THE EFFECT OF BRACKET BASE DESIGN ON SHEAR BOND STRENGTH—AT THE BRACKET BASE-CEMENT INTERFACE

by

MARK A. NAISBITT

JOHN O. BURGESS, COMMITTEE CHAIR
DENIZ CAKIR
CHRISTOS VLACHOS

A THESIS

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MARK A. NAISBITT

CLINICAL DENTISTRY

ABSTRACT

Provided that a good enamel bonding procedure has taken place, in vitro and in vivo failure of orthodontic brackets most often takes place at the bracket base-cement interface. Current innovations in metal bracket base designs, therefore, most often have focused on improving bond strengths at this interface. Manufacturers claim their particular bracket base design will provide better bond strengths with less bracket failure than their competitors’ design. The purpose of this study was to evaluate the effect bracket base design on mean shear bond strength (SBS) at the bracket base-cement interface. The following four types of metal brackets were compared, ie, 20 Smart Clip brackets (80-gauge single-mesh base), 20 In-Ovation R brackets (SuperMesh, 81.50-gauge double-mesh base), 20 Quick brackets (machined, integral, microetched 3D hook base), and 20 T3 brackets (machined, integral, microetched base with mechanical undercuts). Ten bracket-cylinders of each type were debonded after 30 minutes, to simulate initial arch wire engagement. The remaining bracket-cylinders (10 of each type) were debonded after 24 hours and 2,500 rounds of thermocycling. The mean SBS for 30 minute and 24 hour time intervals were as follows: SmartClip, 14.66 ± 2.0 MPa and 25.55 ± 3.6 MPa; In-Ovation R, 14.56 ± 5.0 MPa and 24.94 ± 2.3 MPa; Quick, 11.82 ± 3.9 MPa and 26.82 ± 4.2 MPa; and T3, 24.24 ± 3.8 MPa and 36.86 ± 3.7 MPa. Debonded specimens were examined using 10X magnification to determine adhesive remnants on the acrylic cylinders and bracket bases. The modified adhesive remnant index (MARI) comparisons indicated that three of
the bracket types (SmartClip, In-Ovation R, Quick) had similar bracket failure modes, ie,
higher frequencies of MARI score 3 (more than half of the adhesive remained on the
cylinders and was removed from the bracket). However, the T3 bracket had higher
incidence of MARI score 2 (more than half of the adhesive remained on the bracket and
was removed from the cylinder). Bracket base design variations were found to
significantly influence SBS. The T3 bracket had significantly higher bond strengths than
the other bracket types (1-way ANOVA, $P \leq .05$) at both 30 minutes and 24 hours. The
Quick bracket had significantly lower SBS than the other bracket types at 30 minutes, but
SBS values were not significantly different from the mesh-based brackets at 24 hours ($P \leq
.05$). All four bracket types showed a significant increase in SBS from 30 minutes to 24
hours (2-way ANOVA, $P \leq .05$).
ACKNOWLEDGEMENTS

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INTRODUCTION

Direct Bonding in Orthodontics

In contemporary orthodontics, direct bonding of orthodontic brackets to enamel is essential. Since Buonocore’s\(^2\) inception of enamel conditioning via acid etching and Newman’s\(^3\) adaptation for orthodontic attachments, direct bonding in orthodontics has become the standard for over 30 years. Compared to circumferential banding, patients prefer the comfort and esthetic benefit. But the advantages for the clinician are even greater—mainly, eliminating the time, expense, and discomfort associated with banding each tooth. For anterior teeth, decalcification under loose bands as well as residual band spaces after debanding are a thing of the past.\(^4,5\) However, to accommodate for the loss of surface area and retention associated with tight-fitting bands, numerous bracket design modifications have been manufactured and tested. Additionally, modern brackets are often made smaller to be more esthetic, reducing surface area for bonding and increasing the risk of debonding.\(^6\) Although, studies have shown statistically insignificant differences in bond strengths due to differences in surface areas alone.\(^5,6\) Failure, or inadvertent debonding of a bracket from the tooth surface during treatment, can increase treatment time, decrease patient satisfaction, increase risk for decalcification, and increase in-office chair time and expense.\(^5,8\) A wide range of bracket bond failure rates are reported clinically, likely due to technique variations and contamination of the field during bonding.\(^6,7\) With the conventional 37% phosphoric acid etch technique, clinical failure rates during the course of treatment are usually considered to be between 7% and
It has been suggested that higher bond strengths obtained with more retentive brackets can lead to a decrease in unexpected debonding during treatment.\textsuperscript{10,11}

**Shear Bond Strength**

Orthodontic brackets undergo numerous insults from occlusal forces and mastication during treatment.\textsuperscript{12} It has been suggested that orthodontic brackets be able to resist 11 to 33 lbs of occlusal forces to remain attached to the tooth throughout the course of treatment.\textsuperscript{13-15} The retention of the appliance must be sufficient enough to withstand these forces immediately, upon engagement, and throughout the duration of treatment.\textsuperscript{16-18} The ability of a bracket to withstand these forces and stay attached to the tooth surface is most often characterized as bond strength. Bond strengths have been measured in the literature by multiple testing types; most commonly shear, peel, tension and torsion.\textsuperscript{19} Tension and shearing tests are the most common methods of testing bracket bond strengths. Both are considered to provide similar and clinically comparable values.\textsuperscript{7,20,21} The shearing force created by mastication and occlusal forces, if greater than bond strengths, will result in bracket failure.\textsuperscript{13} Clinically acceptable shear bond strengths have been reported in the literature to be between 6 and 8MPa,\textsuperscript{22-25} with the bare minimum being 2.86MPa.\textsuperscript{22}

