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Shear Bond Strength and FEM of a Resin-modified Glass Ionomer Cement — Effects of Tooth Enamel Shape and Orthodontic Bracket Base Configuration

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The objective of this study was to evaluate the influences of enamel shape and bracket base configuration on shear bond strength from a biomechanical point of view. To this end, shear bond test and stress analysis using finite element method (FEM) were performed. Results obtained from both tests were then comprehensively investigated. Maxillary incisors were prepared for plane specimens, while mandibular premolars were prepared for curvature specimens. Shear bond test was carried out with three different test conditions. Two finite element models of enamel shape and bracket base configuration were also created. An approximate mean load of 200 N was applied. Results revealed that the shear bond strength of plane model was higher than that of curvature model. In conclusion, the present study revealed that shear bond strength was significantly influenced by enamel shape and bracket base configuration, whereby a curvature configuration tended to have lower bond strength.

Keywords: Resin-modified glass ionomer cement, Bond strength, FEM

INTRODUCTION

The ideal orthodontic adhesive should be sufficiently strong to endure a course of dynamic orthodontic treatment. On the other hand, after treatment, the ideal adhesive should be sufficiently weak to permit easy bracket removal for the maintenance of enamel integrity. Therefore, in clinical practice, it is critical to understand the bond strengths of different orthodontic adhesives[1-3].

Orthodontic bond tests are usually carried out with enamel and orthodontic bracket being bonded with an orthodontic adhesive. There is, however, no consensus on the methods for orthodontic bond strength test. As a result, a variety of test materials such as extracted untreated enamel surface[4-8] and polished flat enamel surface[9] have been used as specimens[10].

To comply with enamel shape, curvature and plane configurations have been adopted for orthodontic bracket bases. However, the influence of bracket base configuration on bond strength of orthodontic adhesives is usually ignored.

In a previous report[11], the authors evaluated the influence of enamel shape (plane *versus* curvature) and bracket base configuration (plane *versus* curvature) on the shear bond strength of an orthodontic adhesive (resin-modified glass ionomer cement). Results showed that enamel shape affected shear bond strength.

Expanding upon the previous study[11], the objective of this study was to evaluate the influence of enamel shape and bracket base configuration on shear bond strength from a biomechanical point of view. To this end, shear bond test and stress analysis using finite element method (FEM) were performed. Results obtained from both tests were then comprehensively investigated.

MATERIALS AND METHODS

Shear bond strength test

1. Materials

Table 1 shows the materials used in this study. Twelve human maxillary incisors and six premolars, which had been extracted within a year, were used for specimens and were stored in a 0.1% thymol solution in a cool dark place.

Two types of stainless steel orthodontic brackets (Twin brackets, U1L and L5L, A Company, USA) were used in this study. In other words, bracket with plane base configuration was for maxillary incisors and bracket with curvature base configuration was for mandibular premolars (Fig. 1).

Table 1 Bonded materials and cement

	Material		Component	Lot. No.	Mfr.
Tooth	Polished incisors	PI			
	Non polished Insisors	NI			
	Non polished premolars	NP			
Cement	Fuji Ortho		Chemically cured resin-modified glass ionomer cement	0309021	GC
Brackets	Twin bracket				
	(maxillary incisors)	P	Stainless steel	03J254J	A Company
	(mandibular premolar)	C		03D258D	

The areas of both bracket bases and enamel surface, including the radius of curvature, were measured with a CAD/CAM system (VDM system Cadim 107D, ADVANCE Co. Ltd., Tokyo, Japan) and a CAD software (VX CAD, Machineware Inc., Tokyo, Japan). Mean value of each bracket base area was obtained, and unevenness of bracket base was disregarded. The radius of curvature of bracket base was measured, and likewise the radii of curvature in the mesiodistal direction and along the long axis of crown for the enamel surface. A resin-modified glass ionomer cement (Fuji Ortho, GC Corporation, Tokyo, Japan) (FO) was used for orthodontic adhesive.

