Original Article

Effects of cyclic loading on the bond strength of metal orthodontic brackets bonded to a porcelain surface using different conditioning protocols

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ABSTRACT

Objective: To evaluate cyclic and static shear bond strengths (SSBSs) of metal orthodontic brackets bonded to a porcelain surface using different conditioning protocols.

Materials and Methods: A total of 100 feldspathic porcelain disks were fabricated. The specimens were divided into four equal groups. Porcelain surfaces were conditioned with different protocols. In group 1, hydrofluoric acid and Embrace First-Coat primer were used. In group 2, hydrofluoric acid and silane were utilized. In groups 3 and 4, sandblasting with aluminum oxide powder was done instead of etching. Metal brackets were bonded to the porcelain surfaces using Transbond XT adhesive. SSBS testing was carried out in 10 specimens, while cyclic shear bond strength (CSBS) testing was done in 15 specimens from each group. The data were subjected to analysis of variance, least significant difference post hoc, and Student's *t*-tests.

Results: Embrace First-Coat and silane exhibited a comparable SSBS. The sandblasting process significantly increased SSBS. No significant difference was found in bond SSBS utilizing either hydrofluoric acid and Embrace First-Coat or sandblasting and silane. With regard to CSBS, the use of sandblasting and Embrace First-Coat revealed the highest significant CSBS value, followed by sandblasting and silane. Etching with hydrofluoric acid prior to application of either primer exhibited the least CSBS values; however, no significant difference was found between them. The SSBS was significantly higher than CSBS.

Conclusion: Embrace First-Coat could be used successfully as an alternative to silane. Sandblasting provides higher bond strength than did hydrofluoric acid. Cyclic loading significantly decreased bond strength. (*Angle Orthod.* 2011;81:1064–1069.)

KEY WORDS: Cyclic loading; Bond strength; Orthodontic brackets; Porcelain surface

INTRODUCTION

In clinical practice the orthodontist may have to bond brackets to porcelain crowns. This procedure has been considered a challenging task. The traditional technique of bracket bonding to enamel surfaces is not sufficient to provide adequate bond strength to porcelain surfaces because of the physical properties of glazed surfaces and the chemical properties of bonding resins.[1]

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In order to improve bond strength, several protocols were addressed in the literature which aimed to alter the porcelain surfaces either mechanically or chemically. Mechanical alteration included the use of diamond burs,[2] green stones,[3] abrasive disks,[4] sandblasting,[5] and laser irradiation.[1] On the other hand, chemical alteration of the porcelain surface could be performed by either etching with strong acid, such as hydrofluoric acid,[6,7] or with the application of a silane coupling agent.[7–10] Silane forms a chemical bond with both the porcelain and the resin, forming a bridge between the two materials.[11–14] Self-etching primers and 4-META resins have also been described[7] for porcelain surface preparation. An alternative technique for increasing bond strength could be inferred from restorative dentistry. A solvent-free, resin-based primer (Embrace First-Coat, EFC) was introduced and used in porcelain repair. This primer eliminates the use of silane coupling agent. However, insufficient information was found regarding its effect on bond strength.

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Table 1. Materials Used in the Study

Materials	Composition	Manufacturer (Location)
Porcelain Etch Gel	9.6% Hydrofluoric acid in a proprietary gel base	Pulpdent (Watertown, Mass)
Transbond XT primer	Bisphenol A diglycidyl ether dimethacrylate, triethylene glycol dimethacrylate	3M Unitek (Monrovia, Calif)
Transbond XT adhesive	Silane-treated quartz, bisphenol A diglycidyl ether dimethacrylate, bisphenol A bis(2-hydroxyethyl ether) dimethacrylate, dichlorodimethylsilane reaction product with silica	3M Unitek
Silane Bond Enhancer	Ethyl alcohol preparation with other organic solvents	Pulpdent (Watertown, Mass)
Embrace First-Coat Primer	Light-cured resin with no bisphenol A	Pulpdent (Watertown, Mass)

In clinical situations brackets could be subjected to cyclic stresses caused by mastication, occlusion, and orthodontic appliances.[15–17] Although these cyclic stresses could be of lower magnitude than the static bond strength of the bracket, they could lead to failure of the bracket during the treatment period, a condition defined as fatigue. Fatigue is the phenomenon through which failure is induced by subjecting the material or structure to repeated subcritical loads.[18,19] Since it is very important to simulate the oral environment condition in the in vitro bond strength studies, it is advantageous to evaluate the effects of cyclic loading on bond strength. Therefore, the present study was conducted to evaluate and compare the cyclic shear bond strengths (CSBSs) and static shear bond strengths (SSBSs) of metal orthodontic brackets bonded to porcelain surfaces using different conditioning protocols.

