

## Article

# Comparison of Bond Strength Performance and Adhesive Remnant Patterns of APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free Orthodontic Brackets: *In Vitro* Study on Human Teeth

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## Abstract

This *in vitro* study compared the bond strength performance and adhesive remnant characteristics of two metallic orthodontic pre-coated bracket systems: APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free. Forty extracted human premolars were randomly allocated to two groups (n = 20). Following enamel etching with 37% phosphoric acid, brackets were bonded according to the manufacturers' recommendations. Bond strength testing was performed using a custom-made apparatus in which failure was induced through a progressively increasing load. Because the experimental setup generated a combined loading configuration involving shear, tensile, and bending components, the measured values should be interpreted as comparative bond strength measurements rather than absolute shear bond strength values. Adhesive Remnant Index (ARI) scores were recorded after debonding to evaluate failure patterns. Median bond strength values were 17.75 MPa (IQR: 13.53–21.98) for APC<sup>TM</sup> Plus and 14.28 MPa (IQR: 9.81–18.74) for APC<sup>TM</sup> Flash Free. No statistically significant difference was found between groups (Mann–Whitney U test,  $p = 0.102$ ). In contrast, ARI score distributions differed significantly (Fisher's exact test,  $p = 0.001$ ). APC<sup>TM</sup> Plus brackets predominantly exhibited ARI scores of 2–3, whereas APC<sup>TM</sup> Flash Free brackets mainly demonstrated ARI scores of 1–2, indicating less adhesive remaining on the enamel surface after debonding. Three enamel fractures were observed in the APC<sup>TM</sup> Plus group, while none occurred in the APC<sup>TM</sup> Flash Free group; however, no statistically significant association between bracket type and enamel fracture was identified. Within the limitations of this *in vitro* study, both bracket systems demonstrated comparable bond strength performance under the experimental conditions investigated. APC<sup>TM</sup> Flash Free brackets were associated with reduced adhesive remnants on enamel, which may facilitate post-debonding cleanup. Further studies using standardized testing methods and prospective clinical investigations are required to confirm these findings and determine their clinical relevance.



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**Keywords:** orthodontic brackets; shear bond strength; APC<sup>TM</sup> Plus; APC<sup>TM</sup> Flash Free; adhesive remnant index; *in vitro* study

## 1. Introduction

The bonding of fixed orthodontic appliances represents the most critical clinical step in multi-bracket treatment. Over the years, adhesive systems have evolved, with manufac-

turers aiming to improve bracket bond strength while simplifying clinical procedures for practitioners [1].

The conventional bonding protocol involves multiple steps: cleaning the enamel surface, etching with 37% phosphoric acid for 30 s, rinsing, drying to a chalky white surface, adhesive application, bracket positioning, the removal of excess adhesive, and light-curing. Strict adherence to this procedure minimizes bond failures, prevents prolonged treatment times, and reduces emergency appointments and additional operational costs [2–6].

Pre-coated brackets, such as APC<sup>TM</sup> Plus, eliminate the step of manually applying adhesive, saving chair time while still requiring the removal of excess material. Incomplete removal can lead to surface roughness, plaque accumulation, and enamel demineralization, ultimately affecting the aesthetic outcome [7,8]. The newer APC<sup>TM</sup> Flash Free brackets further simplify bonding by eliminating the excess removal step through a low-viscosity, fiber-impregnated adhesive, reducing chair time and minimizing iatrogenic enamel damage [9,10].

The failure of bonded brackets occurs at one of three interfaces: enamel–adhesive, within the adhesive, or adhesive–bracket. The Adhesive Remnant Index (ARI) evaluates the site and type of fracture, with an optimal bond leaving minimal adhesive on the enamel to facilitate safe debonding [11–14]. Achieving a balance between sufficient bond strength and ease of adhesive removal is essential to ensure both clinical reliability and enamel preservation [15–19].

The objectives of this study were to compare the shear bond strength and ARI scores of APC<sup>TM</sup> Flash Free and APC<sup>TM</sup> Plus metallic brackets and to verify whether the manufacturer's claims of equivalent performance are supported. Additionally, this work builds upon prior research by Durand et al., assessing whether the shear bond values reported on composite substrates align with those on enamel. The null hypotheses were that there is (1) no difference in shear bond strength between APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free brackets and (2) no difference in ARI scores between the two types of brackets.

## 2. Materials and Methods

### 2.1. Tooth Collection

Forty human premolars were collected from various dental clinics in the Moselle and Meurthe-et-Moselle departments between December 2019 and March 2020. The collection complied with French legislation on surgical waste (*Article L1245-2, Code de la Santé Publique, JO Legifrance*), and only non-opposition from patients was required.