Concerning the use of human teeth, we made an application for the experimental plan to the Ethical Committee of the Nippon Dental University School of Life Dentistry. The reply received was that investigation was not required.

2. Methods

Non-polished labial surfaces of maxillary incisors (NI) and polished labial surfaces of maxillary incisors (PI) were prepared for plane specimens. Non-polished buccal surfaces of mandibular premolars (NP) were prepared for curvature specimens. Brackets for maxillary incisors (P) were bonded to NI and PI specimens. Brackets for mandibular premolar (C) were bonded to NP specimens. Shear bond strength test was carried out with three different test conditions using different combinations of enamel surface and bracket base.

2.1 Fabrication of enamel surface

Human maxillary incisors were embedded in epoxy resin (Epomount, Refinetec Corporation, Kanagawa, Japan) so that the labial surface would be parallel to the shear direction. In the same manner, human premolars were embedded in epoxy resin so that the buccal surface would be exposed (Fig. 2). After embedment, six incisors and six premolars were cleaned using a toothbrush (Merssage Pro, Shofu Inc., Kyoto, Japan) with no fluoride toothpaste (Pressage, Shofu Inc., Kyoto, Japan), then rinsed

Fig. 1 Brackets used in this study.

Fig. 2 Enamel surface of human premolar.

with water and dried. Enamel surfaces of the other six maxillary incisors were ground flat with #1200 waterproof abrasive paper using an automatic polishing machine (Ecomet 3, Buehler, Brussels, Belgium) under running water, until an enamel surface of 6 mm diameter was exposed.

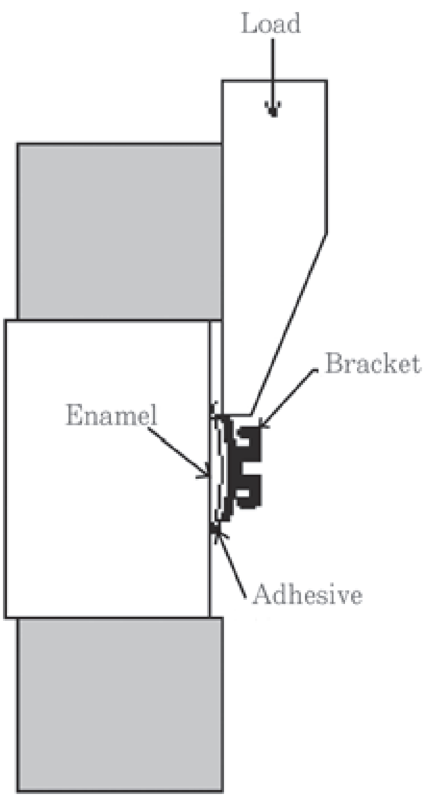

Fig. 3 Schematic diagram of shear bond strength test jig.

2.2 Bonding procedure

Enamel surfaces were pretreated with 10% polyacrylic acid solution (Ortho Conditioner, GC Corporation, Tokyo, Japan) for 20 seconds, then rinsed with water and dried. Appropriate bonding procedure was carried out. After polymerization, specimens were stored in 37°C water for 24 hours.

2.3 Shear bond test

Bond strength of orthodontic adhesives was evaluated in accordance with the shear bond strength test method recommended by ISO/TS[12]. Shear bond strength (MPa) was determined using a universal testing machine (Autograph AG-1, Shimadzu Co. Ltd., Kyoto, Japan) at a crosshead speed of 1 mm/min. Force was applied to the long axis of a bracket so that shear load was exerted adjacent to and directly to the bonding interface (Fig. 3). The ultimate load to failure was recorded. Shear bond strength (MPa) was calculated by dividing the load at failure by the bonding area.

Shear bond strength test was carried out six times with each condition (n=6). One-way analysis of variance (ANOVA) was performed on the data obtained and compared using Tukey's test.