MATERIALS AND METHODS

A total of 100 feldspathic porcelain disks (Vita, Bad Säckingen, Germany), 2 mm thick and 8 mm in diameter, were fabricated. The specimens were divided equally into four groups with 25 disks each. Lower incisor standard twin edgewise metal orthodontic brackets (American Orthodontics, Sheboygan, Wisc) with an average base area of 9 mm^2 were used in this study. Porcelain surfaces were conditioned by etching with 9.6% hydrofluoric acid (HFA; Porcelain Etch Gel, Pulpdent Co, Watertown, Mass) or by sandblasting with aluminum oxide abrasive powder. Then, either Silane Bond Enhancer (Pulpdent Co) or EFC Primer (Pulpdent Co) was used. The brackets were bonded to conditioned porcelain surfaces using Transbond XT adhesive paste (3M Unitek, Monrovia, Calif). A description of the adhesive systems used in this study is presented in Table 1.

Bonding Procedures

In group 1, porcelain surfaces were etched with 9.6% HFA for 2 minutes, thoroughly washed with water, and dried with oil-free air for 15 seconds. A thin coat of EFC was applied and light-cured for 20 seconds. Transbond XT primer was applied. Transbond XT adhesive paste was applied to the base of the bracket and pressed firmly onto the center of the porcelain surface. Excess adhesive was removed from around the base of the bracket, and the adhesive was light-cured (Megalux, Mega-Physik Dental, Rastatt, Germany) on each interproximal side for 10 seconds.

In group 2, similar procedures were performed (as in group 1), but silane was used instead of EFC. Silane was "gentle blown" with oil-free air and allowed to dry for 10 seconds.

In groups 3 and 4, porcelain surfaces were deglazed by sandblasting (Microetcher erc, Danville Engineering Inc, Danville, Calif) with 50-μm aluminum oxide abrasive powder (instead of etching with HFA). Sandblasting was achieved vertically 2 cm away from the porcelain surfaces at a pressure of 2.5 bars for 10 seconds. Then, the same steps were followed as in groups 1 and 2, respectively.

The specimens were allowed to bench set for 30 minutes after bonding and were stored in distilled water at 37°C ± 1°C for 24 hours. Before testing bond strength, all specimens were thermocycled 500 times between two water baths held at 5°C and 55°C, with a dwell time of 30 seconds in each path. Then disks were embedded in autopolymerizing acrylic resin (Duracryl, SpofaDental, Praha, Czech Republic) poured into plastic rings with the glazed surface up and perpendicular to the long axis of the tubes.

SSBS Testing

SSBS testing was carried out for 10 specimens from each group using a computer-controlled materials testing machine (Model LRX-plus; Lloyd Instruments Ltd, Fareham, UK) with a load cell of 5 kN. Each sample was mounted on the lower fixed compartment of the machine. The brackets were subjected to a compressive loading in the occlusogingival direction at a crosshead speed of 0.5 mm/min via monobeveled chisel attached to the upper movable compartment of the testing machine. The load was applied under the incisal wings at the base of each bonded bracket. The load required to dislodge each bracket was recorded in Newtons, and SSBS was calculated in MPa by dividing the load by the cross-sectional area of the bracket

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Table 2. Mean Static and Cyclic Shear Bond Strengths, Standard Deviations, and Results of Least Significant Difference (LSD) Post Hoc and *t*-Tests of the Studied Groups[a]

Group	Means and Standard Deviation, MPa		*t*-Test *P*-Value (Static vs Cyclic)
	Static Shear Bond Strength	Cyclic Shear Bond Strength	
Hydrofluoric acid + Embrace First-Coat	5.48 ± 1.03 A,C	1.95 ± 0.45 A	<.001
Sandblasting + Embrace First-Coat	6.95 ± 1.211 B	4.07 ± 0.50 B	<.001
Hydrofluoric acid + Silane Bond Enhancer	4.50 ± 1.10 A	1.70 ± 0.46 C	<.001
Sandblasting + Silane Bond Enhancer	6.35 ± 1.30 C,B	2.77 ± 0.86 D	<.001

[a] Means with the same letters in the same column are not significantly different at $P < .05$, according to the LSD test.

base. The data were recorded using computer software (Nexygen-MT; Lloyd Instruments).

