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ORIGINAL ARTICLES

Bond strength of orthodontic direct-bonding cement-bracket systems as studied in vitro

V. A. James Buzzitta, D.D.S., M.S.,* Steven E. Hallgren, D.D.S., M.S., and John M. Powers, Ph.D.*****
Ann Arbor, Mich.

Tensile bond strength and failure location were evaluated *in vitro* for three types of direct bonding cements (unfilled, low filled, and highly filled) with three types of brackets (polycarbonate, stainless steel, and ceramic) using natural teeth and plastic as substrates. An unfilled acrylic cement gave the highest values of bond strength for both the plastic and ceramic brackets, whereas a highly-filled diacrylate cement gave the highest bond strength for the metal brackets. Bond failures occurred at the bracket-cement interface with the stainless steel brackets with each cement, whereas failure locations occurred at the bracket-cement interface, within the cement, and within the bracket for the plastic and ceramic brackets. There were no significant differences in bond strength nor failure location between tooth and plastic substrates.

Key words: Orthodontic brackets, orthodontic cements, direct bonding, bond strength

An important step in successful direct bonding of orthodontic brackets would appear to be selection of a compatible bracket-cement system.[1] High bond strengths with plastic brackets were achieved in vitro with unfilled acrylic cements.[1, 2] Improved bonding of filled diacrylate cements to plastic brackets may result from the use of bracket primers. High bond strengths with metal brackets were achieved with filled diacrylate cements, but failures in vitro occurred consistently at the bracket-cement interface.[2-7] Important design parameters of the bases of metal brackets were identified as nominal area, mesh size, and damage caused by spot-welds.[3-8] An attempt to improve esthetics while maintaining bracket strength has resulted recently in the development of a ceramic bracket.

The purpose of this research was to evaluate tensile bond strength and failure location in vitro for three types of direct bonding cements (unfilled, low filled, and highly filled) with three types of brackets (polycarbonate, stainless steel, and ceramic) using natural teeth and plastic as substrates.

MATERIALS AND METHODS

Five commercial direct-bonding bracket-base combinations were tested for tensile bond strength. Three direct-bonding cements were used. Codes, catalog

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Correspondence concerning this article should be directed to Dr. John M. Powers, School of Dentistry, University of Michigan, Ann Arbor, Mich., 48109, telephone (313) 764-1530. Reprints may be requested from Dr. Powers.
*Practicing orthodontist in Ann Arbor, Mich.
**Practicing orthodontist in Mindin, Nev.
***Professor of Dentistry, Department of Dental Materials, School of Dentistry, The University of Michigan.

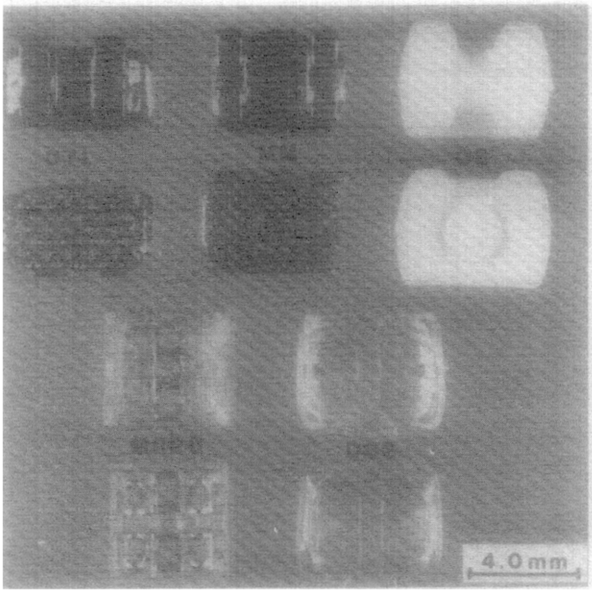

Fig. 1. Photograph of brackets tested.

numbers, and manufacturers of the brackets are listed in Table I, and the brackets are shown in Fig. 1. The polycarbonate and ceramic brackets were constructed in one unit. Of the stainless steel brackets tested, bracket UTL was attached to its base by a spot-welding technique, whereas bracket MM was attached by a brazing process by the manufacturer. The brazing process, however, required a preliminary tack-welding step. Both stainless steel bases were of the foil-mesh type. Table II lists the codes, chemical types, batch numbers, and manufacturers of the direct-bonding cements.

