A comparison of bond strength and adhesive remnant index of 3D-printed and metal orthodontic brackets attached using different adhesives

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Introduction: The aim of this in vitro study was to evaluate the shear bond strength (SBS) and adhesive remnant index (ARI) scores of two different adhesive applications of aesthetic brackets produced from permanent crown material using 3D-printing technology.
Methods: Sixty maxillary premolar teeth extracted for orthodontic reasons were divided into two main groups according to the type of bracket (metal brackets *n*=30, 3D-printed brackets *n*=30) and further divided into two subgroups according to the type of adhesive (flowable composite, Tokuyama SuperLow; non-flowable composite; 3M Transbond XT). SBS and ARI score evaluations were conducted in the experimental and control subgroups (*n*=15). Statistical analysis was performed by a one-way analysis of variance, a post-hoc test, and Fisher's exact test. Statistical significance was accepted as $P < 0.05$.
Results: The bond strength of the specimens was significantly affected by the type of composite and bracket type ($P < 0.001$). However, the SBS values were within or above the desired range for orthodontic treatment in all groups. The highest SBS value was obtained in the Metal Bracket-Transbond XT group (15.03 ± 6.66), while the lowest SBS value was observed in the 3D-Printed Bracket-Transbond XT group (7.91 ± 3.07). It was noted that of all materials evaluated, the most common non-enamel-damaging adhesive–cohesive fractures were in 3D-Printed Bracket Tokuyama SuperLow group (*n*=13).
Conclusions: It is recommended that 3D-printed orthodontic brackets have sufficient and acceptable SBS levels for clinical applications and bonding using non-flowable adhesives to produce high SBS values and using flowable adhesives generating high ARI scores.
(Aust Orthod J 2023; 39: 32 - 39. DOI: 10.2478/aoj-2023-0024)

Received for publication: February, 2023
accepted: June, 2023.

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Introduction

Computer-aided design and computer-aided manufacturing (CAD/CAM) systems have been applied in many branches of dentistry in recent years[1] and are becoming increasingly popular in clinical and laboratory orthodontic practice.[2] CAD/CAM systems that enable effective dental treatment have many advantages related to a reduced production time, the production of high-quality dental products, reduced session times, high accuracy and a customised dental material design.[3]

CAD/CAM technology, especially in complex cases, identified as patients with multiple tooth deficiencies or dentofacial deformities, and in orthognathic

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surgery cases, by creating 3D digital treatment models, can facilitate accurate diagnosis and treatment planning and increase patient-clinician communication.[2,4] CAD/CAM technologies work subtractively in production, while 3D printers work as an additive system.[5]

Additive manufacturing refers to the 3D-printing technique that enables the manufacture of a wide range of products with specific features and shapes that meet the demands of patients.[6] Based on the use of 3D images, a customised bracket system has been introduced to take orthodontic treatment into the next era.[7–9] In a study comparing traditional and customised brackets, it was reported that customised 3D production systems provide acceptable treatment results, increase patient comfort, and significantly reduce total treatment time in addition to the number of scheduled appointments.[10] Following the 1970s, prefabricated ceramic brackets, which were preferred especially among adults for aesthetic requirements, were found to have excessive friction, while plastic brackets did not provide sufficient strength nor torque, which led to the search for new materials.[7,11] Today, 3D printers are at the forefront to meet orthodontic aesthetic expectations. While it is possible to produce brackets with a personalised design and tooth colour using 3D printers, it is uncertain whether ideal bonding strength is achieved throughout treatment after the application of these brackets to the enamel surface using different adhesive agents.[5] The bond strength of orthodontic attachments has been increased by the use of acid roughening and laser application. Brackets are expected to adhere with a strength strong enough to resist separation from the enamel surface during treatment, while allowing debonding leaving the least amount of residual adhesive resin and without damaging the enamel.[9]

The development of 3D printers has created new orthodontic horizons. Many appliances designed in three dimensions can be produced from bio-compatible resins using this technology. Most appliances can be produced specifically for patients, therefore accelerating the workflow, and eliminating the necessity of working through a technical laboratory.[7] Therefore, to add to current knowledge, the aim of the present in vitro study was to determine the SBS and ARI values of aesthetic brackets produced using biocompatible permanent crown resin by 3D printing.