CSBS Testing

CSBS testing was carried out for 15 specimens from each group. Each sample was mounted in the testing machine (LRX-plus; Lloyd Instruments Ltd), as previously mentioned in the evaluation of SSBS. The samples underwent cyclic loading by means of a monobeveled steel chisel that was attached to the upper movable compartment of the machine. The load was applied at the base of bracket in the occlusogingival direction. The load profile was in the form of a sine wave at a rate of 1 Hz. Compressive shear fatigue test for 5000 load cycles were determined by testing according to the staircase (up-and-down) method.[18] The first specimen was tested at 3 MPa stress, which is considered half of the lower limit of the clinically acceptable bond strength.[20,21] Then, in each succeeding test the load was increased or decreased by a fixed amount of 0.6 MPa (10% of the lower limit of the clinically acceptable bond strength) according to whether the previous load resulted in a failure or no failure. Then the mean (X) and standard deviation (SD) of CSBS of each group were calculated from the following equations:

$$X = X0 + d[A/N \pm 1/2] \tag{1}$$

$$SD = 1.62d\{[NB - A2/N2] + 0.029\} \tag{2}$$

where $X0$ = the lowest stress level considered in the analysis; d = the stress increment; N = the sum of the number of failures; $A = \sum in_i$ (the sum of in_i); i = the number of stress level at which failure occurs (the lowest stress level at which a failure occurs is denoted by i = 0, the next at i = 1, etc); n_i = the number of failures that occurs at each stress level; and $B = \sum i^2 n_i$ (the sum of $i^2 n_i$). In X formula, the positive sign is used when the analysis is based on nonfailures, and the negative sign is used when failures are considered.

The mode of bond failure was assessed according to the amount of adhesive left on the porcelain surface utilizing the adhesive remnant index (ARI). The ARI ranges from 0 (no adhesive left on the porcelain surface) to 3 (all adhesive left on the porcelain surface). Less than 50% of the adhesive left on porcelain surface yields a score of 1, while more than 50% of the adhesive left on the porcelain surface yields a score of 2.

Statistical Analysis

The means and SDs of SSBS and CSBS were calculated for all groups. The obtained data were subjected to analysis of variance (ANOVA) and least significant difference (LSD) post hoc tests to determine the significant differences among groups. The Student's *t*-test was used to determine significant differences between the means of SSBS and CSBS. The chi-square test was used to determine significant differences in the ARI scores between different groups. Significance for all statistical tests was predetermined at $P < .05$.

RESULTS

The means and SDs of the SSBS and CSBS and the results of the LSD post hoc and *t*-tests are provided in Table 2. A graphical presentation of these values is shown in Figure 1. In general, there were significant differences in SSBS and CSBS between all studied groups ($P < .0001$).

EFC and silane exhibited comparable SSBS values after either sandblasting or etching with HFA ($P > .05$). Sandblasting prior to application of either primer significantly increased SSBS values ($P < .05$). However, no significant difference was found in the bond strengths utilizing either HFA and EFC or sandblasting and silane ($P > .05$).

With regard to CSBS, sandblasting and EFC revealed the highest significant CSBS value, followed by sandblasting and silane ($P < .05$). On the other hand, etching with HFA prior to application of either EFC or silane yielded the lowest CSBS values ($P < .05$); however, no significant difference was found between them ($P > .05$). In addition, the results of the *t*-test showed a highly significant difference between the SSBS and CSBS values ($P < .001$).