Table 2 Approximation of mechanical properties

	Young's modulus (MPa)	Poisson's ratio
Enamel	8.4×10^{4}	0.3
Adhesive	7.6×10^{3}	0.3
Stainless steel	2.0×10^{5}	0.3

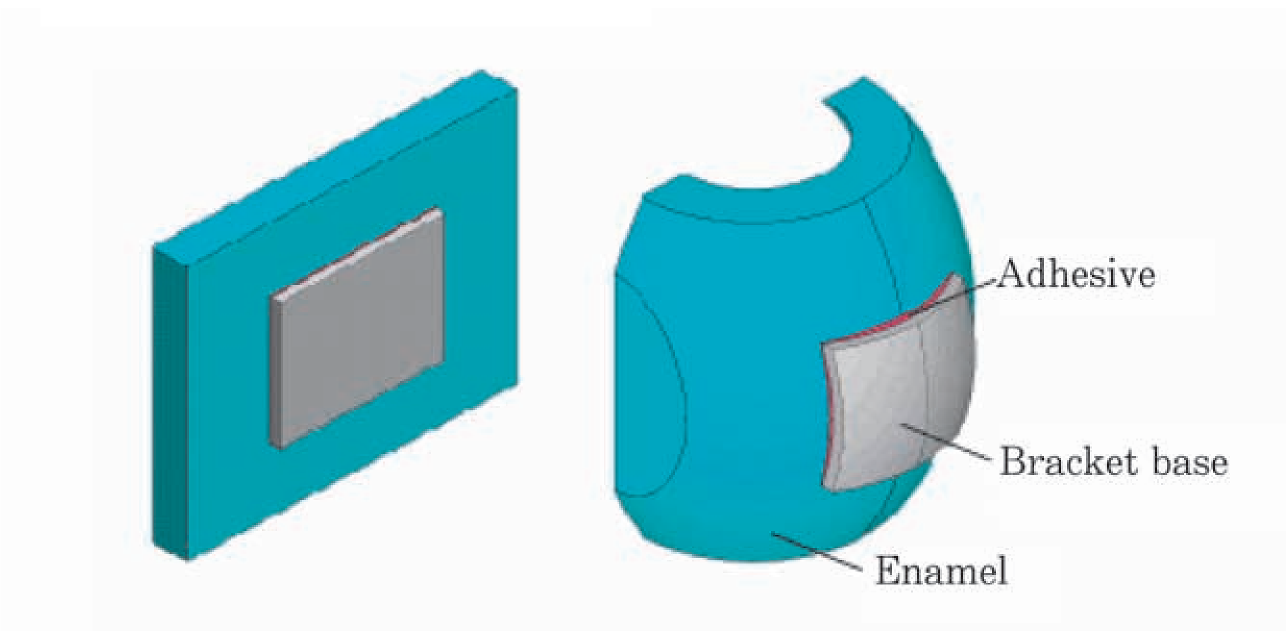

Fig. 4 Three-dimensional finite element models.