Inclusion criteria were: (1) premolars extracted for orthodontic reasons; (2) free of caries and restorations; and (3) no prior chemical treatment. Extracted teeth were thoroughly cleaned to remove residual soft tissues, stored for seven days in 1% Chloramine T solution, rinsed with water, and kept in distilled water (ISO 3696, Grade 3) at  $4 \pm 4$  °C. The storage solution was renewed after two months [20].

### 2.2. Bracket Bonding Protocol

The teeth were randomly assigned to two groups: APC<sup>TM</sup> Plus (Group 1) and APC<sup>TM</sup> Flash Free (Group 2). Brackets and teeth were paired sequentially by a single operator (AH) to ensure random distribution.

A standardized clinical field was prepared with necessary materials including a contra-angle handpiece with a bristle brush, etchant (37% phosphoric acid, Henry Schein Inc., Melville, NY, USA), adhesive (Transbond<sup>TM</sup> XT, Solventum Corporation, Maplewood, MN, USA), microbrushes, tweezers, and a light-curing device (Actéon, SATELEC Li-ion 3.7 V, 2500 mAh, Acteon Group, Mérignac, France). The enamel was cleaned, etched for 30 s,

rinsed for 30 s, and dried to a chalky white appearance. A thin layer of Transbond™ XT adhesive was applied with a microbrush for 5 s and lightly air-dried for 2–5 s.

Brackets were positioned using a gauge and dental probe. For Group 1 (APC™ Plus), excess adhesive was removed before light-curing; Group 2 (APC™ Flash Free) required no removal of excess material. Photopolymerization was performed on mesial, distal, occlusal, and gingival sides for 5 s per side for APC™ Plus and 10 s per side for APC™ Flash Free, following manufacturer recommendations. Bonded teeth were stored in water at 37 °C for 24 h to allow for complete polymerization (ISO 29022, ISO 11405) [21,22].

### 2.3. Embedding of Teeth

Teeth were ligated to a 0.017 × 0.025" stainless steel archwire and positioned in custom silicone molds (4 cm inner diameter, 3 cm height). Autopolymerizing slow-set epoxy resin (Resoltech 1050/1053S, Resoltech SAS, Rousset, France) was poured into molds, and polymerization occurred over ~29 h at room temperature (<38 °C). Once set, resin blocks were stored at 37 °C until testing.

### 2.4. Shear Bond Strength Testing

A custom-made shear testing apparatus was used, consisting of an aluminum frame (38 × 38 × 85 cm) with adjustable feet. Resin blocks were stabilized in the support with the occlusal surface facing upward. Brackets were attached to a 0.028" stainless steel wire linked to a bucket, gradually filled with water via a drip system until bracket failure. The loading rate was dependent on the controlled water flow used to fill the bucket and therefore differs from the constant crosshead speed provided by universal testing machines.

The custom-made apparatus used in this study does not generate a pure shear loading condition comparable to that produced by a universal testing machine. Due to the geometry of the setup, the measured bond strength values likely reflect a combination of shear, tensile, and bending stresses acting simultaneously on the bracket–adhesive–enamel complex. Consequently, the values reported should be interpreted as comparative bond strength measurements obtained under standardized experimental conditions rather than absolute shear bond strength values. The bucket mass was recorded with a precision balance (±10 g) to calculate shear force (N). Shear bond strength (MPa) was calculated using the following:

$$\text{Shear Bond Strength (MPa)} = \text{Force (N)} / \text{Bracket Base Area (mm}^2\text{)}$$

The premolar bracket surface area was 10.382 mm<sup>2</sup>, as provided by the manufacturer. The force was calculated according to the following:

$$\text{Force (N)} = \text{Mass (kg)} \times 9.81 \text{ m/s}^2$$

and shear bond strength was subsequently calculated by dividing the force by the bracket base area supplied by the manufacturer.

To improve reproducibility, specimen positioning was standardized using a custom alignment guide. The water flow rate was calibrated before each testing session, and all measurements were performed by the same operator under identical environmental conditions. Photographic documentation and a schematic representation of the testing apparatus are provided in the Supplementary Material and embedded within this manuscript.

### 2.5. Adhesive Remnant Index (ARI) Assessment

Following debonding, the bracket base and enamel surfaces were photographed and examined under 30× magnification. ARI scores were assessed three times per bracket by the same operator at two-day intervals, according to Artun and Bergland [11]. All

procedures were performed by AH, resident at the Faculty of Odontology, Department of Orthodontics, University of Lorraine, France.

