Fracture Analysis of Post Material and Bonding Condition on A Cylindrical Glass-Resin Bilayer Structure

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Abstract

The study aimed to develop a biomechanics model to identify the effects of post material and bonding condition on the vertical cracking of a glass-resin bilayer structure under applied axial load.

The specimens consisted of cylindrical glass tubes, in which metal or fiber posts were centered and which were filled with a resin core material. Fifty specimens were divided into five groups, a control group without posts, and four experimental groups, depending on the type of post and whether bonding was used. A static load was applied using a universal testing machine and continued at 0.01 mm/min until fracture. The failure load was compared using statistical analysis (*p* <.05). Failure rate, fracture patterns, and failure probability were analyzed.

The control group had the highest failure rate compared to groups in which posts were used. Bonded posts had no significant difference in failure rates, whereas unbonded metal posts had a higher failure rate than unbonded fiber posts. Unbonded metal posts had a significantly higher failure rate than bonded metal posts, whereas both unbonded and bonded fiber posts had no significant difference in failure rates.

Post material and bonding condition affect the fracture resistance of the model. Metal and fiber posts may have similar fracture rates in cases with good bonding condition; however, fiber posts present a lower fracture rate than metal posts in cases with no bonding. Bonding condition can change peak stress concentration from the cervical area to the middle third of the glass tube.

Experimental article (J Int Dent Med Res 2019; 12(3): 870-879)

Keywords: Post materials, Adhesion, Glass model, Vertical root fracture, Fracture mechanics.

Received date: 16 August 2018 **Accept date:** 18 November 2018

Introduction

Vertical root fracture is one of the most common failures of root canal treated teeth[1-4] and is frequently found in teeth with inadequate remaining tooth structure.[5, 6] Vertical root fracture commonly occurs in teeth restored with either cast metal or fiber posts. The incidence of vertical root fracture varies between 4 and 11%.[7-14] Although there is no difference in the incidence of vertical root fracture between both types of post materials,[7] the incidence of catastrophic failure is higher in metal posts.[7-14]

In terms of the relationship between root fracture resistance and post material, teeth restored with posts with a high modulus of elasticity, such as cast metal posts, mostly have a higher resistance to fracture than those restored with fiber posts, due to the rigidity of metal posts.[15-17] A cast metal post absorbs most of the force and has less deformation than a fiber post; therefore, less force and stress are applied to the tooth structure than would be the case with a fiber post.[15] However, with a great amount of difference between the modulus of elasticity of post and tooth structure, shear stress mostly concentrates at the apical area of a metal post, especially in the case of non-axial loading.[18-20] The tooth structure at the apical area is consequently the most susceptible to fracture.[18-22] On the other hand, a tooth restored with a fiber post presents high stress at the cervical area, decreasing towards the apical area[18,19,23] because of a similar modulus of elasticity between a fiber post and dentin.[18,22] A fiber post is susceptible to failure through loss of the post,

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rather than through tooth fracture, as would be the case with a metal post, making it possible to re-restore the tooth, whereas, a metal post, which frequently fractures at the root, cannot be re-restored.[16, 17, 21, 22, 24] Therefore, a difference in the rigidity of a post may have a different effect on the damage to the root of a restored tooth.

Previous studies have shown that resin cement increases the fracture resistance of restored teeth.[25,26] Bonded surfaces from adhesive-type cements have been reported to better distribute stress along the cemented interface than zinc phosphate cement.[19]

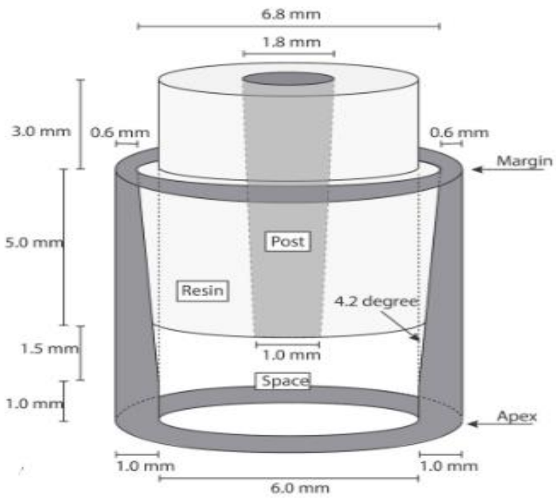
Types of post material and bonding condition in root-canal-treated teeth with inadequate tooth structure are still debatable issues.[7,27] In addition, the mechanism of vertical root fracture is also controversial. Therefore, this experimental study aimed to develop a basic model for studying the stress conditions that induce vertical fracture formation, and to study the effects of different types of post (fiber or cast metal) and of whether or not bonding is used between the post and resin core material on the location of vertical cracks under an axial compressive force.