Throughout the course of orthodontic treatment, bracket bond strength changes.\textsuperscript{26,27} For the first few days bond strengths increase as adhesive polymerization and cross-linking become more complete;\textsuperscript{18} however, from thereafter bond strengths decrease due to the harsh conditions of the oral environment.\textsuperscript{27} Within any given day, intraoral appliances undergo extreme thermal changes, pH fluxuations, and fatigue from
cyclic loading. Pickett et al, demonstrated this decrease in bond strength throughout treatment with a novel device for measuring bond strengths intraorally. They compared in vitro to in vivo bond strengths in the beginning of treatment (12.82 versus 11.02MPa, respectively) to in vivo bond strengths at the end of treatment (average time of 23 months) and found mean shear bond strengths to be significantly lower (5.47MPa). In order to partially simulate the thermal extremes that bonded appliances undergo in the oral environment, it has been suggested that bond strengths be tested following thermocycling. Thermocycling involves cycling the testing samples through hot (55°C) and cold water (5°C) over short periods of time (15 seconds). These temperature extremes are comparable to those that would only be tolerable for a short time in the oral environment. It’s designed to simulate thermal extremes that would occur over and extended time, by forcing the samples to undergo numerous (thousands) hot and cold cycles over a short time. Thermocycling is thought to weaken bond strengths via adhesive degradation coupled with stresses created by the differences in thermal coefficients between the enamel, adhesive and bracket. In addition to thermocycling, Erickson et al suggested bond strengths be measured following cyclic loading to more closely resemble conditions of the oral environment. Orthodontic appliances undergo numerous occlusal and masticatory loading insults throughout the day. It has been shown in previous studies that fatigue from cyclic loading will cause a significant reduction in shear bond strengths. Even when thermocycling, cyclic loading, and adhesive degradation are all accounted for, in vitro testing still does not accurately represent the in vivo environment. For this reason, the incidence of bracket failure in vitro is much lower than is seen clinically, and shear bond strengths are much higher. The literature
is, therefore, replete with studies trying to improve bond strengths and decrease bracket failure rates.\textsuperscript{69}

**Bracket Base Design**

Orthodontic bracket failures can occur at one of three locations: at the enamel-cement interface, within the cement, or at the bracket base-cement interface.\textsuperscript{34-36} The most common failure point has been shown \textit{in vitro} to be at the bracket base-cement interface,\textsuperscript{1,22,35-37} likely because of stress concentrations and defects in the resin film.\textsuperscript{22,35,36} Many attempts have been undertaken to increase adhesive to base retention, including both chemical and mechanical systems.\textsuperscript{38,39} Although silanation and other chemical methods have been shown to chemically bond adhesive to even smooth-based, ceramic brackets, priming of metal brackets has not been shown to reduce the need for mechanical retention at the bracket base.\textsuperscript{24,25,40,41} Improvements in mechanical retention have received the most attention for metal brackets,\textsuperscript{11,13,39,42-47} as the retention of the metal bracket lies in the ability of the bracket base to obtain mechanical retention with the cement.\textsuperscript{1,7,21}

Early metal bases were perforated with 12 to 16 holes or fabricated with lipped-edges, to create undercuts for the adhesive to flow into.\textsuperscript{48} Significantly improved bond strengths were seen when perforated or lipped-edge bases were replaced with stainless steel mesh pads that were welded onto the bracket bases.\textsuperscript{5,49} Retention with wire mesh bases were significantly greater, due to exponentially increased areas for the adhesive to flow into and lock-in the bracket base-cement interface.\textsuperscript{48} Reynolds and von Fraunhofer\textsuperscript{22} found mesh bases to be 2.8 times as retentive as perforated bases. Unfortunately, with
early mesh pads, adhesive could also flow into the areas above the base and interfere with the bracket. The remedy was the laminated “foil-mesh”, wherein stainless steel foil was placed between the base and bracket to prevent the adhesive from seeping through.50

Mesh pads were made by laminating stainless steel wires of differing diameters and configurations to stainless steel foil. The potential exists for numerous variations in mesh size (wires per linear inch), mesh number/gauge (number of openings per linear inch) and aperture size (open areas in the mesh).34,51 These variables have obvious potential to change bond strengths especially when coupled with the many different available adhesives filler particle sizes.51 Matasa compared the mesh base to a “sieve”, which depending on the number and size of the open areas could provide better or worse penetration for some adhesives over others depending on the filler particle size.51 For a long while manufacturers reported 100 gauge mesh (100 wires per linear inch) to be the most popular. Contemporary meshes, however, are usually less dense,51 as recent studies have shown larger meshes, eg, 60-80 gauge, to provide better bond strengths.21,52,62