Materials and methods

An average bracket base area of 9.94 mm² and 0.022 inch-slot 3D brackets were designed using software (TinkerCAD, Autodesk, Montreal, Quebec). The designed brackets were produced using permanent crown resin (Senertek P Crown, Izmir, Turkiye) in Anycubic Photon Mono X (LCD Masked Technology, Anycubic Technology Co., Shenzhen, China). The flexural strength of Senertek P Crown resin was determined by 2 × 2 × 25 mm samples produced and tested (66.0 ± 4.29 MPa) in accordance with ISO 4049 standards. In addition, 10 mm diameter and 2 mm thick discs were produced for the Vickers (63.66 ± 7.12) value (Figure 1). The post-curing processes of the produced brackets were performed in the form of ultrasonic washing in ethanol at 35 W for 3 min and curing in UV light of 36 watts for 20 min in accordance with the manufacturer's recommendations. To increase the SBS values and the surface area of the 3D-printed bracket base, grooves were shaped in the base (Figure 2). The sample size required for the evaluation of SBS and ARI scores was calculated in the G*Power program (version 3.1.9.7; Axel Buchner, Heinrich Heine Universität, Düsseldorf, Germany). The total sample (effect size: 0.60) required to detect an effect of medium size with 95% power was found to be 48. To increase the reliability of the study results, a total of 60 premolar teeth extracted for orthodontic purposes constituted the material for the study.

Premolars extracted for orthodontic reasons were collected and stored at room temperature in distilled water before use. After the tissue residues on the extracted teeth were cleaned with water, they were stored in water with 0.1% thymol added to prevent the proliferation of micro-organisms on the tooth surface. No carious lesions, no hypoplastic enamel tissue and developmental enamel disorders, and no buccal enamel cracks, fractures nor any restored teeth were included in the study.

The 60 teeth were randomly divided into four equal groups (n = 15):

Group 1 (G1): Control group (Metal Bracket + 3M Transbond XT);

Group 2 (G2): Control group (Metal Bracket + Tokuyama SuperLow);

Group 3 (G3): Experimental group (3D Print Bracket + 3M Transbond XT);

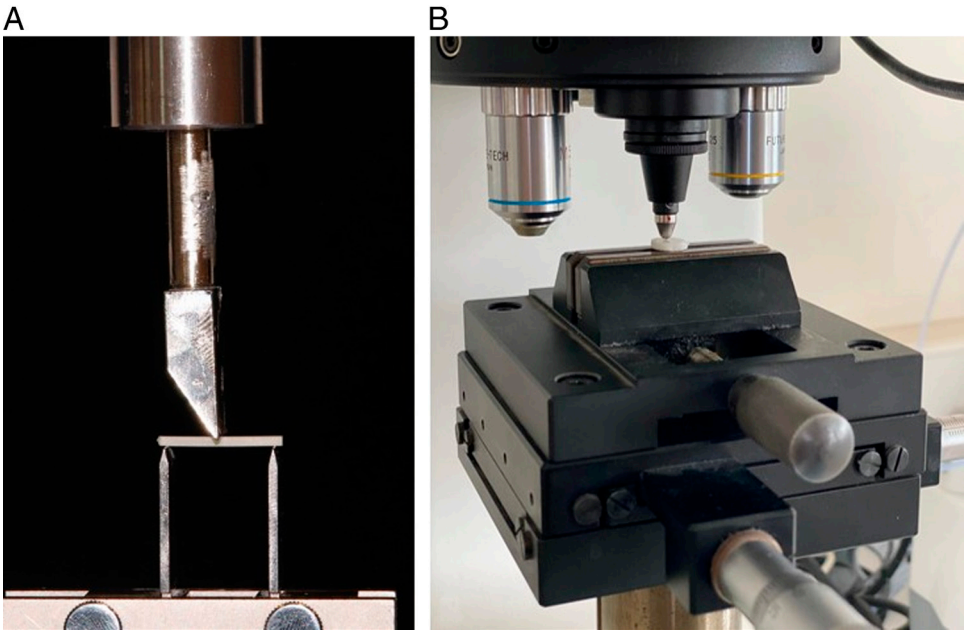


Figure 1. (A) The flexural strength measurement. (B) Vickers Hardness measurement.

Group 4 (G4): Experimental group (3D Print Bracket + Tokuyama SuperLow).