### 2.6. Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics 28.0 (IBM Corp., Armonk, NY, USA). Data were first evaluated for normality using the Shapiro–Wilk test. As the shear bond strength values did not follow a normal distribution, non-parametric tests were applied.

Descriptive statistics included the median, interquartile range (IQR), mean, standard deviation, and coefficient of variation for each group. The Mann–Whitney U test was used to compare shear bond strength between the APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free groups.

The Adhesive Remnant Index (ARI) scores were analyzed as categorical variables. Comparisons between groups were performed using the Chi-square test of independence, Fisher’s exact test, and the likelihood ratio test. The association between ARI score and shear bond strength was assessed using the Kruskal–Wallis test, followed by post hoc pairwise comparisons with the Dunn–Bonferroni method when appropriate.

Spearman rank correlation was calculated to evaluate the relationship between weight, applied force, and shear bond strength. Statistical significance was set at  $p < 0.05$  for all analyses.

A priori power analysis was conducted to determine the minimum sample size required to detect a statistically significant difference in shear bond strength between the two bracket groups (APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free). Based on previous studies reporting mean shear bond strengths of  $17.0 \pm 4.0$  MPa for APC<sup>TM</sup> Plus and  $14.0 \pm 4.0$  MPa for APC<sup>TM</sup> Flash Free [10,23], an effect size (Cohen’s  $d$ ) of 0.75 was estimated. Using a significance level of  $\alpha = 0.05$  and a desired power of 0.80, calculations performed with G\*Power 3.1 indicated that a minimum of 18 samples per group was required. To account for potential sample loss or measurement errors, 20 teeth were included in each group.

This power calculation ensures that this study has a sufficient sample size to detect meaningful differences between groups in shear bond strength while minimizing the risk of Type II errors. All statistical analyses were performed considering this sample size as adequate for both non-parametric comparisons (Mann–Whitney U test) and correlation analyses (Spearman’s  $\rho$ ).

The Chi-square test was used when the expected frequencies met the assumptions required for contingency table analysis.

Fisher’s exact test was applied when expected cell counts were too small for reliable Chi-square analysis.

The likelihood ratio test was used as an alternative measure when appropriate for categorical data comparisons.

The assumptions for each test were assessed and confirmed prior to analysis.

## 3. Results

### 3.1. Shear Bond Strength

Shear bond strength values for each specimen were measured. The median and interquartile range (IQR) were used to describe the results due to non-normal data distribution (Table 1).

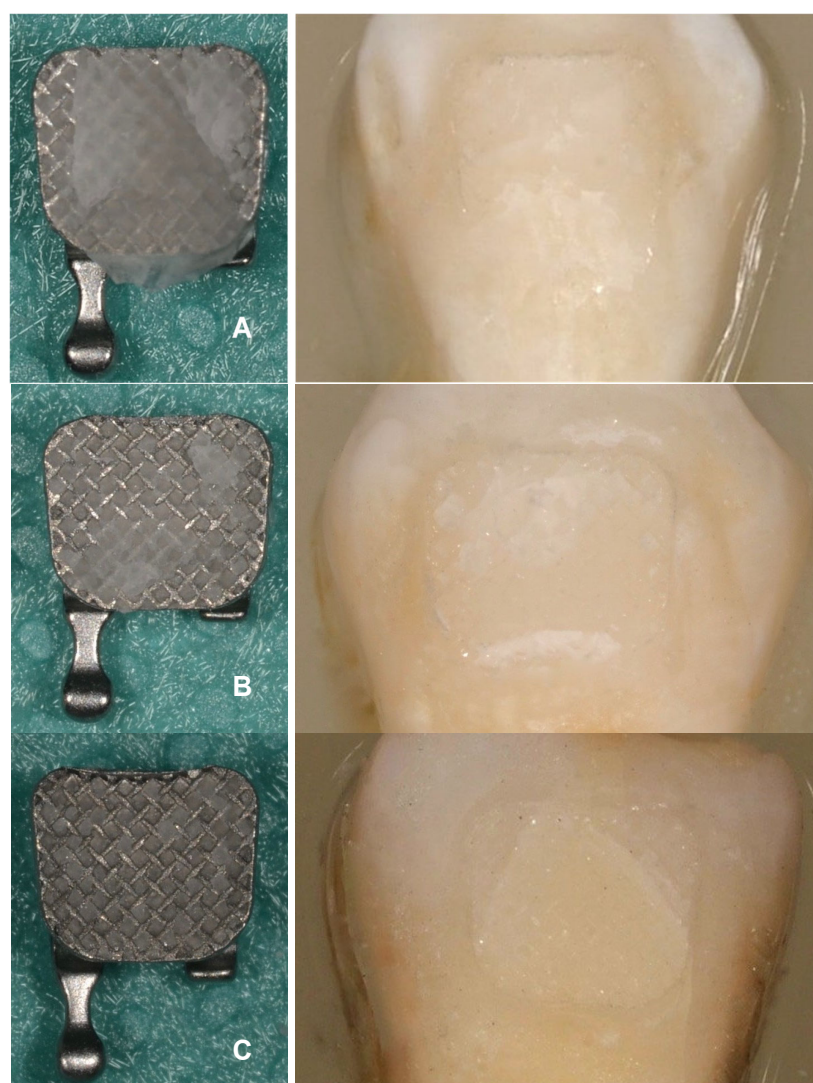
The median shear bond strength was 17.75 MPa (IQR: 13.53–21.98 MPa) for the APC<sup>TM</sup> Plus group and 14.28 MPa (IQR: 9.81–18.74 MPa) for the APC<sup>TM</sup> Flash Free group (Figure 1). The Mann–Whitney U test indicated no statistically significant difference between groups ( $p = 0.102$ ), suggesting comparable shear bond performance for both bracket types (Table 2). Because the loading configuration involved combined stress components rather than pure