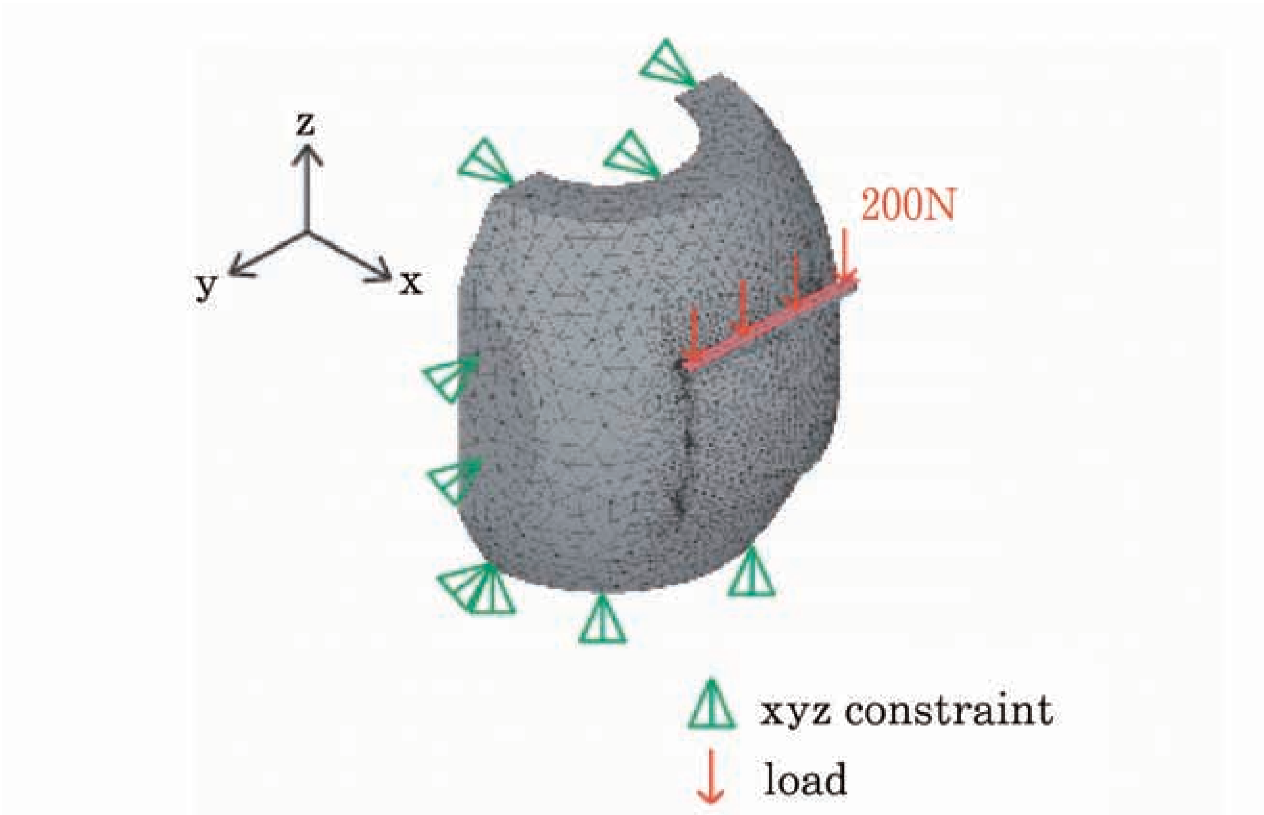

Fig. 5 Boundary conditions.

Three-dimensional FEM analysis

1. Finite element model

Two finite element models of enamel shape and bracket base configuration were created; *i.e.*, a plane model representing PI-P system (polished plane enamel surface-plane bracket base) and a curvature model representing NP-C system (curvature enamel surface-curvature bracket base).

Surface texture of the enamel surface of finite element model (polished, non-polished) was assumed to be a homogenous property. A three-dimensional computer model of enamel-adhesive-bracket base continuum system was constructed. Curvature enamel surface was determined based on the measured values of human premolar enamel surface (radii of curvature in mesiodistal direction and along the long axis of crown). Thickness of enamel according to the anatomical measurement by Fujita[13] was used. Bracket base was determined based on the measured values of P-bracket and C-bracket which had been used in shear bond strength test (radii of curvature in mesiodistal direction and along the long axis of crown). Space between enamel surface and bracket base was assumed to be filled with orthodontic adhesive and set to be 25 μm at the thinnest part.

2. Analysis conditions

The isoparametric approach with 10-node isotropic tetrahedron elements allowed optimal use of computing resources. Three-dimensional finite element models were constructed consisting of 72,180 elements with 102,840 nodes for a plane model and 74,544 elements with 106,604 nodes for a curvature model. Mechanical properties used for this finite element analysis[14,15] are listed in Table 2, and the outlines of models and boundary conditions are given in Figs. 4 and 5, respectively. An approximate mean load of 200 N which had been used in shear bond strength test was applied at a location 25 μm away from the bonding interface. Analysis was presumed to be linear static. Finite element model construction and FEM analysis were performed on a PC workstation (Precision Workstation 650, Dell Inc., USA) using a commercially available FEM software, ANSYS 7.0 (ANSYS Inc., USA). Inner stress generated into the orthodontic cement layer was evaluated as maximum stress.