Before the brackets were bonded, the tooth surfaces were cleaned using fluoride-free pumice for 15 sec and washed with an air-water spray and dried. 37% phosphoric acid in gel form was applied to the buccal surfaces of the extracted teeth, left for 15 sec, then washed with water for 30 sec and dried using an air syringe for 15 sec. According to the groups, the bonding process was performed by a single person after applying the relevant bonding material. The brackets were cured using a VALO Ortho Cordless (Ultradent, South Jordan, UT, USA) curing light.

The brackets used in the control group were 0.022-inch slot, Roth system, premolar metal brackets with an average bracket base area of 9.94 mm^2 (Mini Master Series, American Orthodontics, California, USA). After the tooth specimens were embedded in acrylic blocks, SBS measurements were performed using a universal testing machine (Instron Z020; Zwick/Roell, Ulm, Germany). A mechanism consisting of 3 × 3 screws was installed

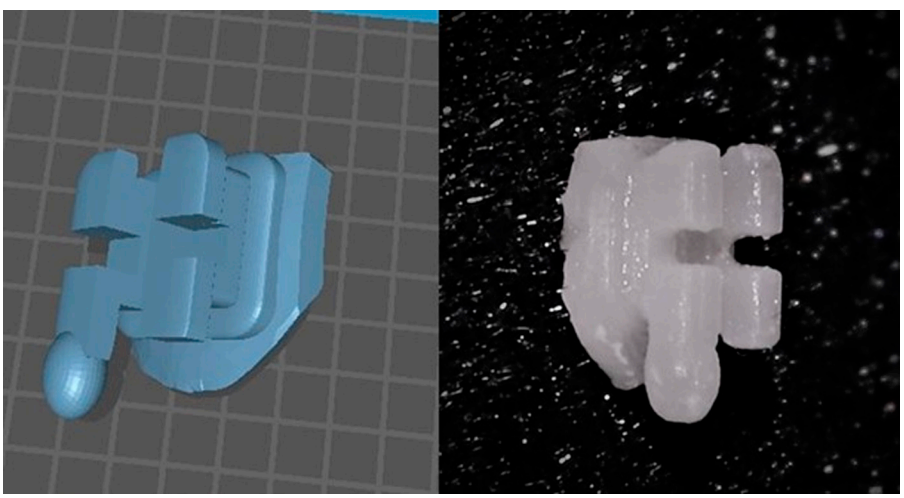


Figure 2. Aesthetic orthodontic bracket made of permanent crown resin using 3D printing technology.

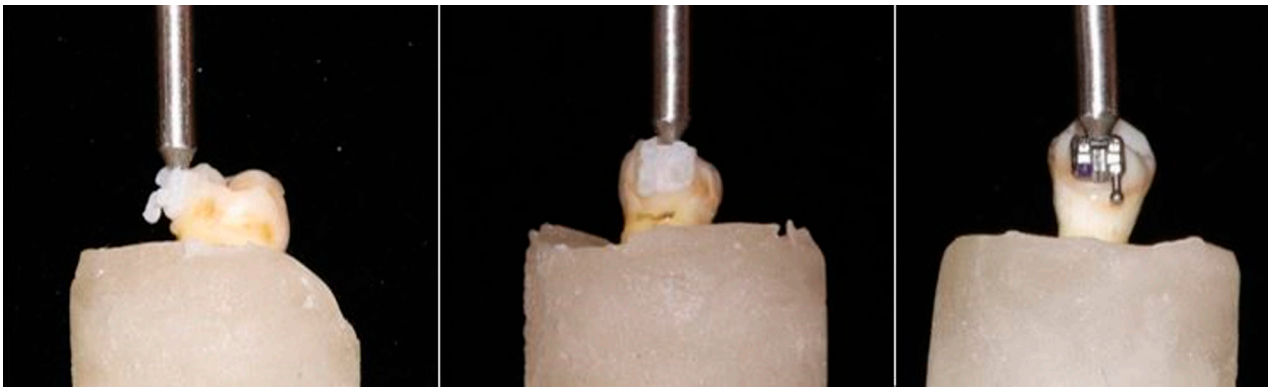


Figure 3. SBS measurement in the experimental and control groups.

to align the sample vertically on the instrument table so that the delivered force was perpendicular to the bracket surface. The SBS test was performed by applying a 2.5 kg load in an occluso-gingival direction (perpendicular) to the bracket base to produce a compressive shear force (Figure 3). For the four groups, the SBS force required to separate the brackets from the tooth surface was recorded in Newtons at a crosshead speed of 1.0 mm/min and the SBS value for the experimental and control groups was obtained.[12]

$$\text{Shear Bond Strength (SBS) (Mpa)} = \frac{\text{F (N)}}{\text{A (mm}^2\text{)}} = \frac{\text{Debonding Force (Newton)}}{\text{Bracket Base Surface Area (mm}^2\text{)}}$$

After the brackets were removed from the tooth surface and SBS values were calculated for all groups, photographs of the bracket bases and buccal enamel tissue were obtained at 10X magnification (Figure 4).



