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Corresponding Author:
Supassara Sirabanchongkran,
Department of Orthodontics and Pediatric Dentistry, Faculty of Dentistry, Chiang Mai University,
Chiang Mai 50200, Thailand
E-mail: supassara.siraban@cmu.ac.th

Shear Bond Strength of Composite Resin Attachments in Clear Aligner Orthodontic Appliances with Different Adhesive Systems

Siriwan Thongkom[1], Wikanda Khemaleelakul[2], Supassara Sirabanchongkran[2]

[1]Dental Department of Phichit Hospital, Thailand
[2]Department of Orthodontics and Pediatric Dentistry, Faculty of Dentistry, Chiang Mai University, Thailand

Abstract

Objectives: Orthodontic treatments with clear aligners are popular. Loss of composite resin attachments during treatment remains a concern. Self-adhesive composite resins were introduced to simplify bonding. This study compared the shear bond strength (SBS) and evaluated the failure modes of self-adhesive and conventional composite resin.

Methods: Eighty-four intact upper first premolars were used, 80 were randomly allocated into five groups with different bonding protocols: Group 1 (etch and rinse + conventional flowable composite resin), Group 2 (self-etching + conventional flowable composite resin), Group 3 (self-adhesive composite resin), Group 4 (etching + self-adhesive composite resin), and Group 5 (self-etching + self-adhesive composite resin). After thermocycling, the SBS was tested using a universal testing machine and analyzed with one-way ANOVA (p<0.05). Failure modes were determined under a stereomicroscope. The enamel surface of four unallocated teeth with different preparations were assessed by a scanning electron microscope.

Results: 62.5% of attachments in Group 3 dislodged after thermocycling. The mean SBS (MPa) was significantly higher in Group 1 (17.72±5.37), Group 2 (19.13±5.37), Group 4 (19.03±6.91), and Group 5 (13.21±4.87) than in Group 3 (3.69±1.30); (p<0.05). Most failures in Groups 1, 2, 4, and 5 were mixed, while Group 3 exhibited only adhesive failure.

Conclusions: Self-adhesive composite resin alone had the lowest SBS. Pretreatment with 37% phosphoric acid or a self-etching primer significantly improved the SBS.

Keywords: attachment of clear aligner, intact enamel surface, self-adhesive composite resin, shear bond strength

Introduction

Today, orthodontic patients place greater emphasis on aesthetics during treatment, which has led to the widespread use of clear thermoplastic materials for orthodontic aligners.(1) Additional components, such as attachments, are incorporated into these clear aligners to achieve effective tooth movement and address complex malocclusions.(2) These attachments are essential not only for guiding proper tooth movement but also for improving appliance retention.(3)

Composite resin is widely utilized for orthodontic attachments owing to its aesthetic compatibility, ease of manipulation in clinical settings, and ability to establish micromechanical retention with etched enamel surfaces.(4) Moreover, the mechanical properties of composite resins specifically hardness and bond strength are frequently considered integral factors in their selection and performance as orthodontic attachment materials.(4,5) Attachment loss may lead to substantial clinical challenges, including prolonged treatment duration, an increased frequency of rebonding appointments, and diminished efficacy of tooth movement.(3,5-7) In orthodontics, bond strength must be adequate to prevent bond failure during treatment while not being strong enough to damage the tooth surface during debonding.(8) Clear aligners exhibit a retention force as high as approximately 49.3 newtons (N).(9) A shear bond strength (SBS) of 5.9-7.8 MPa is recommended for clinically acceptable direct orthodontic bonding systems to withstand masticatory forces effectively.(10)

The etch and rinse method is considered the most reliable for enamel bonding. However, the rinsing and drying process can introduce complexity and impact technique sensitivity. Recent advances in dental materials aim to simplify bonding procedures, reduce technique sensitivity, and shorten chair-side time.(11) These innovations include two-step etch and rinse, two-step self-etch, and one-step self-etch methods.(11) In addition, self-adhesive composite resins that do not require rinsing have also been introduced. These materials are commonly used for small Class I and II cavity restorations and porcelain repairs. Self-adhesive composite resins are also used for bracket bonding.(12)

Given the restricted data on the bonding of self-adhesive composite resin as an attachment of clear aligner orthodontic appliances, this study aimed to (i) compare the SBS and (ii) evaluate the mode of failure of self-adhesive composite resin and conventional composite resin with different adhesive protocols for fabricating the attachments of clear aligner orthodontic appliances.