RESULTS

Surface area of bracket base was 17.48 mm^2 for a maxillary incisor bracket, and 14.44 mm^2 for a mandibular premolar bracket. Mean radii of curvature of human premolar enamel surface were 4.5 mm for mesiodistal direction and 8.5 mm along the long axis of crown. Mean radii of curvature of mandibular premolar bracket base was 3.8 mm for mesiodistal direction and 7.3 mm along the long axis of crown.

Shear bond strength of cement

Figure 6 shows the results of shear bond strength test. Mean shear bond strength values ranged from 9.0 to 18.8 MPa. In particular, PI-P showed the highest mean shear bond strength value at 18.8 MPa. On the other hand, NP-C showed the lowest mean shear bond strength value at 9.0 MPa — which was a decrease by about 50% compared to that of PI-P. Since significant differences in shear bond strength among the three systems was confirmed by one-way ANOVA ($p<0.01$) (Table 3), Tukey's test was performed. Significant difference was noted between PI-P and NP-C ($p<0.05$).

Table 3 Statistical results of one-way ANOVA for shear bond testing

Source	DF	SS	MS	F ratio
Enamel shape configuration	2	290.49	145.25	8.98**
Error	15	242.52	16.17	
Total	17	533.02		

**p<0.01

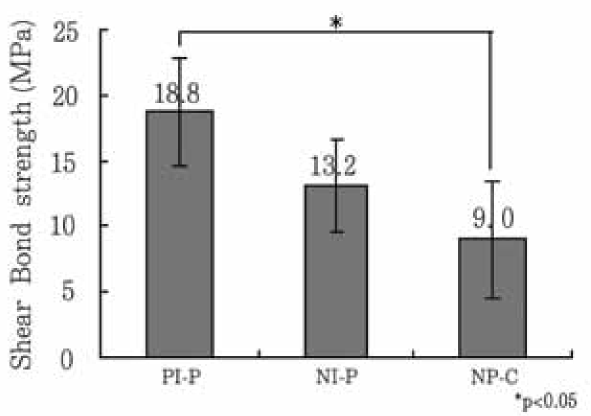

Fig. 6 Means and standard deviations of shear bond strength.

Three-dimensional FEM analysis of shear bond test

Figure 7 presents the maximum principal stress distribution of each model. With the plane model, a maximum principal stress of 208 MPa was distributed toward adhesive bottom and underlying both ends of enamel surface. Stresses ranging from 100 to 200 MPa were distributed toward adhesive bottom and underlying the whole enamel surface. Stresses ranging from 25 to 100 MPa were distributed along one-eighth of adhesive surface. Stress less than 25 MPa was distributed across the whole adhesive surface.

With the curvature model, a maximum principal stress of 287 MPa was distributed toward adhesive bottom and underlying the central part of enamel surface. Stresses exceeding 200 MPa were distributed toward the periphery of maximum principal stress area of 287 MPa. Stresses ranging from 100 to 200 MPa were distributed toward adhesive bottom and underlying the enamel surface. Stresses ranging from 25 to 100 MPa were distributed along one-eighth of adhesive surface. Stress less than 25 MPa was distributed across the whole adhesive surface.

Upon comparison between a plane model and a curvature model, it was found that the latter generated a higher maximum principal stress — which was about 38% higher than the maximum value of the plane model.