Early on, foil mesh pads were spot welded to the base. The spot welding process, however, was shown to damage the mesh base by creating flat areas where the welds occurred.7,34 These flat areas created voids in the base-cement interface that were potential areas for failure to occur, both by separation of the base from the cement or the base from the bracket.7,34 Additionally, the spot welded areas created metal spurs that often prevented complete or even seating of the bracket, trapping in air and decreasing bond strengths.7,34 These shortcomings were overcome when mesh bases were united with brackets via brazing instead of spot-welding, leaving an intact mesh pad secured to the bracket.51
In an attempt to improve retention, different manufacturers have altered bracket bases by welding (brazing or laser-welding) on different diameters and patterns of mesh or creating undercuts to replace the mesh.\textsuperscript{21,39} Additionally, modification of bases via sandblasting/microetching,\textsuperscript{13,24,53,54} photo-etching,\textsuperscript{55} laser-structuring,\textsuperscript{11} or coating/fusing the base with polymer\textsuperscript{25,54} or metal particles,\textsuperscript{56} and tribochemical silica coating,\textsuperscript{1,24,74} have all been attempted. Unfortunately, these studies have reported that there is no clear improvement in bond strength from base treatment.\textsuperscript{1,24,39}

There is little agreement in the literature on which bracket base type provides the highest shear bond strengths.\textsuperscript{39} Some studies have reported higher bond strengths with mesh bases than integral undercut bases.\textsuperscript{6,22,58-60} E.g. Lopez, et al\textsuperscript{58} found mesh brackets vs. integral bases debonded at 21.5MPa ± 3.5 and 13.83MPa ± 2.78 (psi→Mpa), respectively. Willems, et al\textsuperscript{63} found mesh brackets vs. integral bases debonded at 13.0MPa ± 2.1 and 3.9MPa ± 0.8, respectively. Whereas some studies have found integral undercut bases to have higher bond strengths.\textsuperscript{21,39,47,61} E.g. Sharma-Sayal, et al\textsuperscript{21} found integral undercut bases vs. mesh brackets debonded at 9.73MPa ± 1.64 and 8.05MPa ± 2.75, respectively. Wang, et al\textsuperscript{52} found integral undercut bases vs. mesh brackets debonded at 9.32MPa ± 1.77 and 8.04MPa ± 2.46, respectively. Regardless of the study or bracket type, less variation in bond strengths have been shown with brazed-mesh bases than other base types,\textsuperscript{31} so that they continue to be the most commonly used.\textsuperscript{11} Even so, studies differ on whether fine or course gauge meshes perform better; although recent studies have suggested courser gauges, eg 60-80 gauge, provide higher bond strengths.\textsuperscript{21,52,62}
Reynolds and Von Fraunhofer\textsuperscript{59} (1976) found that finer meshes were less retentive than courser meshes. They concluded that there was no correlation between bond strength and the surface area of the base, and that all failures occurred at the bracket base-cement interface.

Reynolds and Von Fraunhofer\textsuperscript{60} (1977) evaluated perforated versus foil-mesh pads welded to buttons. They found that stainless steel mesh was 2.8 times as retentive as perforated pads.

Thanos et al\textsuperscript{49} (1979) evaluated tensile, shear and torsional bond strengths of foil-mesh bases and metal-bases with five different adhesives. They found higher tensile bond strengths with foil-mesh bases and higher shear bond strengths with metal-bases.

Lopez\textsuperscript{58} (1980) evaluated the shear bond strengths of sixteen different bases at 24 hours and 30 days. He concluded that foil mesh bases had higher shear bond strengths than the perforated or undercut solid base designs, and that the adhesive retention was not significantly affected by placement in 37\textdegree C distilled water for 24 hours or 30 days.

Dickinson and Powers\textsuperscript{7} (1980) evaluated fourteen different bracket bases of differing mesh sizes or perforations for tensile bond strengths using two different adhesives. They found that tensile bond strength was independent of nominal area and mesh size for the bases they tested. They suggested that lower bond strengths found with spot-welded brackets were likely due to spot welding damage reducing retentive area for the adhesive, as well as producing areas of stress concentration that may initiate the fracture of the adhesive at the base-cement interface. They concluded that laminated mesh bases and perforated bases had the lowest bond strengths. Additionally, they found that bond failures all occurred at the bracket base-cement interface.
Maijer and Smith (1981) evaluated 7 different bracket bases to determine variables that might affect bond strengths. They concluded that flat areas and weld spurs from spot welding could cause lower bond strengths, and that bracket bases should be designed to prevent air entrapment under the base. They found that the best resin penetration and bond strengths were obtained when fine, woven foil-mesh bracket bases were used.

Siomka and Powers (1985) evaluated the effect of surface treatments on the tensile bond strength of three types of metal bases; a mesh, a photo-etched and an integral undercut base. They found the integral undercut base to have the highest bond strength when untreated and improved another 56% more with etching. They concluded that silanation improved the bond strength of the mesh bracket by 28% at 24 hours, but that surface treatments had no effect on the photo-etched bracket.

Regan and Van Noort (1989) tested foil-mesh and integral base brackets in both tension and shear and found integral bases to be more retentive.

Smith and Reynolds (1991) evaluated the performance of three groups of orthodontic bracket bases; fine-mesh, coarse-mesh, and undercut bracket bases. They concluded that the fine-mesh base had higher tensile bond strength than the coarse mesh, and that both performed better than the undercut base.