Materials and Methods

This study received ethical approval from the Human Experimentation Committee of the Faculty of Dentistry, Chiang Mai University, Chiang Mai, Thailand (No. 37/2022).

Teeth preparation

The inclusion criteria for the teeth were as follows: intact upper first premolars without restorations on the buccal surface, without enamel abnormalities, and recently extracted as part of orthodontic treatment. After extraction, the teeth were rinsed with water to eliminate any residual connective tissue and subsequently stored in a 10% formalin solution, which is recommended for tooth preservation and does not adversely affect shear bond strength.(13,14) The sample size was determined from an earlier study.(15) The total calculated sample size from n4 Studies application was 10 for each group. However, this study involved 84 intact upper first premolars. Then, 80 intact upper first premolars were randomly selected and assigned to five groups based on the adhesive system used (16 per group):

Group 1: Etch and rinse+conventional flowable composite resin

Adper™ Scotchbond Multi-Purpose etchant+ Adper™ Scotchbond Multi-Purpose primer+Adper™ Scotchbond Multi-Purpose adhesive+Filtek™ Z350 XT Flowable Composite

Group 2: Self-etching+conventional flowable composite resin

Transbond™ Plus Self Etching+Adper™ Scotchbond Multi-Purpose adhesive+Filtek™ Z350 XT Flowable Composite

Group 3: Self-adhesive composite resin

Vertise® Flow™ Resin

Group 4: Phosphoric acid etching+self-adhesive composite resin

Adper™ Scotchbond Multi-Purpose etchant+ Vertise® Flow™ Resin

Group 5: Self-etching+self-adhesive composite resin

Transbond™ Plus Self Etching + Vertise® Flow™ Resin

The teeth in each group were embedded in plaster of Paris blocks, with four per block. Next, the models were scanned using an intraoral scanner (iTero Element™ 2 imaging system; Align Technology, Tempe, AZ, USA) to create 3D models, which were exported as Standard Triangle Language (STL) files. Then, a rectangular 2.5×3.0×2.0 mm box was designed using Blender 3.1 software (Blender, Amsterdam, Netherlands) to serve as the shape of the attachment. This attachment was then incorporated into the 3D model and printed as a resin model using a 3D printer (Form 2 3D Printer; Formlabs, Somerville, MA, USA). Then, the resin model was used to fabricate individual templates. Next, the teeth were cleaned using pumice for 10 seconds with a rubber cup, followed by thorough rinsing with water and air drying. Finally, the adhesive systems and composite resins were applied as described in Table 1.

After preparation, all samples were aged using a thermal cycling machine (Model TC 301 with cold and hot water baths, models CWB332R and HWB332R, Medical and Environment Equipment Research Laboratory, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand) for 1,000 cycles between 5°C and 55°C with a dipping time of 20 seconds and a transfer time of 10 seconds.

Shear bond strength test

All samples were sectioned 2 mm apical to the cementoenamel junction using a diamond bur. Then, they were embedded in PVC molds (20 mm in diameter, 15 mm in height) with plaster of Paris, leaving only the buccal surface exposed (Figure 1A). The occlusal and gingival surfaces of the attachment were oriented perpendicular to the horizontal plane of the mold. The SBS test was performed using a universal testing machine (UTM) (Instron 5566; Instron Calibration Laboratory, Canton, MA, USA) at a crosshead speed of 1 mm/min. A load was applied to the occlusal surface of the attachment in the occluso-gingival direction using a 2 mm-wide metal band until bond failure occurred (Figure 1B). The SBS was recorded in Newtons (N), and the SBS was calculated using the formula SBS (MPa) = Force (N) / A (mm²), where A is the actual enamel surface area located beneath the attachment base, which was calculated for every samples using the Materialise 3-matic Research software (version 13.0; Materialise, Leuven, Belgium). The details and reference landmarks about finding the enamel surface areas were demonstrated in Figure 2A-D.