The nominal area of the base of each bracket was measured by planimetry* of enlarged photographs of the brackets. Where applicable, the mesh size (wires per linear inch) also was determined from these photographs.

Plastic cylinders with undercuts were used as retaining devices for the bonding cement as described elsewhere.[7] A mounting jig was constructed to ensure uniform placement of each bracket so as to minimize shear forces during loading. The brackets were tied to the jig with 0.010 inch stainless steel ligature wire.†

The direct-bonding cements were mixed according to manufacturers' instructions and loaded into the cylinders. The manufacturers of cements EN and ST recommended the use of their plastic bracket primer for bonding plastic brackets. These recommendations were followed during preparation of the samples. The ceramic brackets were tested both with and without a bracket primer (S).* A small portion of the cement was applied directly to the base to improve the adaptation of the cement to the retentive areas. The jig-bracket assembly was then pressed to place on the plastic cylinder.

After cementation, each bracket was inspected under magnification for overlapping cement. Any cement found on the labial surface of the bracket was removed. Five replications were tested for each bracket-cement combination.

After 24 hours, the mounted brackets were tied for testing of tensile bond strength. The mounted and tied brackets were immersed in distilled water at a temperature of 37° C. for 24 hours prior to testing. Immediately on removal from the water bath, the samples were placed in a loading jig described in detail elsewhere.[9] This loading jig was designed to distribute the load evenly during tension while minimizing shear forces. The samples were loaded by a testing machine† at a crosshead rate of 0.2 cm. per minute. The force at bond failure was recorded and was divided by the nominal area of the base to obtain the bond strength.

The bond failure sites were examined optically under low-power magnification. The failure sites were identified as within-cement, cement-bracket interface, or within-bracket.

Freshly extracted human maxillary central incisors were embedded in acrylic cylinders with the labial plate of enamel exposed. Each tooth was centrally placed, and the exposed enamel was aligned parallel with the cylinder surface. The enamel was cleansed for 60 seconds with a fluoride-free pumice paste.‡

The bracket-cement combination with the highest tensile bond strength from each bracket category was bonded to these teeth in accordance with manufacturers' recommendations. These combinations were MRPB with BE, UTL with ST, and CB(S) with BE. The testing procedures were done as described for the plastic substrates. The failure sites examined included the enamel-cement interface, within-cement, cement-bracket interface, or within-bracket. Five replications of each combination were tested.

Mean values and standard deviations of bond strength were computed. The data were analyzed statistically by analysis of variance[10] using a factorial design. Means were ranked by a Tukey interval[11] calculated at the 95 percent level of confidence. Differences between two means that were larger than the Tukey interval were statistically significant.

*Polar planimeter, Model 620015, Keuffel and Esser Company, Morristown, N. J.

†Unitek Corporation, Monrovia, Calif.

*Silane coupling agent A174, Union Carbide Corporation, New York, N. Y., diluted with denatured alcohol (50 percent by weight).

†Model TT-BM, Instron Corporation, Canton, Mass.

‡Precise, Lee Pharmaceuticals, South El Monte, Calif.

Table I. Code, catalog number, and manufacturer of the brackets tested

Code	Product	Catalog No.	Manufacturer
Plastic bracket:			
DBS*	Rocky Mountain's direct bond system bracket	A-3043	Rocky Mountain Orthodontics P.O. Box 17085 Denver, Colo. 80217
MRPB	Ormco's metal reinforced plastic bracket	130-0104	Ormco Corporation 1332 S. Lone Hill Ave. Glendora, Calif. 91740
Metal bracket:			
UTL	American Orthodontics' Ultra-Trim Line base	663-008 base 002-008 bracket	American Orthodontics 1714 Cambridge Ave. Sheboygan, Wis. 53081
MM	Ormco's Mini-Mesh base	300-0059 base 342-0401 bracket	Ormco Corporation
Ceramic bracket:			
CB	Zalauf's Ceramibond bracket	—	Zulauf, Inc. P.O. Box 6661 Lubbock, Texas 79413

*All brackets tested were for maxillary central incisors, with bracket slot dimensions of 0.022 by 0.028 inch, and were nontorqued and nonangulated.