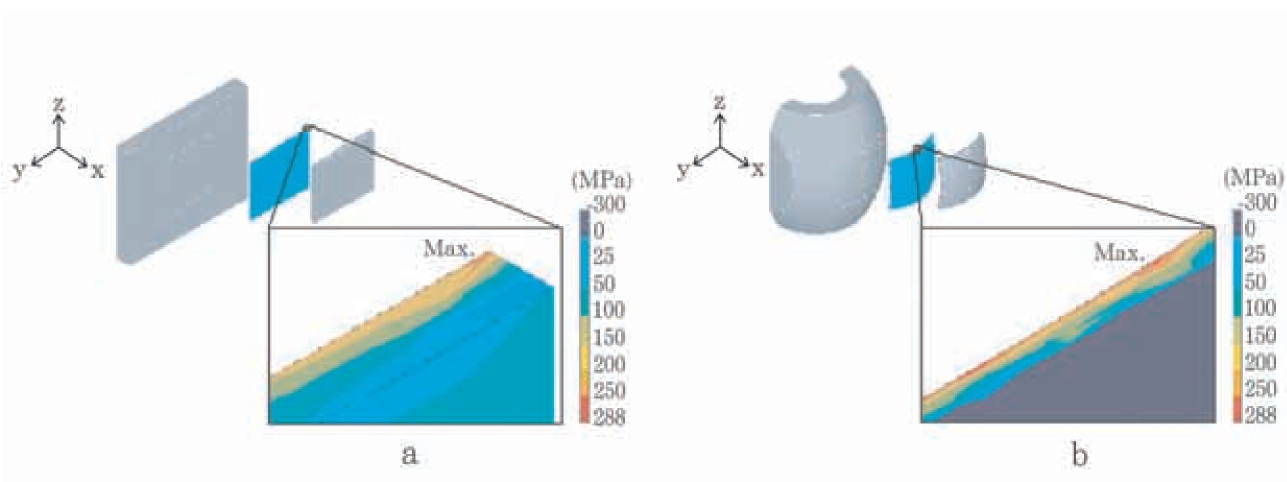

Fig. 7 Maximum principal stress distribution: (a) Plane model; (b) Curvature model.

DISCUSSION

Shear bond strength test

1. Test method

When using the enamel surface for specimens in a shear bond test, we must take into consideration that the anatomical shape of enamel varies depending on tooth type, *i.e.*, incisor or molar[16]. It has been reported that the bond strength of a polished plane enamel surface mainly depends on mechanical interlocking, which is achieved by enamel decalcification with phosphoric acid etching[17]. However, in our previous report[11] whereby the authors evaluated the influence of polished and non-polished enamel on shear bond strength of orthodontic adhesive (resin-modified glass ionomer cement), it was found that there were no significant differences between polished and non-polished enamel surfaces.

In this study, three types of enamel specimen — non-polished incisors, polished incisors, and non-polished premolars — were selected according to the orthodontic bonding test method recommended by ISO/TS. Configurations of orthodontic bracket bases in shear bond test are usually similar to the topographic properties of enamel specimens. On this ground, the authors deliberately selected brackets of which the base configurations were similar to those of the enamel specimens used in this study.

2. Shear bond strength test results

When the shear bond strength of PI-P system (polished incisor-plane bracket) was compared with that of NP-C system (non-polished premolar-curvature bracket), PI-P system showed a shear bond strength which was more than two times higher than that of NP-C system. In the case of NI-P system (non-polished incisor-plane bracket), a medium shear bond strength value between PI-P system and NP-C system was obtained (Fig. 6). Tukey's test showed that a significant difference was observed between PI-P system and NP-C system (Table 3). Indeed, test result showed that the shear bond strength of curvature system was lower than that of plane system. In this connection, Hobson *et al.*[18] reported that the bond strength of anterior teeth was higher than that of posterior teeth, which was consistent with this test result.

On the other hand, there was no statistical difference between NI-P system and PI-P system. Likewise, no statistical difference was observed between NI-P system and NP-C system (Fig. 6). It is noteworthy that the anatomical morphology of maxillary incisor was slightly curved. As such, the curved shape of NI enamel and P-bracket base design might have affected shear bond strength.

Three-dimensional FEM analysis

1. FEM analysis

To evaluate the bond strength of a complicated three-dimensional finite element model (like the one in this study) and stress distribution generated within an adhesive layer are usually difficult and challenging work. Against this background, this study was undertaken to investigate the difference in stress distribution generated within an adhesive layer using FEM analysis.