shear loading, the measured values should be interpreted as comparative indicators of bond performance between the two bracket systems rather than absolute shear bond strength values.

**Table 1.** Distribution of ARI scores for both bracket types compared with theoretical frequencies (50% ARI = 1 and 50% ARI = 2).

| Group | Type     | ARI Score 1 | ARI Score 2 | ARI Score 3 | Total |
|-------|----------|-------------|-------------|-------------|-------|
| 1     | Observed | 2           | 7           | 8           | 17    |
| 1     | Expected | 4.1         | 9.2         | 3.7         | 17.0  |
| 2     | Observed | 7           | 13          | 0           | 20    |
| 2     | Expected | 4.9         | 10.8        | 4.3         | 20.0  |
| Total | Observed | 9           | 20          | 8           | 37    |
| Total | Expected | 9.0         | 20.0        | 8.0         | 37.0  |

Notes: Observed values correspond to the recorded ARI scores for both bracket types. Expected values represent the theoretical frequencies assuming a distribution of 50% ARI score = 1 and 50% ARI score = 2. ARI = Adhesive Remnant Index.



**Figure 1.** APC™ Plus attachments associated with their buccal surfaces and corresponding ARI scores: (A) = score 1; (B) = score 2; (C) = score 3.

**Table 2.** Summary of Kruskal–Wallis test/influence of bracket type on shear strength.

| # | Null Hypothesis                                                                 | Test                                      | Sig.   | Decision                   |
|---|---------------------------------------------------------------------------------|-------------------------------------------|--------|----------------------------|
| 1 | The distribution of WEIGHT (kg) is identical across sample categories.          | Mann–Whitney U test (independent samples) | 0.1021 | Retain the null hypothesis |
| 2 | The distribution of FORCE (N) is identical across sample categories.            | Mann–Whitney U test (independent samples) | 0.1021 | Retain the null hypothesis |
| 3 | The distribution of Shear Strength (MPa) is identical across sample categories. | Mann–Whitney U test (independent samples) | 0.1021 | Retain the null hypothesis |

### 3.2. Adhesive Remnant Index (ARI) (Figures 1–4)

ARI scores for the two groups are summarized in Table 3. For APC<sup>TM</sup> Plus brackets, scores were distributed as follows, ARI 1 = 2, ARI 2 = 7, and ARI 3 = 8, with three enamel fractures preventing ARI evaluation. For APC<sup>TM</sup> Flash Free brackets, ARI 1 = 7, ARI 2 = 13, and ARI 3 = 0 (Table 1).

**Table 3.** Chi-square tests. <sup>a</sup>. Four cells (66.7%) have expected counts less than 5. The minimum expected count is 3.68. <sup>b</sup>. Based on linear-by-linear association.

| Test                         | Value               | df | Asymptotic Significance (2-Sided) | Exact Sig. (2-Sided) | Exact Sig. (1-Sided) |
|------------------------------|---------------------|----|-----------------------------------|----------------------|----------------------|
| Pearson Chi-Square           | 12.416 <sup>a</sup> | 2  | 0.002                             | 0.001                |                      |
| Likelihood Ratio             | 15.617              | 2  | 0.000                             | 0.001                |                      |
| Fisher’s Exact Test          | 12.745              |    |                                   | 0.001                |                      |
| Linear-by-Linear Association | 9.631 <sup>b</sup>  | 1  | 0.002                             | 0.003                | 0.001                |
| N of Valid Cases             | 37                  |    |                                   |                      |                      |