Evaluation of the mode of failure

All samples were examined under a stereomicroscope (model CK 40 culture microscope and DP 12 digital camera, Olympus, Japan) at 10× and 20× magnification to determine the adhesive remnant index (ARI) after bond failure. The ARI evaluation was repeated after four weeks to assess intra-rater reliability. The criteria used to evaluate the ARI were adapted from Årtun and Bergland.[16] The ARI was classified into the following categories: 1)

Table 1: Materials in this study and their application.

Product	Manufacturer (Lot, Exp. date)	Application
1.Adper™ Scotchbond Multi-Purpose etchant	3M ESPE, St. Paul, MN, USA (Lot: 7574156, 2024-01-26)	Etch for 15 seconds on enamel, rinse for 15 seconds, remove excess water with an air syringe
2.Adper™ Scotchbond Multi-Purpose primer	3M ESPE, St. Paul, MN, USA (Lot: NC73875,2023-07-21)	Apply to enamel and dry gently for 5 seconds
3.Adper™ Scotchbond Multi-Purpose adhesive	3M ESPE, St. Paul, MN, USA (Lot: NE18400, 2024-01-22)	Apply to enamel, light cure for 10 seconds
4.Transbond™ Plus Self Etching	3M ESPE Monrovia, CA, USA) (Lot: 831721, 2023-07-03)	Apply liquid onto enamel while applying some pressure for a minimum of 5 seconds per tooth, gentle air burst for 2 seconds to each tooth to dry primer into a thin film.
5.Vertise® Flow™ Resin	Kerr, Orange, CA, USA (Lot:10136401, 2025-06-09)	Apply a 0.5 mm thin layer to the center of the tooth, then fill the template with Vertise® Flow™ Resin and place it on the corresponding tooth, light cure for 20 seconds
6.Filtek™ Z350XT Flowable Composite	3M ESPE Monrovia, CA, USA) (Lot:10100202, 2025-04-23)	Fill the template with Filtek™ Z350XT and place it on the corresponding tooth, light cure for 20 seconds

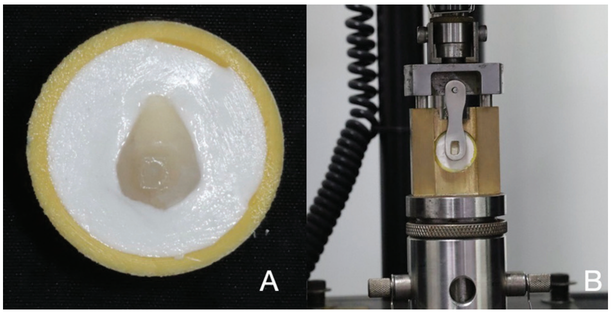

Figure 1: (A) The teeth with attachment was embedded in a mold; (B) The sample was assembled on the universal testing machine with a pull force in occluso-gingival direction and the shear bond strength was recorded.