Similar to this study, Katona *et al.*[19-21], Knox *et al.*[22], and other researchers[23,24] used three-dimensional FEM models of enamel-adhesive-bracket continuum system to determine bond strength. Likewise, DeHoff *et al.*[25] and Versluis *et al.*[26] evaluated the shear bond strength of different adhesives to dentin using FEM analysis.

To investigate the influence of a three-dimensional curvature, the bonding interface was presumed to be homogeneous and that a perfect bond between different materials was attained. A fine FE mesh was used to represent material interface. In general, increasingly fine mesh size insures convergence of a FE solution.

In this study, the maximum principal stress was evaluated based on the maximum principal stress theory.

2. Evaluation of maximum principal stress value generated within adhesive layer

FEM analysis result demonstrated that the two models had different maximum principal stress distribution patterns and different maximum principal values when the same load was applied to the upper portion of the adhesive layer.

In this study, the fracture strength of adhesive was assumed to be constant. With the plane model, a smaller maximum principal stress value was generated within the adhesive layer, thus the adhesive layer was less prone to fracture. In short, maximum principal stress value is inversely proportional to bond strength. Therefore, where a higher maximum principal stress value was obtained with the curvature model, the adhesive layer was more prone to fracture as it had a lower bond strength than that of plane model. In this light, the maximum principal stress distribution pattern seemed to be correlated with the weak links of the adhesive layer.

Evaluation of shear bond strength test and FEM analysis

The authors evaluated the influences of enamel shape and orthodontic bracket base configuration on shear bond strength based on the results obtained from shear bond strength test and FEM analysis.

Mean shear bond strength of PI-P system (a plane enamel surface-adhesive-plane bracket base continuum system) was 18.8 MPa, showing the highest shear bond strength in this study. By means of FEM analysis, maximum principal stress value of plane model was shown to be 208 MPa. These test results suggested that a plane model had higher bond strength and fracture resistance as compared with a curvature one.

On the other hand, mean shear bond strength of NP-C system (a curvature enamel surface-adhesive-curvature bracket base continuum system) was 9.0 MPa, showing the lowest shear bond strength in this study. By means of FEM analysis, maximum principal stress value of curvature model was shown to be 287 MPa. In other words, the curvature model had a lower fracture resistance as compared with a plane one.

Indeed, shear bond strength test and FEM analysis indicated that enamel shape and bracket base configuration significantly affected shear bond strength, irrespective of adhesive. To put it concretely, a plane configuration was more advantageous than a curvature one for obtaining higher bond strength.

Clinical implications

The present test results implied that the shapes of the bracket and enamel played an important role in determining the shear bond strength of orthodontic adhesives. Therefore, assuming factors that affect shear bond test such as enamel shape, bracket base configuration, and testing methods were well regulated, then the shear bond strength results obtained in this study were comparable with those of other studies. It is absolutely important for orthodontists to understand the exact bond strengths of different orthodontic adhesives to the end of selecting the optimal one for the clinical situation at hand. Where regulation is difficult, specifying of test conditions is necessary.

Orthodontists must also realize that bond strength varies depending on tooth type. Thus, this factor must also be used as a guideline for the selection of an optimal orthodontic adhesive, to the end of ultimately benefiting the patient.

CONCLUSIONS

Within the limitations of this *in vitro* study, the following conclusions were drawn:

1. In shear bond test, mean shear bond strength values ranged from 9.0 to 18.8 MPa for the three different combinations of enamel shape and bracket base configuration.
2. FEM analysis results demonstrated that the two models had different maximum principal stress distribution patterns and different maximum principal values when the same load was applied.
3. FEM analysis results demonstrated that the maximum principal stress value of curvature model was 287 MPa, while that of plane model was 208 MPa.
4. Results of shear bond strength test and FEM analysis revealed that shear bond strength and fracture resistance of plane model was higher than that of curvature model.

Therefore, the present test concluded that shear bond strength was significantly influenced by enamel shape and bracket base configuration

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