Table II. Code, chemical type, batch number, and manufacturer of direct-bonding cements tested

Code	Product	Chemical type	Batch No.		Manufacturer
Unfilled cement:					
BE	Bond-Eze	Unfilled poly(methyl methacrylate) resin	Cement powder Cement liquid	061180 100879	Unitek Corporation 2724 South Peck Rd. Monrovia, Calif. 91016
Low-filled cement:					
EN	Endur	Sealant: Bis-GMA resin with dimethacrylate monomers Adhesive: Bis-GMA resin with dimethacrylate monomers and silica filler (28% by weight) Primer: Ethyl acetate solvent with poly(methyl methacrylate)	Adhesive resin Adhesive catalyst Sealant resin Sealant catalyst Plastic bracket primer	0K030 0J040 0H050 0H060 0D350	Ormco Corporation 1332 S. Lone Hill Ave. Glendora, Calif. 91740
Highly filled cement:					
ST	Solo-Tach	Sealant: Bis-GMA resin Adhesive: Bisphenol-A comonomer with vitreous fillers (55% by weight) Primer: Methyl methacrylate	Adhesive base, catalyst, and activator Sealant base Sealant catalyst Plastic bracket primer	090280 092380 092380 T0T579	L.D. Caulk Company P.O. Box 359 Milford, Del. 19963

RESULTS

Mean values and standard deviations of tensile bond strength for each of the brackets tested with cements BE, EN, and ST with the plastic substrates are listed in Table III. Also listed there are dimensions and nominal areas of the bases of the brackets, which ranged from 16.8 mm.^{2} for UTL to 21.2 mm.^{2} for CB. The base of UTL was 60 mesh, whereas that of MM was 100 mesh.

The mean tensile bond strength for cement BE ranged from 0.56 kg./mm.^{2} with MM to 1.26 kg./mm.^{2} with CB(S). The mean tensile bond strength for cement EN ranged from 0.47 kg./mm.^{2} with CB to 0.90 kg./mm.^{2} with UTL, and for cement ST it ranged from 0.52 kg./mm.^{2} with CB to 1.33 kg./mm.^{2} with UTL. The Tukey intervals for comparing brackets and cements for tensile bond strength were 0.11 kg./mm.^{2} and 0.06 kg./mm.^{2}, respectively. The coefficient of variation for the bond strength data was 12 percent.

The location of the failure varied with the type of bracket and cement (see Fig. 2). The metal brackets (UTL and MM) failed at the bracket-cement interface with all three cements. The plastic brackets (DBS and MRPB) failed more often at the base-cement interface but also within the bracket. Bracket DBS failed entirely within the bracket with cements BE and ST, whereas

Table III. Code, base dimensions, nominal area, and bond strength for brackets and cements tested

Code	Base dimensions (height-width) (mm.)	Nominal area (mm.²)	Bond strength (kg./mm.²)		
			BE	EN	ST
DBS	3.9 × 5.3	18.3	0.83 (0.02)*	0.58 (0.06)	0.80 (0.04)
MRPB	4.3 × 4.5	20.0	1.10 (0.06)	0.52 (0.08)	1.08 (0.07)
UTL	3.1 × 5.8	16.8	0.79 (0.14)	0.90 (0.07)	1.33 (0.16)
MM	3.8 × 5.1	17.4	0.56 (0.10)	0.59 (0.09)	0.87 (0.12)
CB	3.9 × 5.8	21.2	1.12 (0.14)	0.47 (0.04)	0.52 (0.13)
CB(S)†	—	—	1.26 (0.14)	0.49 (0.05)	0.56 (0.09)

*Mean of five replications with standard deviations in parentheses. Tukey intervals for comparisons of bond strength among bases and among cements were 0.11 and 0.06 kg./mm.², respectively.
†CB with silanation treatment.

Table IV. Comparison of mean tensile bond strength using plastic cylinders and natural teeth

Bracket code	Cement code	Tensile bond strength (kg./mm.²)	
		Plastic cylinders	Natural teeth
MRPB	BE	1.10 (0.06)*	1.06 (0.06)
UTL	ST	1.33 (0.16)	1.32 (0.17)
CB(S)	BE	1.26 (0.14)	1.29 (0.11)

*Mean value of five replications with standard deviations in parentheses.

the reinforced bracket (MRPB) had fewer within-bracket failures. Cement EN failed at the bracket-cement interface with both plastic brackets. Bond failure with the ceramic bracket occurred most frequently at the bracket-cement interface except with cement BE for which within-cement failures also occurred. The use of a silane primer with the ceramic bracket increased within-cement failure and, with cement BE, resulted in several within-bracket failures.