Materials and methods

The specimens consisted of cylindrical glass tubes, in which metal or fiber posts were centered and which were filled with a resin core material. Fifty specimens were divided into five groups according to the type of post material and type of bonding condition: Group 1, no post (Control); Group 2, fiber post without bonding; Group 3, cast metal post without bonding; Group 4, fiber post with bonding; and Group 5, cast metal post with bonding. Each group contained ten samples.

Specimen preparation

Simple models were prepared in shape and geometry as described in Figure 1. Glass cylinders were prepared from Borosilicate glass tubes (volumetric pipette 15 ml., (Precicolor HBG HGB Henneberg-Sander GmbH, Hessen, Germany). The degrees of convergence (4.2°±°0.5) of the walls of glass tube were generated by a round-end, tapered, diamond bur mounted in a high-speed hand piece with water spray. The glass cylinders were placed upright under water to clearly see the surface and easily detect cracks larger than the roughness of the diamond bur. The wall thickness of the glass cylinders was measured with a micrometer after each preparation presenting no cracks.



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B

Figure 1. A. Geometric Diagram of the Specimen Shape, **B.** Longitudinal Section of the Specimen.

Fiber posts size 3 (FRC postec plus size 3, Ivoclar Vivadent, Schaan, Liechtenstein) were prepared for Groups 2 and 4. In Groups 3 and 5, cast metal posts (Auriloy N.P, Aurium Research San Diego, California, USA) were cast in the same size as the fiber posts. In regard to the types of bonding condition between post and resin core material, the non-adhesive type posts were wrapped with one layer of polytetrafluoroethylene (PTFE) tape, and the adhesive type posts were cleaned with alcohol, then applied with silane coupling agent (Porcelain liner M, Sun Medical, Moriyama, Japan) or with metal primer (Monobond N, Ivoclar Vivadent) for one minute and dried with a blown hot air stream.[28] Posts were positioned upright in the middle of the glass cylinders with a surveyor. Then, MultiCore® Flow (Ivoclar Vivadent) was injected into the space and extended from the glass margin to a height of 3 mm. After polymerization in the dark for 24 hours, the resins were polished.

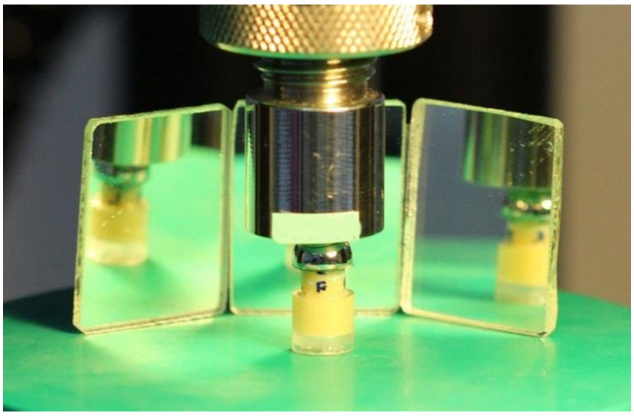


Figure 2. The Setting of the Specimen on A Universal Testing Machine.