Scott, Kucklick and Eichmiller (1992) evaluated the shear bond strengths of 80 gauge mesh versus 100 gauge mesh with macrofilled resins. They found 80 gauge meshes to have higher bond strengths than 100 gauge mesh bases.

Willems et al (1997) evaluated 17 different bracket types to determine the effect of base design variation and sandblasting on shear bond strength. They found the highest
bond strengths with the ceramic bracket, but two of the stainless steel mesh base brackets had similarly high bond strengths. They found sandblasting of recycled brackets to have no clear improvement in bond strength; however the integral undercut base design showed better shear bond strengths with sandblasting than any others.

MacColl and Rossouw et al\textsuperscript{10} (1998) evaluated the effects on shear bond strength by various bracket base types, bracket surface treatments and/or enamel treatments. They concluded that no significant differences in shear bond strength occurred with bracket base surface areas between 6.8 and 12.4mm\textsuperscript{2} but decreased when the surface area was at 2.4 mm\textsuperscript{2}. They found that microetching and/or sandblasting of foil-mesh bases increased the shear bond strength.

Knox et al\textsuperscript{12} (2000) evaluated the influence of bracket base design and adhesive type on the tensile bond strength at the bracket-adhesive interface. They tested brackets with 60, 80 and 100 single mesh bases, a double mesh base, and an integral base with undercuts using different adhesives (chemical-cure resin, light-cured resin, and light-cured glass ionomer cement). They concluded that the adhesive used significantly affected bond strength achieved with particular base design, as the particular base may allow for improved cement and/or curing light penetration. Additionally, they concluded that the dimension and distribution of resin tags produced by a particular base could cause stress distributions that could be better resisted by one adhesive rather than another.

Sorel\textsuperscript{6} (2002) compared the tensile bond strengths of a single-mesh based bracket and a laser structured base bracket. They found the laser structured base bracket to have twice the bond strength found with the simple foil mesh bracket.
Cucu et al\textsuperscript{65} (2002) evaluated the shear bond strength of brackets of differing mesh sizes/gauges. They concluded that there were no significant differences in shear bond strength between 80 and 100 gauge mesh bases.

Sharma-Sayal et al\textsuperscript{21} (2003) evaluated the shear bond strengths of six different bracket base types at 1 hour and 24 hours after bonding them to bovine teeth. They found that all of the bracket types tested showed increases in bond strength from 1 hour to 24 hours. They concluded that differences in bracket base design significantly affected shear bond strengths, with the 60 gauge foil-mesh and integral undercut base having higher shear bond strengths.

Bishara et al\textsuperscript{39} (2004) evaluated the shear bond strengths of two brackets of differing mesh designs, one with single-mesh and the other with a double-mesh (Super-mesh). In order to simulate initial archwire engagement, both bracket types were bonded with a light cured adhesive and tested to shear failure after 30 minutes. They found no difference in shear bond strength between the two base types, single or double-mesh.

Wang et al\textsuperscript{52} (2004) evaluated bond strengths of six types of brackets with various base designs, both mesh and integral undercut bases. They found that bracket base design affected bond strength and that larger mesh spacing (coarser gauge) produced higher bond strengths.

Atsu et al\textsuperscript{74} (2006) evaluated the effect of tribochemical silicoating and silane surface treatment of metal and ceramic brackets. They found tribochemical silicoating with silane produced higher bond strengths in both metal and ceramic brackets than controls, whereas silane alone provided no benefit to metal brackets.
Algera et al\textsuperscript{1} (2008) evaluated the effects of different base treatments on shear and tensile bond strengths. They treated bases via sandblasting, silicoating and tin-plating. They found no clear improvement in bond strength from any of the base treatments.

Faltermeiera et al\textsuperscript{45} (2009) compared the effect of silicoating and sandblasting on shear bond strength of foil-mesh brackets. They found bonding resins to tribochemically silicoated brackets improved shear bond strengths. However, they found combined sandblasting and silane-coupling treatment to be of no benefit to shear bond strength.

Modified Adhesive Remnant Index

Following debonding, the amount of residual adhesive remaining on the bracket and/or enamel surface provides insight into the site of failure within the enamel-cement-bracket base complex.\textsuperscript{6,66,67} The Adhesive Remnant Index (ARI), first described by Artun and Bergland\textsuperscript{68} (1984), is a 4-point scale used to assess the amount of adhesive remaining on the tooth surface upon debonding. A score of 0 indicates no adhesive left on the tooth, 1 indicates less than half of the adhesive remaining on the tooth, 2 indicates more than half of the adhesive remaining on the tooth, and 3 indicates all of the adhesive left on the tooth, with distinct impression of the bracket mesh. Bishara used a modified version of the adhesive remnant index\textsuperscript{66} graded on a scale of 5-1: 5- no composite remaining on the tooth; 4- less than 10% of composite remaining on the tooth; 3- more than 10% but less than 90% of composite remaining on the tooth; 2- more than 90% of composite remaining on the tooth; 1- 100% of composite remaining on the tooth with the mesh pad impression visible. Visualization techniques described for ARI detection range from a
dental light and mouth-mirror, to 5 or 10X optical magnification, stereomicroscope, digital microscope, or even scanning electron microscope.48