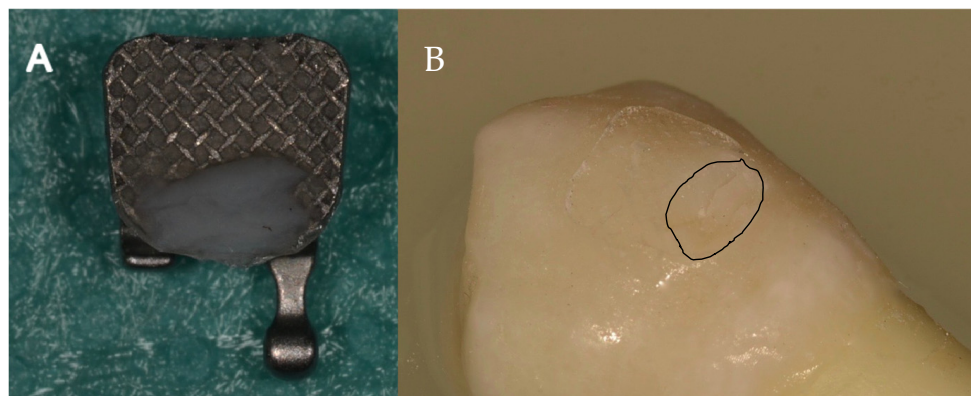
**Figure 2.** The variation in the amount of adhesive remaining on APC<sup>TM</sup> Flash Free fasteners that recorded an ARI score of 2.

Fisher’s exact test revealed a significant difference in ARI score distribution between groups ( $p = 0.001$ ). Specifically, ARI 1 and 2 were more frequent for APC<sup>TM</sup> Flash Free, while ARI 3 occurred only for APC<sup>TM</sup> Plus (Figures 1–4).

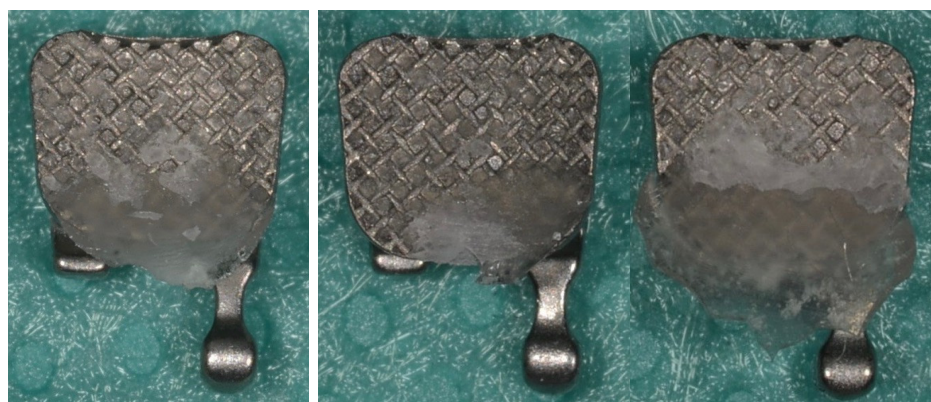
The precise cause of the enamel fractures cannot be determined from the present data.

The absence of a pre-experimental enamel integrity assessment is an additional limitation of this study, and we recommend that future investigations incorporate non-destructive imaging methods such as micro-CT or dye-assisted crack detection before bond testing [24].

Three enamel fractures were observed in the APC<sup>TM</sup> Plus group; however, no significant association was found between bracket type and enamel fracture ( $p = 0.231$ , Tables 2 and 3).



**Figure 3.** Enamel fracture. (A): Orthodontic bracket. (B): Site of enamel fracture on buccal surface of maxillary premolar.



**Figure 4.** The variation in the amount of adhesive remaining on APCTM Flash Free brackets that recorded an ARI score of 2.

### 3.3. Relationship Between ARI and Shear Bond Strength

Kruskal–Wallis analysis demonstrated a statistically significant association between ARI score and shear bond strength ( $p = 0.04$ ) (Table 4). Post hoc testing revealed that brackets with ARI 2 had lower shear bond strength than those with ARI 3 ( $p = 0.042$ ), while no significant differences were observed between ARI 1 and 2 or ARI 1 and 3 (Tables 4 and 5).