Figure 4. Evaluation of ARI scores after debonding.

The photographs were numbered and saved to a computer by a person not involved in the study to avoid evaluation bias. An experienced researcher who had previously worked in a similar study determined ARI scores ranging from 0 to 4 on the numbered photographs.[13] The evaluation of ARI scores was performed according to:

Score 0: No adhesive on the tooth surface,

Score 1: Less than 50% residual adhesive on the tooth surface,

Score 2: More than 50% residual adhesive was present on the tooth surface,

Score 3: All adhesive remained on the enamel surface and bracket marks were present on the surface,

Score 4: Enamel surface fracture noted.

SPSS software (Windows version 26.0; SPSS Inc, Chicago, Illinois) was used for statistical analysis. After applying the normal distribution test, parametric tests (one-way analysis of variance test and Post Hoc tests for MPa values) were applied for non-normally distributed data. ARI values were analysed using Fisher's Exact test. $P < 0.05$ was considered statistically significant.

Results

SBS values obtained in the four groups are shown in Table I. It was noted that the bond strength of the specimens was significantly affected by the type of composite used and the type of bracket ($P < 0.001$). The highest SBS value was obtained in Group 1 (Metal Bracket-Transbond XT) (15.03 ± 6.66), while the lowest SBS value was observed in Group 3 (3D Print Bracket-Transbond XT) (7.91 ± 3.07). There was no statistically significant difference between the SBS values of Group 1 and Group 4 (3D Print Bracket-Tokuyama SuperLow, SBS = 13.07 ± 5.31), while there was no statistically significant difference in the SBS values of Group 2 (Metal Bracket-Tokuyama SuperLow, SBS = 8.32 ± 3.00) and Group 3. When the brackets bonded with Transbond XT were compared, the average SBS value (MPa) of the metal brackets was higher, while the SBS value (MPa) of the 3D printed brackets was higher than the brackets bonded with Tokuyama SuperLow.

ARI scores of the experimental and control groups are shown in Table II. There was a statistically significant difference in ARI scores between the groups ($P = 0.008$). While enamel surface fracture was detected in one specimen from all groups after debonding, the ARI = 0 score, in which all adhesive remained on the bracket surface, was determined in only one specimen in Group 1. ARI = 3 score was detected in 10 specimens in Group 2 and 13 specimens in Group 3. In Group 4, in which 3D-printed brackets were bonded with Tokuyama SuperLow, 7 specimens had an ARI = 3 score, while 4 specimens had an ARI = 1 score.

Table I. Comparison of mean values of the shear bond strength of 3D Print bracket and metal brackets

	Shear bond strength (MPa)		
	Mean	Standard deviation	*P**
3D Print Bracket-Transbond XT	7.91[A]	3.07	
3D Print Bracket-Tokuyama SuperLow	13.07[B]	5.31	<0.001
Metal Bracket-Transbond XT	15.03[B]	6.66	
Metal Bracket-Tokuyama SuperLow	8.32[A]	3.00	

*Results of one-way analysis of variance test, Groups with different uppercase letter are significantly different (Tukey HSD test, $P < 0.05$).

Table II. Distribution of Adhesive Remnant Index (ARI) Scores between the groups

	ARI Scores					
	0	1	2	3	4	*P**
3D Print Bracket-Transbond XT	0	0	1	13	1	
3D Print Bracket-Tokuyama SuperLow	0	4	3	7	1	0.008
Metal Bracket-Transbond XT	1	4	6	3	1	
Metal Bracket-Tokuyama SuperLow	0	0	4	10	1	

*Results of Fischer's Exact test.

Discussion

The aim of the present in-vitro study was to test the bond strength and ARI scores of 3D-printed, aesthetic orthodontic brackets made of permanent crown resin compared to metal brackets using different adhesives. The results showed that the SBS values of the 3D designed, and additively manufactured brackets, were within an acceptable range.