Due to the difficulties in obtaining adequate, quality specimens of human teeth for bonding studies,18,69 and the inaccuracies introduced by the lower bond strengths found with bovine enamel substitutes,70,71 it has been suggested by some that non-enamel substrates be substituted for bond strength studies.63,71 Substrates such as silanated steel rods,63 100 gauge stainless steel mesh sheets, etched marble slabs, etched glass,71 etched porcelain tiles,72 acid-etched ceramic tiles,71 and acrylic cylinders with undercuts for retention of adhesives,7 have all been used in bond strength and/or adhesive remnant studies. Non-enamel substrates have been shown to provide adequate, even superior, bond strengths when compared to human or bovine enamel substrates.63

When non-enamel substrates were used for bonding studies previously,71 a modified adhesive remnant index73 was used that substituted “substrate” for “enamel” and results recorded according to the following scale: 1- all the adhesive is removed from the substrate; 2- less than half of it has remained on the substrate; 3- more than half of it has remained on the substrate; 4- all of the adhesive has remained on the substrate.71 Matasa (2001) used a modified adhesive remnant index to evaluate the mode of failure within the substrate-adhesive-bracket complex of brackets bonded to acid-etched ceramic tiles.71 He scored sites where the glaze of the tile were torn without leaving any adhesive with a 1; sites where no less than half of the adhesive were left on the tile surface with a 2; sites where more than half of the adhesive remained on the tile with a 3; and sites where practically all the adhesive remained on the tile with a 4.
When comparing MARI scores, higher frequency scores of 1 and 2 are suggestive of higher bond strengths at the bracket base-cement interface than scores of 3 and 4. Manufacturers claim their particular bracket base design will provide better bond strengths with less bracket failure than their competitors’ design. The purpose of this study was to evaluate the effect bracket base design on mean shear bond strength (SBS) at the bracket base-cement interface.
SPECIFIC AIMS

1. Bond brackets to acrylic cylinders with undercuts to hold adhesive resin (Transbond™ XT, 3M Unitek, Monrovia, Calif)
   - SmartClip™ (80-gauge woven-mesh base; 3M Unitek, Monrovia, Calif)
   - In-Ovation R™ (laser-welded SuperMesh™, double-mesh base, 81.50-gauge; GAC, Central Islip, NY)
   - Quick™ (machined, integral, microetched 3D hook base; Forestadent USA, St. Louis, MO)
   - T3™ (machined, integral, microetched base with mechanical undercuts; American Orthodontics, Sheboygan, Wis)

2. Apply a shear force to debond the brackets after various treatment conditions:
   - 24 hours post bonding with thermocycling
   - 30 minutes post bonding

3. Compare:
   - Shear bond strength (SBS)
   - Modified adhesive remnant index scores (MARI)
MATERIALS AND METHODS

Eighty orthodontic brackets from four different manufacturers were chosen for evaluation, based on differing base designs. The manufacturers and specific base design configurations are listed in Table 1.

Acrylic cylinders were constructed as a retaining device for the bonding adhesive, according to the design used in a previous study.° The cylinders were 1” x 1” diameter.

A 10mm diameter hole was drilled into one end of the acrylic cylinder to a depth of 4mm. The inside of this hole was then undercut in the periphery with a #4 round bur to gain retention for the bonding adhesive (Fig. 1). Then they were cured for 40 seconds with a 0.5mm plastic sheet over the surface, to create a flat surface for bonding the brackets. Immediately following the initial cure, TransbondXT was applied to the base of each bracket, with special attention given to manipulating the adhesive into all retention...
areas. The brackets were then placed onto cylinders with uniform pressure, flash removed with sharp sickle scaler, and light cured (OrthoLux LED, 1000mW/cm², 3M Unitek, Monrovia, Calif) for 20 seconds according to manufacturer specifications.

Table 1

<table>
<thead>
<tr>
<th>Bracket Type (base design)</th>
<th>Group I (30 minutes)</th>
<th>Group II (3 days Thermocycled)</th>
</tr>
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<tbody>
<tr>
<td><strong>SmartClip</strong></td>
<td>N=10</td>
<td>N=10</td>
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<tr>
<td>(80-gauge woven-mesh base; 3M Unitek, Monrovia, Calif)</td>
<td></td>
<td></td>
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<tr>
<td><strong>In-Ovation R</strong></td>
<td>N=10</td>
<td>N=10</td>
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<tr>
<td>(laser-welded SuperMesh ME, double-mesh base, 81.50-gauge; GAC, Central Islip, NY)</td>
<td></td>
<td></td>
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<tr>
<td><strong>Quick</strong></td>
<td>N=10</td>
<td>N=10</td>
</tr>
<tr>
<td>(machined, integral, microetched 3D hook base; Forestadent USA, St. Louis, MO)</td>
<td></td>
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<tr>
<td><strong>T3</strong></td>
<td>N=10</td>
<td>N=10</td>
</tr>
<tr>
<td>(machined, integral, microetched base with mechanical undercuts; American Orthodontics, Sheboygan, Wis)</td>
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</table>

Care was taken to ensure that no flash overlapped bracket pads, and that bracket base was parallel to acrylic cylinders to allow precise placement of the instron blade. Each bracket-cylinder was oriented on the Universal Testing Machine platform (Model 5565, Instron, Norwood, MA) using the testing device as a guide to insure that the bracket base was parallel to the applied force during the bracket shear bond strength test (see Fig. 2). A steel rod with a knife edge was mounted on the crosshead of the Instron. A shear force was created by applying an occluso-gingival load to the bracket-cement interface using a crosshead speed of 0.5mm/minute until failure (see Fig. 3). The peak failure load was
recorded in Newtons which was divided by the bonding pad area (see Table 3) to calculate the shear bond force. A pc computer connected to the Instron testing machine recorded the results of each test. Bracket-cylinders in Group I were placed in 37°C distilled water and debonded at 30 minutes after being placed and light cured, to simulate initial archwire placement. Bracket-cylinders in Group II were thermocycled for 2,500 cycles in wells of 5°C and 55°C with a 15 second dwell time, and 5 seconds between wells, to simulate the oral environment.