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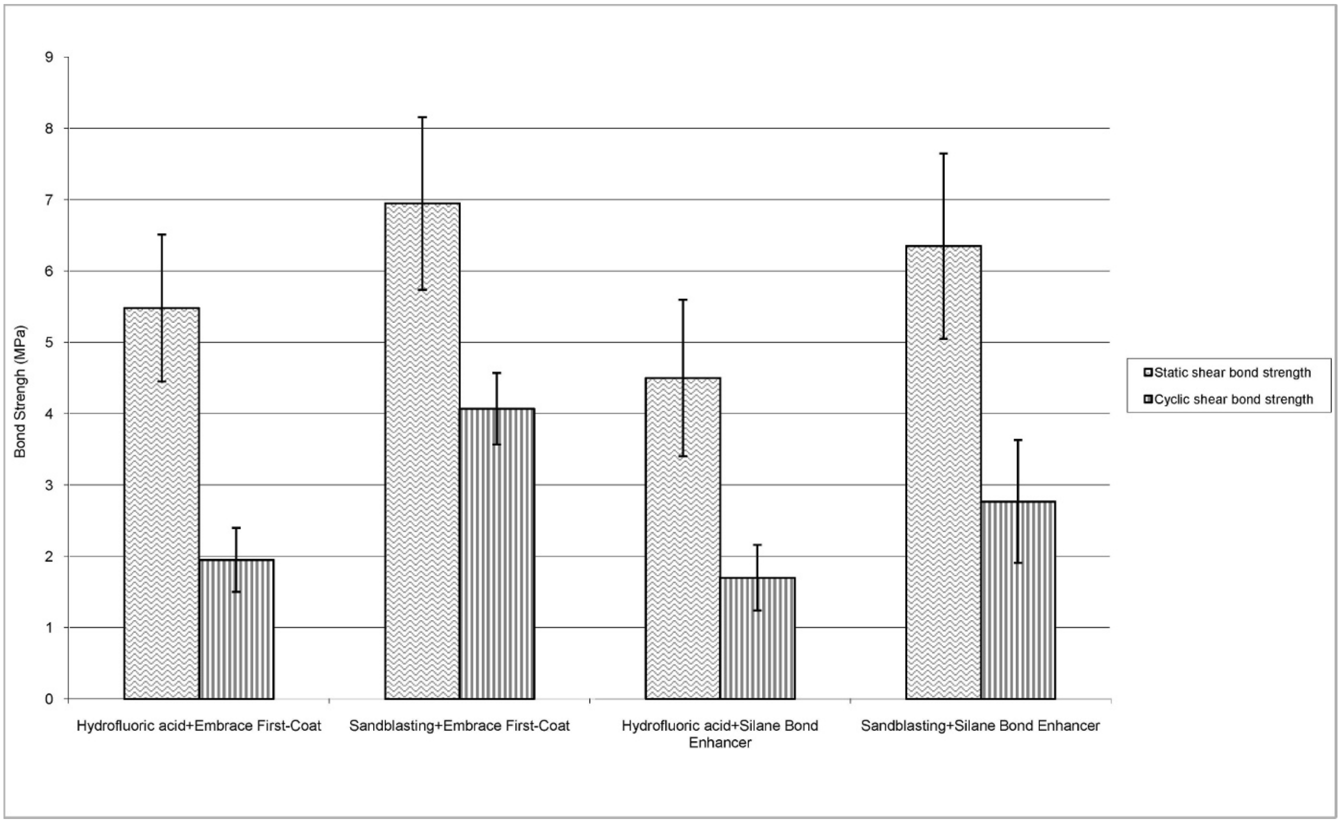

Figure 1. Mean static and cyclic shear bond strengths and standard deviations (in MPa) of all studied groups.

The frequency distribution of ARI scores of both EFC and silane after etching or sandblasting are presented in Table 3. In general, failure was mainly adhesive in all groups. The results of the chi-square test indicated that there were no statistically significant differences between the studied groups of SSBS and CSBS tests ($\chi^2 = 4.57$, $P = .6001$; and $\chi^2 = 1.88$, $P = .930$).

DISCUSSION

The present study was conducted to evaluate the bond strengths of metal orthodontic brackets bonded to porcelain surfaces using either EFC or silane after etching with HFA or sandblasting. Since it is advantageous to simulate the oral environment condition in the in vitro bond strength studies, both CSBSs and SSBSs were evaluated. In addition, bond strengths were assessed after thermocycling.