Orthodontic science utilises digital technologies in all processes of diagnosis, planning and treatment.[14] 3D-printing technology can meet many aesthetic and biomechanical requirements to produce an ideal orthodontic bracket.[15] 3D-printed brackets integrated into a fully digital workflow, individualised production related to tooth shape, colour or size can be realised.[16,17] Other removable or fixed orthodontic appliances can also be completely and individually produced using 3D-printing technology.[15] Orthodontic brackets produced using this method are expected to have adequate biomechanical properties as well as meeting aesthetic and individual and specific requirements. The results of the in-vitro study showed that the brackets produced from permanent crown resin using 3D printing technology had sufficient bond strength.

While the subtractive method used in CAD/CAM technologies is produced by milling from a resin block, the additive method used in 3D-printing technology produces items by adding the material layer by layer.[18] Although the quality, colour stability and marginal accuracy of objects in CAD/CAM manufacturing are higher than those produced by traditional manufacturing methods, the range of motion of these devices and the size of the milling device are limiting factors in generating products of different shapes.[19,20] 3D-printing technology has overcome the shortcomings of the subtractive method and enabled the production of high-precision objects; however, the additive method consumes less raw material than the subtractive method.[21]

The bonding force between the orthodontic bracket and enamel is an important consideration in the treatment of a malocclusion. An orthodontic bracket debond occurring during treatment will increase treatment time, require re-treatment of the enamel surface and likely cause mechanical trauma to the surrounding soft tissues.[22] It is stated that SBS values of 5.9 to 7.8 MPa between the bracket and enamel surface are sufficient and the maximum bond strength should be lower than 14 MPa, which is the enamel fracture threshold.[23] In the present study, it was noted that the SBS values obtained in all control and experimental groups were higher than the specified range. SBS values higher than 14 MPa were obtained only in Group 1. SBS, which indicates the bonding strength of the bracket to the tooth surface, depends on many factors related to the bonding procedure, the material from which the bracket is made, the type of adhesive polymerisation, enamel surface properties, and the type of adhesive.[22] The two important features evaluated in the present study were the material of the bracket and the type of adhesive material. When forming the groups, test materials bonded with flowable and non-flowable composite were classified in both experimental and control groups. In a study evaluating the role of bracket type in improving the bond strength of orthodontic brackets to composite resins, it was concluded that bracket type was a more important factor than the type of adhesive.[24] In the present study, the highest SBS value was obtained in Group 1 (Metal Bracket-Transbond XT) (15.03 ± 6.66), while the lowest SBS value was observed in Group 3 (3D Print Bracket-Transbond XT) (7.91 ± 3.07). In the control group, the highest SBS values were obtained with non-flowable composite (Group 1; 15.03 ± 6.66), while the highest SBS values in 3D-printed brackets were obtained in the group bonded with flowable composites (Group 4; SBS = 13.07 ± 5.31). Therefore, while SBS values increased following the use of flowable composite in attaching 3D-printed brackets, the use of flowable composite for metal brackets decreased the SBS values. The 3D-printed brackets were produced from permanent crown resin, and the lower SBS values in the non-flowable composite compared to the control group are thought to be related to the base properties of the brackets. The currently used metal brackets showed high SBS values due to their advanced mesh structure. In the 3D-printed brackets, grooves were used to increase physical adhesion rather than via a mesh structure. Based on the findings, it is recommended that processes to increase the surface area of the base of the brackets produced by 3D printing, are performed. The number and form of the grooves and/or sandblasting methods are recommended. It is further recommended that more viscous orthodontic adhesives such as Tokuyama SuperLow for bonding 3D printed brackets are preferred rather than more