![Figure 3. Acrylic cylinder with bonded bracket positioned in testing machine before debonding.](image)

Total time from bracket placement to shear testing was 24 hours for Group II, to allow for complete composite polymerization. After the brackets were debonded, the fracture surfaces were examined optically using 10X magnification. Trace adhesive that remained on the acrylic cylinders and bases after bracket removal was graded according to the modified adhesive remnant index (MARI) scale used in a previous study, when...
artificial bonding substrates were used. Specimens were graded according to the following MARI legend (see Fig. 4):

1- all of the adhesive has remained on the bracket and been removed from the substrate.
2- more than half of the adhesive has remained on the bracket and been removed from the substrate.
3- more than half of the adhesive has remained on the substrate and been removed from the bracket.
4- all of the adhesive has remained on the substrate and been removed from the bracket.

Figure 4. Modified Adhesive Remnant Index score legend.

DATA ANALYSIS

Mean SBS values and standard deviations of properties were computed using SAS version 9.1, (Cary, NC). The data was analyzed statistically by 1-way analysis of variance (ANOVA) to determine the effect of bracket base design on mean SBS. A 2-way ANOVA, time versus bracket type, was used to determine the effect of time on mean SBS. Frequencies and chi-square analysis were used to determine significant differences in MARI scores between groups. Statistical significance was determined at $P < .05$. 
RESULTS

The mean SBS with respect to bracket type and time point are listed in Table 2. The wide range of mean SBS found supports findings in previous studies—that even under the same conditions, bracket base designs can behave differently. The bracket base dimensions (height x width), and mean surface area of the bracket bases tested are listed in Table 3. The mean surface areas were 12.08mm² for Smart Clip, 12.42mm² for In-Ovation R, 9.73mm² for Quick, and 10.43mm² for T3.

Table 2

<table>
<thead>
<tr>
<th>Bracket Type</th>
<th>Base Design</th>
<th>Group I: 30min.</th>
<th>Group II: 24hours Thermocycled</th>
</tr>
</thead>
<tbody>
<tr>
<td>SmartClip</td>
<td>80-gauge brazed woven-mesh base; 3M Unitek, Monrovia, Calif</td>
<td>14.66 (± 2.05)</td>
<td>25.55 (± 3.59)</td>
</tr>
<tr>
<td>In-Ovation R</td>
<td>laser-welded SuperMesh ME, double-mesh base, 81.50-gauge; GAC, Central Islip, NY</td>
<td>14.56 (±4.99)</td>
<td>24.94 (± 2.34)</td>
</tr>
<tr>
<td>Quick</td>
<td>laser-welded SuperMesh ME, double-mesh base, 81.50-gauge; GAC, Central Islip, NY</td>
<td>11.82 (± 3.88)</td>
<td>26.82 (± 4.19)</td>
</tr>
<tr>
<td>T3</td>
<td>machined, integral, microetched base with mechanical undercuts; American Orthodontics, Sheboygan, Wis</td>
<td>24.24 (± 3.76)</td>
<td>36.86 (± 3.66)</td>
</tr>
</tbody>
</table>
The results show that the overall mean SBS associated with T3 brackets was significantly higher than the other brackets, at both 30 minutes and 24 hours ($P < .0001$). The mean SBS values for all four bracket types showed statistically significant increases with time. The overall combined mean SBS value at 30 minutes was 16.32MPa and 28.54MPa at 24 hours, an increase of 70%. This increase over time was statistically significant for all four brackets ($P < 0.01$). The mean increases in SBS values from 30 minutes to 24 hours for bracket types were: SmartClip, 70%; In-Ovation R, 71%; Quick, 120%; and T3, 52%. The Quick bracket showed significantly greater increases than the other bracket types in SBS from 30 minutes to 24 hours ($P < 0.05$). The T3 bracket had the highest scores of 1 and 2 (16 (80%)), indicating a greater trend for the adhesive to be removed from the substrate and remain on the bracket base after debonding (Fig 4).

Although not statistically significant ($P > 0.05$), more adhesive was shown to remain on all four bracket types 30 minutes after bonding versus 24 hours.