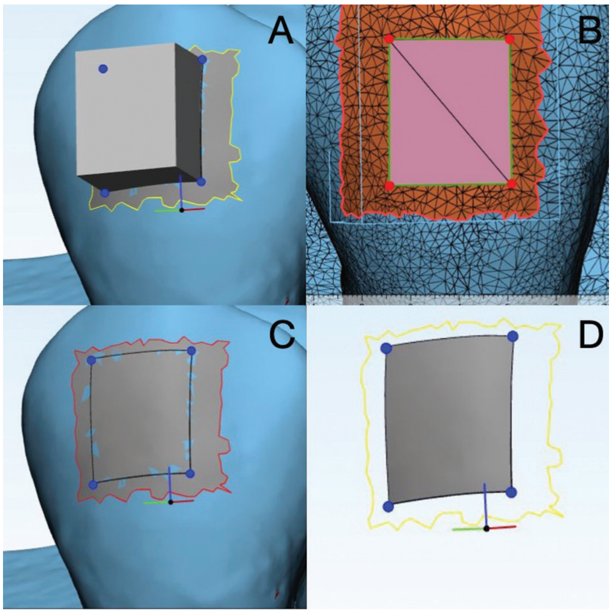

Figure 2: (A) The attachment on intact enamel surface. Four points at the extreme corners of the attachment were located under maximal magnification; (B) Top-view quadrilateral defined by connecting each corner points; (C) The attachment was hidden to reveal the underlying enamel surface bounded by the quadrilateral; (D) Final trimmed surface of bonding under the attachment whose area was measured.

cohesive failure in enamel, 2) interfacial failure between the composite resin and enamel, 3) mixed failure with less than 50% of the bonding area covered by composite resin, 4) mixed failure with at least 50% of the bonding area covered by composite resin, and 5) cohesive failure in the composite resin.

Scanning electron microscope (SEM) analysis

Four teeth were randomly selected to assess the intact enamel surface and enamel surface after preparation with Adper™ Scotchbond Multi-Purpose Etchant, Transbond™ Plus Self Etching, and Vertise® Flow™ Resin. They underwent ultrasonic cleaning, then dehydrated with an ascending ethanol concentration. After that, they were sputter-coated with a thin layer of gold using a sputter coater(model 108; Cressington Scientific Instruments Ltd., Watford, United Kingdom). The surface analysis was performed using SEM (fourth generation VEGA; TESCAN, Brno, Czech Republic) on cross-sectional views in the buccolingual direction at 9000× magnification.

Statistical analysis

The SBS data were presented as mean±standard deviation and analyzed using SPSS Statistics software (version 29.0.2.0[20]; IBM, Armonk, NY, USA). The normality of the data distribution was assessed using the Shapiro-Wilk test. The effect of different attachment bonding protocols on the SBS was evaluated using a one-way analysis of variance (ANOVA) followed by post hoc Dunnett's T3 tests when a significant difference among groups was detected ($p<0.05$). The ARI data were presented as percentages and frequency and analyzed using descriptive statistics.

Results

After thermocycling, most (62.50%) of the attachments in Group 3 dislodged, resulting in only six samples from Group 3 being included in the statistical analysis. The means and standard deviations of the SBS in the five groups are presented in Table 2 and Figure 3. The mean SBS was significantly higher in Groups 1, 2, 4, and 5 than in Group 3 ($p<0.05$). In addition, the mean SBS was significantly higher in Group 2 than in Group 5 ($p<0.05$). However, the mean SBS did not differ significantly between Groups 1, 2, and 4 ($p>0.05$) or Groups 1, 4, and 5 ($p>0.05$).

The ARI evaluation demonstrated good to excellent consistency within each group, with intraclass correlation coefficients (ICC) ranging from >0.75 to >0.90. The remaining composite resins after bond failure are presented as percentages and frequencies in Table 3. Most samples within Groups 1, 2, and 5 exhibited mixed failure with <50% of bonding areas covered by composite resin (score=3) and mixed failure with ≥50% of bonding areas covered by composite resin (score=4). All samples in Group 3 exhibited interfacial failure between the composite resin and enamel (score=2). Most samples in Group 4 exhibited mixed failure with ≥50% of bonding areas covered by composite resin (score=4) and cohesive failure in the composite resin (score=5).

SEM analysis found a demineralization zone using Adper™ Scotchbond Multi-Purpose etchant with a depth of 12.75 µm, Transbond™ Plus Self-Etching Primer with a depth of 13.21 µm, and Vertise® Flow Resin with a depth of 4.04 µm (Figures 4A-D).

Table 2: Mean and standard deviation of shear bond strength in 5 groups.