Load application and recorded failure load

The specimens were set on a universal testing machine (Instron® 5566, Ithaca, New York, USA) (Fig.3) with a rubber dam (Dental dam, Coltène/Whaledent Inc., Cuyahoga Falls, Ohio, USA) (0.18 mm thickness) beneath the base of the specimens and between the specimens and the tip of a steel compressor. The rubber dam was used in order to simulate periodontal ligament and also to decrease local stress concentration from the steel compressor or the platform. Then, an axial compressive force was applied on the resin core side of the specimens via a semicircular steel compressor (8mm diameter) at a crosshead speed of 0.5 mm/min until 300 N and continued at 0.01 mm/min until fracture. Three digital cameras (digital camera EOS 650 D, Canon, Taipei, Taiwan) were used to directly and indirectly record the failure process of the specimens with a rate of 50 frames/sec. Three additional reflective mirrors were placed obliquely behind and lateral to the specimens to enhance visualization of crack observation (Fig. 2). After complete failure, the video recordings were re-analyzed to follow the events of fracture of the specimens related to force, using the Adobe Premiere Pro CS6 program (Adobe Systems, Incorporated, San Jose, California, USA).

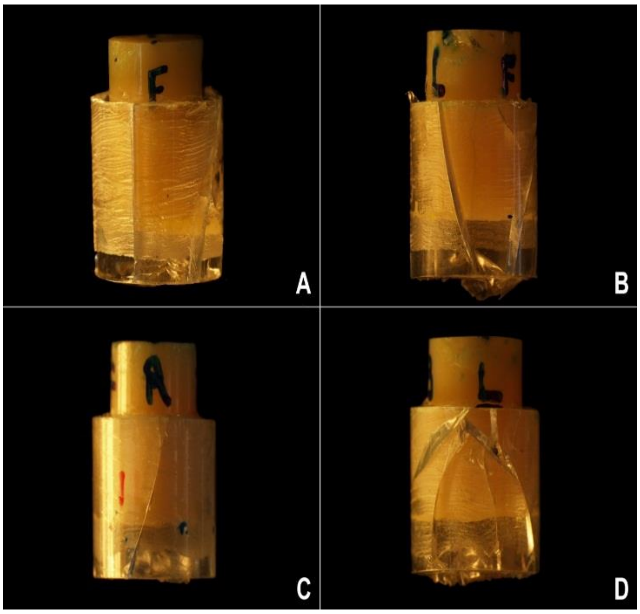


Figure 3. Patterns of Primary and Secondary Cracks. **A.** Straight Primary Crack. **B.** Curved Primary Crack. **C.** Single Secondary Crack. **D.** Branched Secondary Crack.

Failure load, failure probability and failure rate analysis

The amount of force which creates an initial crack is called the failure load. One-way ANOVA and Tukey's multiple comparison test with the 95% confidence level was used for the statistical analysis, using the SPSS program (SPSS version 17.0 for Windows, IBM, Chicago, Illinois, USA).

The survival probability from fracture (reliability: R_x) of the specimens was calculated using Equation 1.

$$R_x = e^{-\left(\frac{x}{F_w}\right)^m} \quad (1)$$

where x is the force applied to the structure, Fw is the characteristic failure load, m is the Weibull modulus, which was analyzed by Free Statistics Software, Office for Research Development and Education, version 1.1.23-r7 (http://www.wessa.net/rwasp_fitdistrweibull.wasp/).

The failure probability was calculated using Equation 2.

$$\text{failure probability} = 1 - R_x \qquad (2)$$

All the data were plotted in a failure probability using the Microsoft Excel 2010 program (Microsoft Corp., Redmond, Washington, USA), then the failure rate was analyzed from the linear part of the graph, which was in the failure probability range of 0.25 to 0.8. The failure rate was represented by the change in the probability of fracture per unit change in applied force, represented as the slope of the linear part of the failure probability graph. The failure rates were used to compare the fracture resistance between the different bonding systems.

Fracture pattern and fracture surface analysis

The first crack that extends vertically downwards from the fracture origin (360^0 as described by Bradt, 2011) is called the primary crack. When the primary crack eventually bifurcates or forks, the resultant crack is called a secondary crack[29]. The fracture patterns of the primary and secondary cracks were observed with a stereomicroscope (OLYMPUS, Tokyo, Japan) with 8x magnification. The fracture patterns of the primary cracks were divided into two patterns; straight and curved (Figs. 3a and 3b). The fracture patterns of the secondary cracks were also divided into two patterns; single and branched (Figs. 3c and 3d).