**Table 3**

*Bracket Base Dimensions*

<table>
<thead>
<tr>
<th>Bracket Type</th>
<th>Base dimension</th>
<th>Mean surface Area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SmartClip</strong> (3M Unitek, Monrovia, Calif)</td>
<td>3.86mm x 3.13mm</td>
<td>12.08mm$^2$</td>
</tr>
<tr>
<td><strong>In-Ovation R</strong> (GAC, Central Islip, NY)</td>
<td>3.62mm x 3.43mm</td>
<td>12.42mm$^2$</td>
</tr>
<tr>
<td><strong>Quick</strong> (Forestadent USA, St. Louis, MO)</td>
<td>3.20mm x 3.04mm</td>
<td>9.73mm$^2$</td>
</tr>
<tr>
<td><strong>T3</strong> (American Orthodontics, Sheboygan, Wis)</td>
<td>3.17mm x 3.28mm</td>
<td>10.40mm$^2$</td>
</tr>
</tbody>
</table>

The modified adhesive remnant index (MARI) scores associated with each time group are listed in Table 4.

Chi-squared comparisons of the MARI indicated a higher frequency of a MARI score of 3 (more than half of the adhesive has remained on the substrate and been
removed from the bracket) associated with all brackets except the T3 bracket, which had higher frequencies of 1 and 2 (more than half of the adhesive has remained on the bracket and been removed from the substrate) ($P < .05$). SmartClip (14 (70%)), In-Ovation R (10 (50%)), and Quick (10 (50%)) had higher frequencies of 3 on the MARI scale. This indicated a greater trend for most of the adhesive to separate from the base of these bracket types, leaving a distinct impression of the bracket mesh on the acrylic cylinder.

Table 4

*Modified Adhesive Remnant Index Scores*

<table>
<thead>
<tr>
<th>Bracket Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SmartClip</strong> (80-gauge single-mesh base)</td>
<td>1 (5%)</td>
<td>0</td>
<td>14 (70%)</td>
<td>5 (25%)</td>
</tr>
<tr>
<td><strong>In-Ovation R</strong> (SuperMesh double-mesh base, 81.50-gauge)</td>
<td>3 (15%)</td>
<td>2 (10%)</td>
<td>10 (50%)</td>
<td>5 (25%)</td>
</tr>
<tr>
<td><strong>Quick</strong> (machined, integral, microetched base)</td>
<td>3 (15%)</td>
<td>6 (30%)</td>
<td>10 (50%)</td>
<td>1 (5%)</td>
</tr>
<tr>
<td><strong>T3</strong> (machined, integral, microetched base)</td>
<td>8 (40%)</td>
<td>8 (40%)</td>
<td>4 (20%)</td>
<td>0</td>
</tr>
</tbody>
</table>

1, all of the adhesive has remained on the bracket and been removed from the substrate; 2, more than half of the adhesive has remained on the bracket and been removed from the substrate; 3, more than half of the adhesive has remained on the substrate and been removed from the bracket; 4, all of the adhesive has remained on the substrate and been removed from the bracket.
DISCUSSION

This study evaluated the effect of bracket base design on SBS at the bracket base-cement interface. Although bracket failure can occur at the other two interfaces—the enamel-cement interface and within the cement—the most common failure point has been shown in vitro to be the latter, at the bracket base-cement interface, likely because of stress concentrations and defects in the resin film. In vivo failures occur at the enamel-adhesive interface as well, likely because ideal bonding to enamel is much more difficult clinically. The variation introduced by the enamel-adhesive interface was eliminated in this study by implementing a previously described method of using acrylic cylinders as retaining devices for the adhesive. Other methods of testing bond strength have been used in the literature, especially tensile tests, but it has been reported that the bond strength differences between shear and tensile induced failure are not significant.

The T3 bracket, with a machined-in integral undercut base showed significantly higher mean shear bond strengths (P < .0001) at both 30 minutes and 24 hours than the other bracket base types. Previous integral undercut bracket base designs were reported in some studies to have lower bond strengths than conventional mesh bases. However, contemporary designs have been improved with deeper and wider integral undercuts, which may be responsible for the higher bond strengths measured in this and other recent studies for integral undercut brackets. Improvements in the performance of integral bases in some studies was also linked to the use of a highly-filled
resin. Thus, the higher SBS shown in this and other studies\textsuperscript{21} of integral undercut brackets may be due to improved undercut designs allowing for further penetration and interlocking of the base with a highly-filled resin (e.g. Transbond XT).\textsuperscript{21}

Although the Quick bracket also has an integral undercut base, a 3D hook base, its undercuts are narrow and shallow. This may be the reason why its mean SBS were lower than the other bracket base types at 30 minutes ($P < .05$). The small areas available for interlocking may have hindered the cement from obtaining sufficient areas for mechanical interlocking. Additionally, the edges of the 3D hooks may have increased stress concentrations in an already incompletely polymerized composite resin (at 30 minutes), leading to lower SBS. Although at 30 minutes the Quick bracket had lower mean SBS than the other bracket types tested (11.82MPa) it was still well above the minimally acceptable clinical bond strength level of 6-8MPa.\textsuperscript{23,24} The Quick bracket showed significant increases in SBS from 30 minutes to 24 hours (120%); however, its SBS levels were not significantly different than the single and double-mesh brackets at 24 hours.