Group	N	Mean SBS ± SD (MPa)	Maximum (MPa)	Minimum (MPa)	Group difference†
1	16	17.72±5.37	26.35	9.50	A, B
2	16	19.13±5.37	27.24	9.95	A
3	6	3.69±1.30	5.12	1.57	C
4	16	19.03±6.91	32.40	9.30	A, B
5	16	13.21±4.87	21.28	6.16	B

Group 1: Etch and rinse+conventional flowable composite resin, **2:** Self etching+conventional flowable composite resin, **3:** Self-adhesive composite resin, **4:** Etching+Self-adhesive composite resin, **5:** Self etching+Self- adhesive composite resin

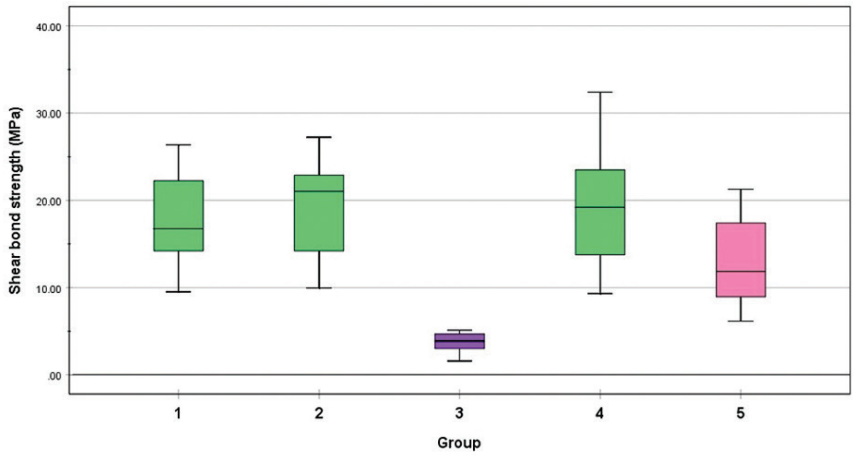

Figure 3: Boxplot of the mean of shear bond strength (SBS). **1:** Etch and rinse+conventional flowable composite resin, **2:** Self etching+ conventional flowable composite resin, **3:** Self-adhesive composite resin, **4:** Etching+Self-adhesive composite resin, **5:** Self etching+ Self-adhesive composite resin.

Table 3: Percentage and frequency (f) of ARI score in 5 groups.

Group \ ARI %(f)	1	2	3	4	5	Total
1	0 % (0)	6.25% (1)	75.00% (12)	12.50% (2)	6.25% (1)	22.86% (16)
2	0 % (0)	6.25% (1)	43.75% (7)	40.63% (6.5)	9.38% (1.5)	22.86% (16)
3	0 % (0)	100% (6)	0% (0)	0% (0)	0% (0)	8.56% (6)
4	0 % (0)	0% (0)	15.63% (2.5)	37.60% (6)	46.88% (7.5)	22.86% (16)
5	0 % (0)	18.75% (3)	53.11% (8.5)	21.88% (3.5)	6.26% (1)	22.86% (16)
Total	0 % (0)	15.71% (11)	42.87% (30)	25.71% (18)	15.71% (11)	100% (70)

Group 1: Etch and rinse+conventional flowable composite resin, **2:** Self etching+conventional flowable composite resin, **3:** Self-adhesive composite resin, **4:** Etching+Self-adhesive composite resin, **5:** Self etching+Self- adhesive composite resin

ARI 1: Cohesive failure in enamel, **2:** Interfacial failure between composite resin and enamel, **3:** Mixed failure with less than 50% of the bonding area covered by composite resin, **4:** Mixed failure with 50% or more of the bonding area covered by composite resin, and **5:** Cohesive failure in composite resin.