The mean values and standard deviations for the tensile bond strength using natural teeth and plastic substrates with base-cement combinations MRPB-BE, UTL-ST, and CB(S)-BE are listed in Table IV. There was no significant difference in bond strength between the tooth and plastic substrate for each bracket-cement combination at the 95 percent level of confidence.

DISCUSSION

In this study, when natural teeth were tested in vitro there were no failures at the enamel-cement interface. In vivo, however, more failures may be observed at this interface because of difficulties with isolation and access. Because of salivary contamination, ideal bonding to enamel is much more difficult to achieve in vivo.

The plastic bracket–cement combination MRPB-BE results in a high tensile bond strength. Cement BE is an unfilled acrylic which can chemically bond to the plastic bracket. Values obtained for the combination MRPB-ST are also quite high, while those for MRPB-EN are significantly lower. The observed values for EN and ST are noteworthy since a 1978 study by Faust and associates[2] concluded that these cements did not bond to plastic. The observed bond strengths have resulted from the recent addition of plastic bracket primers to these cement systems. The large discrepancy in values obtained between EN and ST using plastic brackets may be attributed to differences in composition between the respective bracket primers.

Differences in values of bond strength obtained for the two types of plastic bracket tested may be attributed to differences in strength of the brackets themselves. When used with cements BE and ST, bracket DBS failed within the bracket in all samples tested. This was a result of tensile bond strengths exceeding the strength of the bracket, resulting in fracture of the wings. MRPB, having a stainless steel endoskeleton, resulted in fewer within-bracket failures. The high percentage of within-bracket failures is consistent with clinical observations.[12]

The two metal brackets tested had foil-mesh bases. The metal brackets–cement combination with the highest tensile bond strength was UTL-ST. The greater values of tensile bond strength obtained for cements EN and ST support other recent studies[2-5] which indicate that diacrylate resins are the strongest cements when

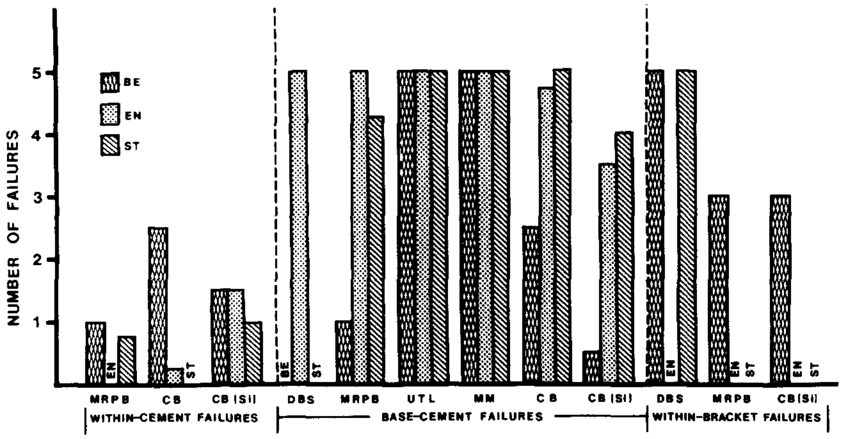

Fig. 2. Number of within-cement, base-cement, and within-bracket failures for cement-bracket systems studied. A fractional number indicates that failure of a sample occurred at more than one interface. Zero failures are indicated by absence of a bar.

metal brackets are used. EN contains 28 percent inorganic filler by weight, whereas ST contains 55 percent. Diametral tensile strengths for ST, EN, and BE were reported as 4.49, 3.21, and 2.52 kg./mm.^{2}, respectively.[2] These values demonstrate that as the amount of filler increases, the diametral tensile strength of the cement increases. The values obtained for metal brackets in this study indicate that as the diametral tensile strength of the cement increases, the tensile bond strength increases.