viscous orthodontic adhesives such as Transbond XT.[25] In a study using Transbond XT and a resin modified glass ionomer composite, SBS values of 20.03 MPa for metal brackets and 22.52 MPa for ceramic brackets in the Transbond XT group were obtained, which corresponded with values of 6.63 MPa (metal) and 8.69 MPa (ceramic) in the resin modified glass ionomer composite group. The lower values obtained using Transbond XT in the present study may be explained by the surface area of the brackets used, the storage conditions of the tooth samples and the preference for 3D-printed brackets in the experimental group. Yang et al.[14] evaluated the biomechanical properties of 3D-printed ceramic brackets and found that the SBS values of silane-treated and non-silane-treated 3D-printed ceramic bracket groups were above 10 MPa. In the present study, the SBS values of 3D-printed brackets bonded with Tokuyama SuperLow were found to be 13.07 ± 5.31 MPa, while this value was below 10 MPa in 3D-printed brackets bonded with Transbond XT. This difference is thought to be related to the bonding procedure. It is thought that the SBS values of the 3D-printed ceramic brackets produced by Yang et al.[14] and bonded using Transbond XT, may have increased since ceramic silane during the bonding stage was preferred. Material changes in the bonding agents and procedural changes significantly affect the SBS values.

High ARI scores are indicative of a weaker bond between the bracket and composite resin and are preferred to avoid enamel cracks and fractures during debonding.[26] There is an inverse correlation between the excessive amount of adhesive remaining on the tooth surface and the development of enamel fractures. Very high SBS values may damage the enamel or existing restorations.[14] Therefore, adhesive failures and a high ARI score are more suitable to avoid enamel fractures during debonding. In the present study, mean SBS values lower than 14 MPa and higher than 6 to 8 MPa were obtained for all groups except for Group 1, and enamel surface defects were detected in only one specimen for each group. 3D-printed brackets bonded with both a fluid composite and a non-fluid composite achieved adequate performance in the bonding and debonding processes. In Group 1, in which the mean SBS values were 15.03 ± 6.66, ARI scores were zero in one sample, while the scores were mostly concentrated as ARI = 1 and ARI = 2. This confirms the high adhesive-bracket bond. In comparing the ARI scores of Group 3 with the 3D-printed brackets bonded using Transbond XT, 13 specimens scored ARI = 3 and one specimen scored ARI = 2. The ARI scores of the 3D-printed brackets bonded with Tokuyama SuperLow were ARI = 1 for four specimens, ARI = 2 for three specimens and ARI = 3 for seven specimens. It should be noted that 3D-printed brackets bonded using Transbond XT had lower SBS values but higher ARI scores than the Tokuyama SuperLow group. Therefore, it is suggested that using Transbond XT adhesive for bonding 3D-printed brackets is a better combination during debonding because the weaker chemical bond facilitates the removal of adhesive residues from the enamel surface.[27] During the treatment process, it should be recognised that lower SBS values may cause recurrent bracket breakages.

The present study had limitations. Firstly, it was not possible to replicate the oral conditions that affect SBS values and ARI scores, such as the presence of saliva, intraoral temperature, occlusal forces, diet, and hygiene habits. In future studies, it may be advisable to subject the brackets to thermal cycling before performing the necessary laboratory tests. Secondly, the mechanical properties of brackets 3D printed from permanent crown material do not only involve SBS and ARI scores. It would be appropriate to investigate other biomechanical properties such as static and kinetic frictional resistance, torque capacity, colour stability, residual monomer amount and then plan in-vivo studies. Thirdly, in the control group, stainless steel metal brackets were preferred because of their cost, the most frequently used treatment alternative and the generalisability of the results to clinical settings.[27] However, it would be informative to perform mechanical and aesthetic evaluations of 3D-printed resin-containing brackets against ceramic brackets in future studies.

However, the present in-vitro study had several strengths. Firstly, the statistical analysis used a higher number of tooth samples than the required number of teeth in each group, allowing the results to be interpreted with higher accuracy. The homogeneity of the experimental and control groups facilitated the interpretation of the obtained results. The same preparation procedures were applied for all teeth before the placement of the brackets and the enamel surfaces were handled with great care according to the inclusion criteria to avoid any interpretation errors and to maintain homogeneous test conditions.

Conclusions

The SBS values of the 3D-printed orthodontic brackets bonded with Transbond XT were within a reasonable range to facilitate orthodontic treatment, and an ARI = 3 score, which is preferred for debonding, was obtained for most of the specimens. The SBS values of the 3D-printed orthodontic brackets bonded with Tokuyama SuperLow were within an acceptable range for orthodontic treatment and higher SBS values were obtained compared to the 3D-printed bracket group bonded with non-flowable composite. 3D-printed orthodontic bracket systems can be considered adequate for clinical applications and can provide an alternative material to metal orthodontic brackets.

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Conflict of interest

The authors declare that there is no conflict of interest.

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