulus reflects a close grouping of results and therefore increased bond-reliability. Taking all the parameters of the Weibull analysis into consideration, the above bracket-adhesive combinations would be preferred to the others tested in this study, if bond strength and bracket-survival were considered to be the only important clinical factors.

If the combination least likely to cause damage during debonding to the RC surface itself were the mere choice, according to the results of this study, the Spirit MB brackets bonded with Transbond XT would be preferred. This combination was, however, found to have only a 67 per cent probability of survival according to the clinically acceptable bond strength recommendation of Maijer and Smith.[22] This means that, to decrease the clinical risk of damage occurring to the RC surface, a higher rate of bond failure may have to be accepted. Brackets may therefore have to be rebonded several times during treatment, in order to limit the potential for damage during debonding. This perhaps highlights the fact that this is not simply a search for the strongest bond, but instead for one that is clinically useful, allowing brackets to be retained throughout the active treatment period, before being then removed efficiently at the end of active treatment without damaging the bonding surface, whether that be enamel, RC or anything else. Furthermore, with 73 per cent of the RC specimens experiencing some form of surface damage, if this study were to truly mimic what might happen clinically, patients would have to be informed that surfaces of RC restorations with bonded brackets would very likely be damaged upon intentional or unintentional debonding, requiring further restoration of the involved tooth.

Limitations of this study

1. Extrapolation of laboratory results to the clinical situation must be made with caution,[39,45] although many factors in this study were considered to mimic ideal clinical situations.
2. The resin-composite cylinders were only thermocycled after the bonding of brackets to them. Thermocycling before bonding may have more closely simulated the normal ageing of resin-composite restorations in the mouth.
3. Hand pressure only was used to ensure close adaptation of bracket bases to the bonding surfaces, much as would be done in normal clinical practice. Neither a special gauge (such as a modified Dontrix gauge; Chamda and Stein[29]) nor any extra weight was used to apply pressure to the bonded brackets before initial set. It is possible that hand pressure alone may not result in a really consistent thickness of adhesive. This, in turn, might somehow have influenced the bond strengths of the specimens. In addition, since adhesive thickness was not measured, variation in film thickness may have occurred. It is also likely that the thickness of cement would have varied across the bases of individual brackets, since most bracket bases are designed with some curvature on their seating surfaces, to facilitate close adaptation to the tooth surfaces.

Conclusions

1. Mean bond strengths were significantly different for the four varieties of bracket, although the bond strengths were not influenced by the various bonding systems used within each bracket variety.
2. All bracket-adhesive combinations had mean bond strengths that were assessed to be clinically satisfactory, except for the Spirit MB-System 1+ combination.
3. Thermocycling affected only the Optimesh steel brackets bonded with both light- and chemical-cured composite adhesives. The mean bond strength for Optimesh brackets bonded with Transbond XT was enhanced by 157 per cent, while the mean bond strength for Optimesh brackets bonded with System 1+ was diminished by 34 per cent, when compared with non-thermocycled controls.
4. With thermocycling, both the Optimesh-Transbond XT and Victory-System 1+ combinations showed greater mean bond strengths (26.8 and 24.4 Mpa, respectively) than all other combinations ($p<0.05$).

5. The Weibull survival analysis, used for predicting clinical performance of bracket-adhesive combinations, indicated that Victory-System 1+, Transcend 6000-Fuji Ortho LC, Victory-Fuji Ortho LC, and Spirit MB-Transbond XT combinations all have survival probabilities of greater than 90 per cent; that is, their survival rates when bonded to RC would all be clinically acceptable.
6. The bond failure site was mainly (64 per cent) cohesive RC fracture; that is, the RC restorative surfaces were damaged in most cases.
7. The bracket-adhesive combination with the lowest frequency of cohesive type RC fractures, and therefore the least likely to damage the RC surfaces, was the Spirit MB-Transbond XT system. That said, bond strength and the potential for surface damage during debonding are not the only bracket and/or adhesive properties to be considered when choosing brackets for bonding. These properties should also be considered alongside others such as the strength of the bracket itself, friction within the bracket slot, patients' wishes, cost of materials and the actual presenting problems.