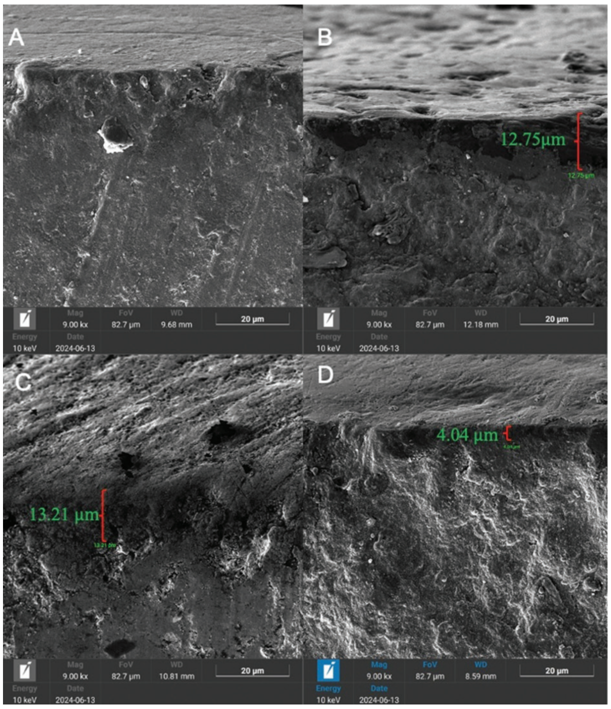

Figure 4: SEM with 9,000x magnification of (A) Intact enamel surface; (B) Demineralization zone using Adper™ Scotchbond Multi-Purpose etchant; (C) Demineralization zone using Transbond™ Plus Self Etching; (D) Demineralization zone using Vertise® Flow Resin.

Discussion

The ideal material for clear aligner attachments should offer resistance to slipping, durability, and ease of application.(17) The etch and rinse system remains the most reliable technique for bonding to enamel. Recent advances in dental materials focus on simplifying bonding procedures to reduce technique sensitivity and chair time.(11) The development of self-adhesive composite resin also offers significant benefits by simplifying the bonding process. Our study aimed to compare the SBS and assess the failure mode of the attachment of clear aligners on intact enamel surfaces with different bonding protocols.

The success of a dental adhesive system depends on its ability to demineralize the tooth surface to enhance its receptiveness and the penetration of monomers into the demineralized zone.(11) A previous study indicated that the etch and rinse and self-etch systems produce comparable SBS on enamel, consistent with our findings that the SBS was similar between Groups 1 and 2.(15)

The bonding mechanism of the Vertise® Flow™ Resin involves two processes: chemical adhesion, where the phosphate group of the glycerophosphate dimethacrylate monomer (GPDM) binds to calcium ions in the tooth structure, and micromechanical interlocking through etching, which creates a network between polymerized monomers and dentin collagen fibers.(18) Our study found that Group 3 had the lowest mean SBS, significantly lower than the other groups. SEM analysis revealed an enamel surface with a shallow demineralized zone in Group 3 (Figure 4D), which can be attributed to the Vertise® Flow™ Resin's low acidity (pH 1.9), which reduces enamel demineralization. In addition, its high viscosity limited monomer penetration into the demineralized zone.(18,19)

Our study observed that 62.5% of the attachments in Group 3 dislodged after thermocycling. These findings are consistent with Goracci *et al.*, who reported a significant decrease in the SBS for the Vertise® Flow™ Resin after aging.(15) However, the SBS of the self-adhesive composite resin was increased by pretreating the surface with phosphoric acid etching (Group 4) and self-etching (Group 5). This finding aligns with the results of prior studies.(20,21) Group 3 showed a high failure rate, leaving only six samples for analysis. Post hoc Dunnett's T3 test was performed for this unequal group sizes with valid results and unchanged reliability.(22) Nevertheless, the high early failure rate itself provides clinically relevant information, indicating that self-adhesive resin, when used without additional surface pretreatment, may not provide adequate bonding performance for attachment retention. Surface pretreatment with either phosphoric acid etching or a self-etching primer should be performed prior to its application to ensure adequate bonding effectiveness.