The results of the current study reveal that EFC provided higher, but not significant, SSBS values compared to silane after etching with HFA or sandblasting. On the other hand, sandblasting of porcelain surfaces significantly enhanced the SSBS. This finding was in agreement with those of other studies.[2,7] This could be explained by the fact that sandblasting increased the surface roughness more than did etching with HFA, which subsequently improved the mechanical retention of the adhesives. Unfortunately, mechanical alteration of porcelain surfaces leads to irreversible damage to porcelain glaze and could result in a higher incidence of porcelain fracture during debonding.[22,23] However, sandblasting with aluminum oxide particles may be safer than utilizing burs or

Table 3. Frequency Distribution and Results of Chi-Square Analysis of Adhesive Remnant Index (ARI) of the Studied Groups[a]

Group	Static Shear Bond Strength				Cyclic Shear Bond Strength			
Score	0	1	2	3	0	1	2	3
Hydrofluoric acid + Embrace First-Coat	6	3	1	0	5	3	0	0
Sandblasting + Embrace First-Coat	5	2	3	0	3	2	1	0
Hydrofluoric acid + Silane Bond Enhancer	7	2	1	0	6	2	1	0
Sandblasting + Silane Bond Enhancer	5	3	2	0	4	3	1	0

[a] $\chi^2 = 4.57$; $\chi^2 = 1.88$; $P = .60$; $P = .93$.

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stones, since the procedure is more uniform and less aggressive.[7] In spite of the positive effect of sandblasting on SSBS, the use of HFA with EFC provided nonsignificant SSBS values in comparison to utilization of sandblasting and silane. This finding could be attributed to the fact that EFC may have had a stronger potential to wet the porcelain surface and flow into the pores of the conditioned porcelain, compared with silane. In addition, EFC is a solvent-free primer, while silane contains solvent (organic solvents). If residual solvent was left behind, it may have negatively affected bond strength. Ikeda et al.[24] reported that complete evaporation of solvents is difficult to achieve, even with thorough air-drying. However, HFA should be utilized with great care to avoid soft tissue trauma, as it is very corrosive.[6,7,13]

CSBS provides more realistic and valuable information (compared to SSBS) about the material's long-term performance in the clinical situation. In other words, CSBS could be used as a predictive indicator for its behavior in the oral environment.[16–19] In the present study, the staircase method was used to determine CSBS. In this method the data are concentrated around the mean stress; hence, the number of specimens is smaller than required with other techniques, and subsequently this method is less time consuming.[18] In spite of the relatively low magnitude of the cyclic loads, this method could lead to microcracks and structural failure, a phenomena commonly known as fatigue.[18,19] Several factors could affect fatigue, such as stress concentration, corrosion, temperature, overload, microstructure, and residual stresses.[25] In the current study, utilization of either EFC or silane after etching provided comparable CSBS values.

Accordingly, the teeth could withstand the stresses of mastication and orthodontic appliances (fatigue resistance) at the same level. Sandblasting of porcelain surfaces significantly improved the CSBS. Furthermore, the use of EFC after sandblasting provided significantly higher CSBS values compared to silane. Hence, this bonding protocol could provide more positive bracket durability in the oral environment. This could be explained by the fact that EFC formed a stronger chemical bond with both the porcelain and the resin, with less microcrack formation and structural failure than is associated with silane when it is subjected to cyclic stresses. This may be related to the differences in composition and bonding affinity between them. EFC is a light-cured resin with no bisphenol A. On the other hand, silane is an ethyl alcohol preparation with other organic solvents. In addition, the possibility of the presence of defects as a result of residual solvent with the use of silane may cause stress concentration and hence affect the CSBS.[26]

In addition, the results of the present study revealed that CSBS values were significantly lower than SSBS values ($P < .001$). This finding was in harmony with those of other studies.[15,16,19] This could explain why bracket failure occurs in the oral environment when teeth are subjected to forces of low magnitude. Andreasen and Stieg[26] reported a significant decrease (48% to 52%) in in vivo shear bond strength when compared with in vitro bond strength. They attributed that decrease to mechanical and masticatory stresses affecting the bonds in the oral environment in addition to other factors, such as moisture contamination during bonding, intraoral thermal fluctuation, and the constant bathing effects of saliva. Therefore, it is advantageous to evaluate the effect of cyclic loading on the bond strength of the adhesive systems utilized in orthodontic practice.

The ARI scores showed that bond failure predominantly occurred between the porcelain and the adhesive, as the majority of the adhesive remained on the bracket bases in all groups. These results were in harmony with those of other authours.[13] However, no significant differences were found in ARI scores in all groups using either EFC or silane with or without sandblasting.

CONCLUSIONS

- Both EFC and silane showed comparable SSBS and CSBS.
- Sandblasting with aluminum oxide abrasive powder provided higher bond strengths than did etching with HFA.
- The use of EFC after sandblasting exhibited the highest CSBS.
- Cyclic loading significantly decreased bond strength.

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