Acknowledgments

The authors would like to thank Ms Florence Choo from The University of Melbourne Statistical Consulting Centre for her help with the statistical treatment of data in this study. They would also like to thank Ormco Corporation, 3M Unitek Dental Products and GC America Inc., for their donations of the commercial products necessary for this study. This project was supported in part by a grant from The Australian Society of Orthodontists Foundation for Research and Education.

Address for correspondence and reprints:

Associate Professor M. Woods
Orthodontic Unit, School of Dental Science
The University of Melbourne
711 Elizabeth Street,
Melbourne, Victoria 3000
Australia

References

1. McKiernan EXF, McKiernan F, Jones ML. Psychological profiles and motives of adults seeking orthodontic treatment. Int J Adult Orthod Orthognath Surg 1992; 7: 187-98.
2. Salonen L, Mohlin B, Gotzlinger B, Hellden L. Need and demand for orthodontic treatment in an adult Swedish population. Eur J Orthod 1992; 14: 359-68.
3. Gottlieb EL, Nelson AH, Vogels DS. 1990 JCO study of orthodontic diagnosis and treatment procedures. Part 1: Results and trend. J Clin Orthod 1991; 25: 145-56.
4. Barnard PD. National Oral Health Survey Australia 1987-88: Canberra: Australian Government Publishing Services, 1993: 46-7.
5. Downer MC. Changing trends in dental caries experience in Great Britain. Adv Dent Res 1993; 7: 19-24.
6. Downer MC. The 1993 national survey of children's dental health: a commentary on the preliminary report. Br Dent J 1994; 176: 209-14.
7. Nattrass C, Sandy JR. Adult Orthodontics a review. Brit J Orthod 1995; 22: 331-7
8. Ravn JJ. Dental injuries in Copenhagen school children, school years 1967-72. Comm Dent Oral Epidemiol 1974; 2: 231-45.
9. Garcia-Godoy F, Sanchez JR, Sanchez RP. Proclination of teeth and its relationship with traumatic injuries in preschool and school children. J Pedod 1982; 6: 114-9.
10. Dearing SG. Overbite, overjet, lip-drape and incisor tooth fracture in children. N Z Dent J 1984; 80: 50-2.
11. Newman SM, Dressler KB, Grenadier MR. Direct bonding of orthodontic brackets to esthetic restorative materials using a silane. Am J Orthod 1984; 86: 503-6.
12. Kao EC, Elisades T, Rezvan E, Johnston WM. Torsional bond strength and failure pattern of ceramic brackets bonded to composite laminate veneers. Eur J Orthod 1995; 17: 533-40.
13. Schwartz RE, Tyas MJ, West VC. The bonding of orthodontic brackets to composite resin surfaces. Current note No. 71. Aust Dent J 1990; 35: 472-3.
14. Chunhacheevachaloke E, Tyas MJ. Shear bond strength of ceramic brackets to composite resin surfaces. Aust J Orthod 1997; 15: 10-15.
15. Lopez JI. Retentive shear strengths of various bonding attachment bases. Am J Orthod 1980; 77: 669-78.
16. Wright WL, Powers JM. In vitro tensile bond strength of reconditioned brackets. Am J Orthod 1985; 87: 247-52.
17. Eliades T, Viazis AD, Eliades G. Bonding of ceramic brackets to enamel: morphologic and structural considerations. Am J Orthod Dentofac Orthop 1991; 99: 369-75.
18. Burger KM, Cooley RL, Garcia-Godoy F. Effect of thermocycling times on dentin bond strength. J Esthet Dent 1992; 4: 197-8.
19. Akin Nergiz N, Nergiz I, Behlfelt K, Platzer U. Shear bond strength of a new polycarbonate bracket: an in vitro study with 14 adhesives. Eur J Orthod 1996; 18: 295-301.
20. Carty G, Tyas MJ. Shear bond strength of a mechanically retained ceramic bracket. Aust Orthod J 1993; 13: 13-18.
21. Reynolds I. A review of direct orthodontic bonding. Br J Orthod 1975; 2: 171-8.
22. Maijer R, Smith DC. A new surface treatment for bonding J Biomed Mater Res 1979; 13: 975-85.
23. Reynolds IR, von Fraunhofer JA. Direct bonding in orthodontics: a comparison of attachments. Br J Orthod 1977; 4: 65-9.
24. Dickinson PT, Powers JM. Evaluation of fourteen direct-bonding orthodontic bases. Am J Orthod 1980; 78: 30-9.
25. Buzzitta VAJ, Hallgren SE, Powers JM. Bond strength of orthodontic direct-bonding cement-bracket systems as studied in vitro. Am J Orthod 1982; 81: 87-92.