Clear aligners exhibit a retention force as high as approximately 49.3 N.(9) SBS of 5.9-7.8 MPa is recommended for clinically acceptable direct orthodontic bonding systems to withstand masticatory forces effectively.(10) Therefore, our study found that the SBS of Groups 1, 2, 4, and 5 are acceptable for clinical use. Nevertheless, the bond strength in orthodontics should be sufficient to minimize bond failure during treatment but not high enough to damage the substrate surface during debonding.(8) A report indicated that enamel fractures might be associated with a high bond strength, with the risk of enamel damage increasing by nearly 50% when adhesion forces exceed 14.7 MPa.(23) Therefore, clinicians should carefully balance the requirement for reliable attachment stability with the potential risk of irreversible enamel damage by targeting an optimal range of shear bond strength that is sufficient for clinical retention but not excessively high. Based on the findings of the present study, Group 5 appears to provide the most favorable outcome, offering adequate retention force while minimizing the risk of enamel damage.

It is widely recognized that the failure mode indicates bonding effectiveness, with adhesive or interfacial failure between the composite resin and the enamel signifying low bond strength.(19) Our results indicated a predominance of adhesive failure in Group 3, consistent with the previously reported low bond strengths and corroborating earlier findings.(19) The low acidity and high viscosity of the Vertise® Flow™ Resin might have caused a decrease in the SBS.(18,19) Similarly, the ARI increased with the SBS for self-adhesive composite resins applied after surface pretreatment with phosphoric acid etching (Group 4) and self-etching (Group 5). The increased presence of material remnants in the bonding area leads to surface roughness and the loss of the intact enamel surface after these remnants are removed.(12) Nevertheless, if the SBS is considered acceptable for clinical use, we expect that the attachment will remain adhered to the enamel surface throughout the treatment period. Finally, the attachment will be removed using a dental bur, surface roughness and the loss of the intact enamel surface are unavoidable. Finishing and polishing are necessary after removing the attachment.

The impact of various sterilizing procedures on shear bond strength test has been investigated. The most significant decrease in bond strength was reported for storage in 5.25% sodium hypochlorite (NaOCl) because of enamel deproteinization. NaOCl is not recommended as a storage solution.(14) On the other hand, sterilization and storage in 10% formalin was shown no significant effect on bond strengths.(14) The 10% formalin also demonstrated that sterilization is completely effective.(24) Centers for Disease Control and Prevention (CDC) guidelines suggest immersion in a 10% formalin solution for 2 weeks should be effective for disinfecting.(25) From *in vitro* dental bonding investigations, immersion in 10% formalin might be the best option for storage and sterilizing.(14) In addition, the shear bond strength was not statistically different when storing the teeth in 10% formalin for 24 hours and 2 months.(13) Regarding methodology for surface finding, various studies evaluating the SBS on enamel surfaces conducted successive grinding and polishing to create a uniform flat surface to regulate the size of the bonding area.(26,27) Grinding and polishing to create a uniform flat surface might not represent the SBS on an intact enamel surface. Our study aimed to assess the SBS on intact enamel surfaces. However, the actual enamel surface beneath the attachment base exceeds the area of the attachment base due to the curvature of the tooth surface. Therefore, the Materialise 3-Matic Research software was used to calculate the actual intact enamel surface beneath the attachment base for every sample. (Figure 2A-D).

The limitations of our study were its *in vitro* design and the possibility that its findings may not precisely reflect clinical situations. Moreover, while thermocycling is commonly employed to simulate adhesive aging *in vitro*, it may not fully replicate intraoral conditions such as salivary moisture, enzymatic activity, ionic fluctuations, and occlusal forces. Therefore, the findings should be interpreted with caution, as they may not accurately reflect the long-term clinical performance. A randomized controlled split-mouth clinical trial should be conducted to address these issues.

Conclusions

Attachments made from self-adhesive composite resin had the lowest SBS, which appeared clinically unsuitable. However, surface pretreatment with either 37% phosphoric acid or self-etching primer before applying the self-adhesive composite resin significantly improved the SBS, making it clinically acceptable.

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Conflict of interest

The authors declare no conflicts of interest.

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