**Table 4.** Distribution of Adhesive Remnant Index (ARI) scores according to bracket type.

| Bracket Type                 | ARI = 1 | ARI = 2 | ARI = 3 | Total |
|------------------------------|---------|---------|---------|-------|
| APC <sup>TM</sup> Plus       | 2       | 7       | 8       | 17 *  |
| APC <sup>TM</sup> Flash Free | 7       | 13      | 0       | 20    |
| Total                        | 9       | 20      | 8       | 37    |

\* Three specimens in the APC<sup>TM</sup> Plus group exhibited enamel fractures during debonding and could not be assigned an ARI score. **Notes:** ARI = Adhesive Remnant Index. ARI score 1 indicates that less than 50% of the adhesive remained on the enamel surface after debonding; ARI score 2 indicates that more than 50% of the adhesive remained on the enamel; ARI score 3 indicates that all adhesive remained on the enamel surface with an impression of the bracket mesh. A statistical comparison of ARI distributions between groups was performed using Fisher's exact test and Chi-square analysis.

**Table 5.** Summary of Kruskal–Wallis tests: influence of ARI score on shear bond strength.

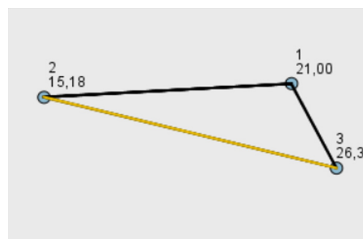
| # | Null Hypothesis                                                                    | Test                                      | <i>p</i> -Value | Decision     | Interpretation                        |
|---|------------------------------------------------------------------------------------|-------------------------------------------|-----------------|--------------|---------------------------------------|
| 1 | The distribution of WEIGHT (kg) is identical across ARI score categories.          | Kruskal–Wallis test (independent samples) | 0.040           | Reject $H_0$ | Significant difference between groups |
| 2 | The distribution of FORCE (N) is identical across ARI score categories.            | Kruskal–Wallis test (independent samples) | 0.040           | Reject $H_0$ | Significant difference between groups |
| 3 | The distribution of Shear Strength (MPa) is identical across ARI score categories. | Kruskal–Wallis test (independent samples) | 0.040           | Reject $H_0$ | Significant difference between groups |

**Notes:** Asymptotic significances are displayed. The significance level is set at  $p < 0.05$ .

### 3.4. Summary of Results

Due to the high correlation between weight, force, and shear bond strength (Spearman's  $\rho = 1.000$ ,  $p < 0.01$ ; Table 5), only shear bond strength is reported here.

Overall, APC<sup>TM</sup> Plus brackets showed slightly higher median shear bond strength, whereas APC<sup>TM</sup> Flash Free brackets exhibited lower ARI scores and no enamel fractures (Tables 6 and 7). Both bracket types demonstrated clinically acceptable bond strengths.

**Table 6.** Pairwise comparisons of ARI scores with Bonferroni adjustment.**Pairwise Comparisons of ARI Scores.**

| Comparison (I–J) | Test Statistic | Std. Error | Standardized Test Statistic | <i>p</i> -Value | Adjusted <i>p</i> -Value |
|------------------|----------------|------------|-----------------------------|-----------------|--------------------------|
| 2–1              | 5.825          | 4.344      | 1.341                       | 0.180           | 0.540                    |
| 2–3              | −11.137        | 4.528      | −2.460                      | 0.014           | 0.042                    |
| 1–3              | −5.312         | 5.259      | −1.010                      | 0.312           | 0.937                    |

**Notes:** Each node represents the mean rank of the ARI score. Each row tests the null hypothesis that the distributions of the two samples are identical. Asymptotic two-sided significances are reported. The significance level is set at  $p < 0.05$ . *p*-values were adjusted using the Bonferroni correction for multiple comparisons.

**Table 7.** Distribution of observed and expected frequencies by group.

| Group | Type     | Category 1 | Category 2 | Category 3 | Total |
|-------|----------|------------|------------|------------|-------|
| 1     | Observed | 2          | 7          | 8          | 17    |
| 1     | Expected | 4.1        | 9.2        | 3.7        | 17.0  |
| 2     | Observed | 7          | 13         | 0          | 20    |
| 2     | Expected | 4.9        | 10.8       | 4.3        | 20.0  |
| Total | Observed | 9          | 20         | 8          | 37    |
| Total | Expected | 9.0        | 20.0       | 8.0        | 37.0  |

**Notes:** Observed = actual counts; Expected = theoretical counts under the null hypothesis.

## 4. Discussion

The present study compared the shear bond strength (SBS) and adhesive remnant patterns of APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free metallic orthodontic brackets bonded to human enamel. Although APC<sup>TM</sup> Plus brackets exhibited higher median SBS values than APC<sup>TM</sup> Flash Free brackets (17.75 MPa versus 14.28 MPa), the difference was not statistically significant. However, significant differences were observed in the distribution of Adhesive Remnant Index (ARI) scores, suggesting distinct debonding mechanisms between the two systems.