26. Wang WN, Meng CL. A study of bond strength between light- and self-cured orthodontic resin. Am J Orthod Dentofacial Orthop 1992; 101: 350-4.
27. Smith RT, Shivapuja PK. The evaluation of dual cement resins in orthodontic bonding. Am J Orthod Dentofac Orthop 1993; 103: 448-51.
28. Aasrum E, Ng'ang'a PM, Dahm S, Ogaard B. Tensile bond strength of orthodontic brackets bonded with a fluoride-releasing light-curing adhesive: an in vitro comparative study. Am J Orthod Dentofac Orthop 1993; 104: 48-50.
29. Chamda RA, Stein E. Time-related bond strengths of light-cured and chemically cured bonding systems: an in vitro study. Am J Orthod Dentofac Orthop 1996; 110: 378-82.
30. Newman GV. Current status of bonding attachments. J Clin Orthod 1973; 7: 425-34.
31. de Pulido LG, Powers JM. Bond strength of orthodontic direct-bonding cement-plastic bracket systems in vitro. Am J Orthod 1983; 83: 124-30.
32. Britton JC, McInnes P, Weinberg R, Ledoux WR, Retief DH. Shear bond strength of ceramic orthodontic brackets to enamel. Am J Orthod Dentofac Orthop 1990; 98: 348-53.
33. Feldner JC, Sarkar NK, Sheridan JJ, Lancaster DM. In vitro torque-deformation characteristics of orthodontic polycarbonate brackets. Am J Orthod Dentofac Orthop 1994; 106: 265-72.
34. Sinha PK, Nanda RS. Esthetic orthodontic appliances and bonding concerns for adults. Dent Clin Nth Am 1997; 41: 89-109.
35. Bazakidou E, Nanda RS, Duncanson MG, Sinha PK. Evaluation of frictional resistance in esthetic brackets. Am J Orthod Dentofac Orthop 1997; 112: 138-44.
36. Klockowski R, Davis EL, Joynt RB, Wieczkowski G, McDonald A. Bond strength and durability of glass ionomer cements used as bonding agents in the placement of orthodontic brackets. Am J Orthod Dentofac Orthop 1989; 96: 60-4.
37. Millett DT, McCabe JF. Orthodontic bonding with glass ionomer cement: a review. Eur J Orthod 1996; 18: 385-99.
38. Newman GV, Sun BC, Ozsoylu SA, Newman RA. Update on bonding brackets: an in vitro survey. J Clin Orthod 1994; 28: 396-402.
39. Fox NA, McCabe JF, Gordon PH. Bond strengths of orthodontic bonding materials: an in vitro study. Br J Orthod 1991; 18: 125-30.
40. Mitchell L. An investigation into the effect of a fluoride releasing adhesive on the prevalence of enamel surface changes associated with directly bonded orthodontic attachments. Br J Orthod 1992; 19: 207-14.
41. Mitchell CA, O'Hagan E, Walker JM. Probability of failure of orthodontic brackets bonded with different cementing agents. Dent Mater 1995; 11: 317-22.
42. Millett D, McCabe JF, Gordon PH. The role of sandblasting on the retention of metallic brackets applied with glass ionomer cement. Br J Orthod 1993; 20: 117-22.
43. Fox NA, McCabe JF, Buckley JG. A critique of bond strength testing in orthodontics. Br J Orthod 1994; 21: 33-43.
44. Miller JR. Commentary: Basic concepts concerning bracket failure research. Angle Orthod 1997; 67: 167-8.
45. Winchester LJ. Bond strength of five different ceramic brackets: an in vitro study. Eur J Orthod 1991; 13: 293-305.