With each of the three cements used, the values of tensile bond strength for UTL were significantly greater than those for MM. Three characteristics of base design important in retention of direct bond cements are nominal area, mesh size, and spot welds.[6-8] The nominal areas of UTL and MM are similar. Reynolds and von Fraunhofer[3, 6] have shown that larger mesh size (50 to 70) generally results in higher bond strength. Our investigation seems to support their findings, since the base of UTL has a mesh size of 60 and the base of MM has a mesh size of 100. Recently, studies by Dickinson and Powers[7] and Maijer and Smith[8] have implicated spot welding as an important factor in bond strength. Spot-welds not only decrease the nominal area available for bonding but also act as areas of stress concentration which can initiate fracture of the cement at the bracket-cement interface.[7] Fig. 3 shows the differences in mesh size and spot-welding between UTL (right) and MM (left), respectively. Bracket MM has large areas of spot-welding damage to the retentive mesh, whereas UTL shows minimal damage. The combined effect of small mesh size and large spot-welds may explain the lower values obtained for MM. All bond failures for MM and UTL occurred at the bracket-cement interface, in agreement with earlier studies.[2-4, 7]

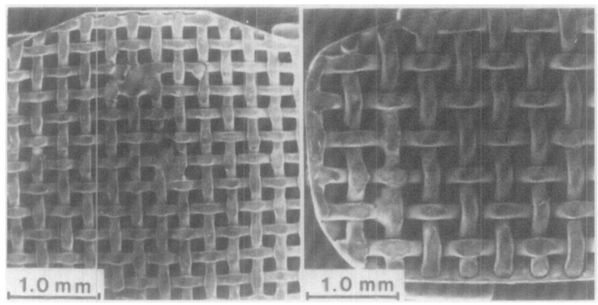

Fig. 3. Scanning electron photomicrographs of the bases of MM *(left)* and UTL *(right)*.

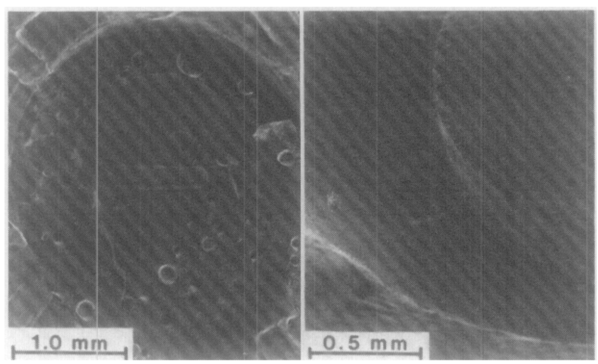

Fig. 4. Scanning electron photomicrographs of representative failure interfaces of bracket CB with cement BE *(left)* and cement EN or ST *(right)*.

The ceramic bracket (CB) is designed so that mechanical retention with the cement is obtained by a dovetailed circular undercut ring built into the center of its base. In an attempt to obtain a chemical bond and thus increase the tensile bond strength, a silane primer (S) was tested. A comparison of values of tensile bond strength for CB versus CB(S) indicates that the silane primer made a statistically significant difference only with cement BE. However, these values were not sufficiently different to suggest chemical bonding to the ceramic.

The value of tensile bond strength for CB-BE was more than twice that for cements EN and ST. This is surprising, in that cement BE is an unfilled acrylic cement that has the lowest diametral tensile strength. The failure interface of CB with cement BE is shown in Fig. 4, left. There is cement remaining throughout most of the retentive ring. Examination of samples of CB with cements EN and ST indicated that little or no cement remained in the retentive ring (Fig. 4, right). Observation of the tooth surface also revealed protruding rings of cement remaining. Although EN and ST (filled diacrylate cements) are intrinsically strong, their greater viscosity may prevent engagement into the depth of the retentive ring of bracket CB with an adequate bulk of cement. Cement BE, having a lower viscosity, can penetrate to the depth of this ring, thereby taking full advantage of the dovetail undercut. Shear tests with this ceramic bracket may yield greater bond strengths for the diacrylate ceramic because, in shear, it may not be critical that the cement reach the full depth of the undercut.

As indicated in Table IV, there were no significant differences between the values of tensile bond strength for the plastic cylinders and tooth substrates when combinations MRPB-BE, UTL-ST, and CB(S)-BE were tested. Thus, the plastic cylinder serves as a useful model for evaluating in vitro bond strength when failures occur at the bracket-cement interface or within the bracket.

CONCLUSIONS

1. Testing of three types of brackets with three types of direct bonding cements resulted in the determination of statistically significant differences for in vitro tensile bond strengths.

2. An unfilled acrylic cement gave the highest values of bond strength for both the plastic and the ceramic brackets.

3. A highly filled diacrylate cement gave the highest values of bond strength for the metal brackets.

4. No significant differences in bond strength or failure location were observed between natural teeth and plastic substrates for in vitro testing.

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