### 4.1. Clinical Relevance of Shear Bond Strength

Although the measured bond strength values exceeded commonly cited clinical thresholds, direct comparison with studies using standardized universal testing machines should be undertaken with caution. The present experimental setup generated a complex loading configuration involving shear, tensile, and bending forces. Therefore, the values reported are most appropriately interpreted as relative measures of bond performance between the two bracket systems tested under identical experimental conditions. Reynolds suggested that bond strengths between 6 and 8 MPa are sufficient to withstand routine orthodontic forces, while subsequent authors have proposed values approaching 10 MPa as a desirable clinical target. In the present study, both APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free brackets exceeded these recommendations by a considerable margin, indicating that both systems should provide adequate clinical performance.

Although APC<sup>TM</sup> Plus brackets showed a trend toward higher bond strength, the absence of a statistically significant difference suggests that the Flash Free adhesive technology does not compromise bracket retention. From a clinical perspective, this finding is important because orthodontists increasingly seek bonding systems that simplify procedures and reduce chairside time without sacrificing mechanical reliability. The present results therefore support the manufacturer's claim that APC<sup>TM</sup> Flash Free brackets provide bond strengths comparable to those of conventional APC<sup>TM</sup> Plus systems.

### 4.2. Interpretation of ARI Distribution Patterns

While SBS values were similar between groups, the ARI distributions differed significantly. APC<sup>TM</sup> Plus brackets predominantly exhibited ARI scores of 2 and 3, whereas APC<sup>TM</sup> Flash Free brackets mainly showed ARI scores of 1 and 2. Furthermore, ARI score 3 was observed exclusively in the APC<sup>TM</sup> Plus group.

These findings indicate differences in the location of bond failure. The higher frequency of ARI 3 scores in the APC<sup>TM</sup> Plus group suggests that failure occurred predominantly at the bracket–adhesive interface, leaving substantial adhesive on the enamel surface after debonding. In contrast, APC<sup>TM</sup> Flash Free brackets exhibited more mixed failure patterns and left significantly less residual adhesive on enamel.

One possible explanation lies in the unique composition of the Flash Free adhesive system. The fiber-reinforced adhesive mat incorporated into the bracket base may alter stress distribution during debonding and promote a more cohesive fracture pattern. This may explain why adhesive remnants were reduced without compromising overall bond strength.

The significant association observed between ARI score and SBS further supports this interpretation. Brackets exhibiting ARI 3 scores demonstrated higher bond strengths than those with ARI 2 scores, suggesting that stronger bracket–adhesive interactions may influence the location of bond failure. Nevertheless, because ARI distribution differed substantially between groups, caution is required when attributing these findings solely to bracket design.

#### 4.3. Comparison with Previous Studies

The SBS values observed for APC<sup>TM</sup> Plus brackets are consistent with those reported by Durand [25] and are within the range described by Lee and Kanavakis [10] and by Marc et al. [23]. Similarly, the APC<sup>TM</sup> Flash Free brackets demonstrated bond strengths comparable to those previously reported for Flash Free systems, confirming that the adhesive technology provides clinically reliable attachment to enamel.

The absence of a significant difference between bracket systems agrees with the findings of Marc et al., who reported similar bond strengths between conventional pre-coated and Flash Free systems. However, Lee and Kanavakis [10] observed slightly higher SBS values for Flash Free brackets under different bonding conditions using self-etching primers. Differences in substrate preparation, bonding protocols, and testing methodologies may explain these discrepancies [26,27].

Regarding ARI scores, the present findings are consistent with those of others Kanavakis and González-Serrano et al. [10,28], who reported reduced adhesive remnants with Flash Free systems. Grünheid et al. [15–17] further demonstrated that Flash Free brackets reduced adhesive cleanup time after debonding, supporting the clinical relevance of the lower ARI scores observed in the present study.

Collectively, the available literature suggests that Flash Free technology does not substantially alter bond strength but may modify failure patterns in a clinically advantageous manner by reducing residual adhesive on enamel.

#### 4.4. Clinical Implications

The findings of this study have important practical implications for orthodontic clinicians. Since both bracket systems demonstrated clinically acceptable bond strengths, bracket selection may be guided by secondary considerations such as efficiency during bonding and debonding procedures.

The reduced amount of adhesive remaining on enamel following the debonding of APC<sup>TM</sup> Flash Free brackets may shorten cleanup procedures and decrease chairside time. This could improve clinical efficiency while reducing the risk of enamel damage associated with rotary adhesive removal.