The single and double mesh bracket bases, SmartClip and In-Ovation R brackets, respectively, performed similarly upon debonding. They had similar SBS and MARI scores at both 30 minutes and 24 hours. This was expected, as similar results were found by Bishara in a previous study which compared single and double-mesh brackets.\textsuperscript{39}

Although many different bonding resins are available, only one specific light-cured, bonding resin was used in this study to show that the differences in SBS were due to variations in bracket base designs rather than properties of specific cements. Composite resins, in most studies, have been shown to be the most successful bracket
adhesives. Although, different results may have been produced if other cements had been evaluated. For example, lower-viscosity cements, chemical or dual cure adhesives, with differing wetting characteristics, could potentially reach narrower areas of the bracket bases, providing for higher SBS values. This could have been one reason the Quick bracket had lower bond strengths at 30 minutes, as it has significant numbers of narrow areas that could have restricted the flow of a highly filled composite resin like Transbond XT. Additionally, especially at 30 minutes, incomplete polymerization of the light-cured adhesive is certain, due to the inability of the light to penetrate areas under the metal bracket bases producing lower bond strengths.

For the purpose of simulating initial arch wire ligation, the brackets were sheared to failure at 30 minutes. As shown in other studies, SBS values increased for all brackets tested in this study from 30 minutes to 24 hours. This is expected, since cross-linking and polymerization is not complete at 30 minutes. Some studies, however, have reported SBS values below the clinically acceptable range of 6 to 8MPa after only a 30 minute cure. Within the conditions of the present study, however, all brackets performed well above this range (of minimally acceptable SBS) at 30 minutes. These findings are supported by previous studies using Transbond XT, which found sufficient bond strengths after a 30 minute cure. The greatest increase in SBS from 30 minutes to 24 hours was seen with the Quick bracket (120%), followed by SmartClip (74%), In-Ovation R (71%) and T3 (52%).

The Modified Adhesive Remnant Index (MARI) provides insight into the mode of failure within the bracket-cement-enamel/substrate complex (Table 4). The T3 bracket
had less residual composite on the acrylic cylinders (more adhesive remained on the bracket bases), ie, there was a higher number of MARI scores of 1 and 2 (80%) compared to the other brackets (Fig. 5). The remaining bracket types, SmartClip, In-Ovation R, and Quick had higher numbers of MARI scores of 3, ie, there was more composite remaining on the acrylic cylinders and less remaining on the bracket bases (Fig. 5). Fifty percent of SmartClip, 70% of In-Ovation R, and 50% of Quick, had more composite remaining on the acrylic cylinders/minimal adhesive remaining on the bracket base, compared to only 20% of the T3 brackets. Although not statistically significant ($P > .05$), more adhesive remained on the brackets 30 minutes after bonding versus 24 hours which is likely due to incomplete polymerization of the adhesive in undercut areas of the bases where light is unable to penetrate during curing.$^8$

Figure 5. 40 X magnification of bracket bases after debonding.

Brackets were examined under 40 X magnification with a digital microscope (Keyence, VHX-600 Series, Woodcliff Lake, NJ) (Fig. 6), which illuminated
manufacturer descriptions of the individual bracket types, ie, Smart Clip has an 80-gauge single-mesh base, In-Ovation R has an 81.50-gauge SuperMesh/double-mesh base, Quick has an integral undercut 3D hook base, and T3 has an integral undercut base. SmartClip has a brazed-on foil mesh. In-Ovation R has a laser-welded double-mesh. The Quick and T3 brackets have their undercuts machined-in and microetched.

![SmartClip](image1)
**SmartClip** (80-gauge brazed woven-mesh base; 3M Unitek, Monrovia, Calif)

![In-Ovation R](image2)
**In-Ovation R** (laser-welded SuperMesh ME, double-mesh base, 81.50-gauge; GAC, Central Islip, NY)

![Quick](image3)
**Quick** (machined, integral, microetched 3D hook base; Forestadent USA, St. Louis, MO)

![T3](image4)
**T3** (machined, integral, microetched base with mechanical undercuts; American Orthodontics, Sheboygan, Wis)

Figure 6. 40 X magnification of the four bracket types evaluated.
Despite previous studies that have reported that brackets with integral bases have weaker bond strengths than those with foil-mesh bases,\textsuperscript{5,6,10,22,59} this study found the T3 bracket, with integral undercuts, to have higher bond strengths. This is most likely due to the presence of wide undercut-channels\textsuperscript{21} throughout the base (see Figs. 7 and 8).

This is in contrast to the narrow apertures of the foil-mesh bases (SmartClip and In-Ovation R) and 3D hooks (Quick), which may restrict penetration of the adhesive creating voids, resulting in lower SBS (see Fig. 9). However, all bracket types performed well above the minimally acceptable range of 6-8MPa at both 30 minutes and 24 hours.

Figure 7. 300 X magnification of T3 bracket with measurements.

(489µm base; 450µm apex; 225µm height; 7° undercut)

Figure 8. 300 X magnification of debonded T3 bracket cross section.

(resin throughout undercut)

Figure 9. 300 X magnification of Quick 3D hook with measurements.

(large resin void under 3D hook)
CONCLUSIONS

The following conclusions can be made under the conditions of this study:

• Bracket base design significantly influences SBS at the bracket base-cement interface.

• The Quick Bracket, with integral 3D hook undercuts, produced lower SBS at 30 minutes than the three other bracket types tested—SmartClip (single-mesh), In-Ovation R (double-mesh), and T3 (integral undercuts).

• The T3 Bracket, with integral undercuts, produced higher SBS at 30 minutes and 24 hours than the three other bracket types tested.

• SBS at 30 minutes were significantly lower than those found at 24 hours post bonding, but well above clinically acceptable bond strengths for all bracket types.
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