Interestingly, all three enamel fractures observed in the present study occurred in the APC<sup>TM</sup> Plus group, although no statistically significant association with bracket type was identified. Given the limited sample size, definitive conclusions cannot be drawn. Nevertheless, the absence of enamel fractures in the Flash Free group, combined with the reduced amount of adhesive remnants, may suggest a more favorable debonding profile.

From a patient-centered perspective, shorter cleanup procedures may improve comfort and reduce treatment time during appliance removal. Consequently, APC<sup>TM</sup> Flash Free brackets may offer advantages beyond bond strength alone, particularly in high-volume clinical settings where procedural efficiency is important.

#### 4.5. Limitations and Future Directions

Several limitations should be considered when interpreting these results. First, this was an *in vitro* investigation that could not fully reproduce the oral environment [28]. Factors such as saliva, thermal cycling, pH fluctuations, masticatory forces, and long-term aging were not simulated.

Second, the custom-made testing apparatus differs from the universal testing machines commonly used in orthodontic bond strength studies. Although the experimental setup allowed for standardized comparison between groups, it did not generate a pure shear force. The measured bond strength values therefore reflect a combination of shear, tensile,

and bending stresses. This methodological limitation restricts direct comparison with the absolute bond strength values reported in the literature [29–31].

Third, no baseline assessment of enamel microcracks or structural defects was performed before bonding. Consequently, the origin of the enamel fractures observed after debonding cannot be determined with certainty. Future studies should incorporate non-destructive imaging techniques such as micro-computed tomography (micro-CT) or dye-assisted crack detection before mechanical testing.

Finally, although all specimens were prepared according to a standardized protocol, operator-dependent factors and minor variations in specimen positioning may have contributed to measurement variability.

Future investigations should evaluate bracket survival rates, adhesive removal time, enamel surface alterations after debonding, and patient-centered outcomes under clinical conditions. Randomized controlled clinical trials would be particularly valuable to determine whether the reduced adhesive remnants observed *in vitro* translate into meaningful clinical benefits.

#### 4.6. Study Timeline and Data Integrity

The experimental phase of this study was conducted between 2019 and 2020. Following the completion of specimen testing, additional data verification procedures, statistical analyses, manuscript preparation, and subsequent revisions were performed over several years. The COVID-19 pandemic, associated institutional restrictions, and academic commitments contributed to delays between data acquisition and manuscript submission. However, all raw data, laboratory records, and statistical analyses were preserved and independently verified before final manuscript preparation.

## 5. Conclusions

### 1. Bond Strength Performance

Under the experimental conditions of the present study, APC<sup>TM</sup> Plus and APC<sup>TM</sup> Flash Free metallic orthodontic brackets demonstrated comparable bond strength performance. Because the testing apparatus generated a combined loading configuration involving shear, tensile, and bending components, the reported values should be interpreted as comparative bond strength measurements rather than absolute shear bond strength values.

### 2. Adhesive Remnant Index (ARI):

A statistically significant difference was observed in ARI scores between the two types of brackets. APC<sup>TM</sup> Plus brackets showed predominantly ARI = 2 and 3, indicating more adhesive remaining on the tooth surface after debonding, whereas APC<sup>TM</sup> Flash Free brackets mainly exhibited ARI = 1 and 2, leaving less adhesive on the enamel. This suggests that APC<sup>TM</sup> Flash Free brackets may facilitate easier removal of residual adhesive in clinical practice.

### 3. Fracture Pattern:

Enamel fractures were observed only in the APC<sup>TM</sup> Plus group, but no statistically significant correlation was found between bracket type or debonding force and enamel fracture. These occurrences may be related to variations in substrate quality or handling during sample preparation.

### 4. Clinical Implications:

Within the limitations of this *in vitro* study, APC<sup>TM</sup> Flash Free brackets appear to provide bond performance comparable to APC<sup>TM</sup> Plus brackets while leaving less residual adhesive on enamel after debonding. These findings may have practical

implications for clinical efficiency; however, confirmation through well-designed clinical studies remains necessary.

#### 5. Recommendations for Future Research:

Future studies should evaluate the long-term clinical performance of APC<sup>TM</sup> Flash Free brackets, investigate differences in adhesive removal times, and consider standardized protocols for in vitro shear bond testing to improve comparability between studies.

**Take-Home Message:** APC<sup>TM</sup> Flash Free metallic brackets provide clinically acceptable bond strength comparable to APC<sup>TM</sup> Plus while leaving less residual adhesive on teeth. This may simplify debonding and reduce chairside cleanup, but further in vivo studies are needed to confirm these benefits.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/adhesives2030014/s1>.

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