The specimens were also fractographically analyzed with the stereomicroscope (8-56x) following ASTM c1322-05b standard, to identify the fracture origins and the directions of fracture propagation of the primary cracks. There were three locations of fracture origins; inner cervical margin (IM) where the primary crack originated from the inner surface at the upper third of the glass cylinders, inner middle third (IMid) where the primary crack originated from the inner surface at the middle third of the glass cylinders, and outer cervical margin (OM) where the primary crack originated from the outer surface at the upper third of the glass cylinders (Fig. 4).

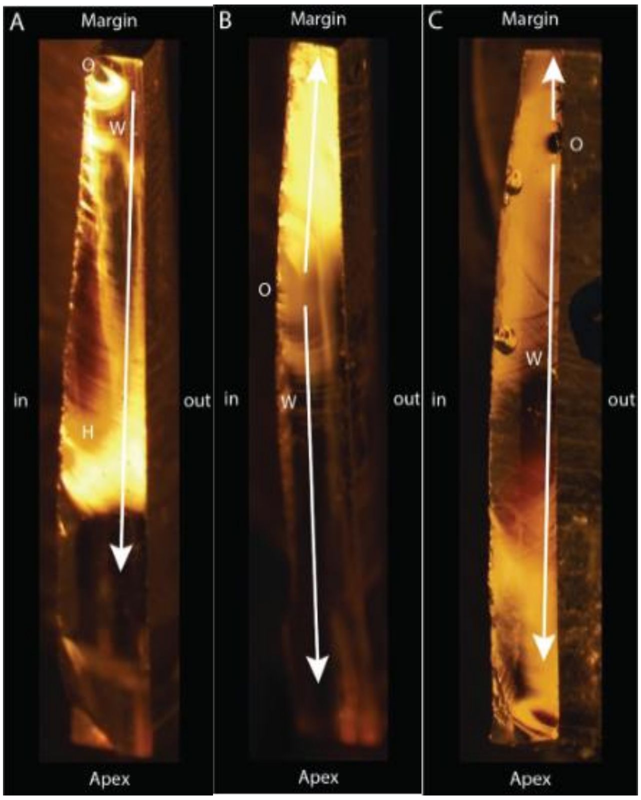


Figure 4. Fracture Origins of Primary Cracks. **A.** Fracture Origin at the Inner Cervical Margin (IM), **B.** Fracture Origin at the Inner Middle Third (Imid), **C.** Fracture Origin at the Outer Cervical Margin (OM). [Inner Surface (In), Outer Surface (Out), Fracture Origin (O), Wallner Lines (W), Hackle Lines (H)].

Results

Fracture patterns of primary cracks, secondary cracks, and fracture origins of primary cracks

Ninety-two percent of primary cracks had a straight pattern and 8% had a curved pattern. Figure 5 shows the fracture origins of the primary cracks in each group. In Groups 1 and 3, the fracture origins were most frequent at IM (80%). In Groups 2, 4 and 5, the fracture origins appeared less frequently at IM (60%, 50%, and 40%, respectively). However, the fracture origins appeared at IMid in Groups 4 and 5 (50% and 40%, respectively), a greater incidence than other groups.

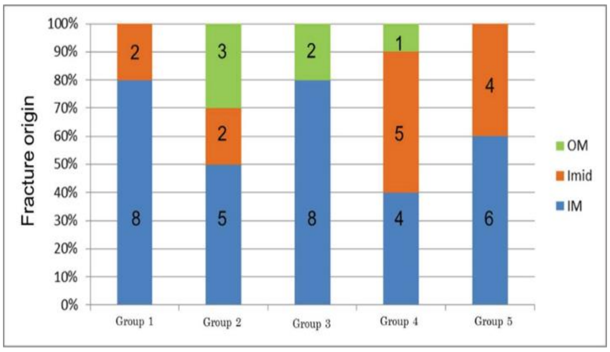


Figure 5. Distribution of Fracture Origins of the Primary Cracks in Each Group.

Table 1 shows the fracture patterns of secondary cracks in each group. The branched pattern appeared most frequently in Groups 1, 2 and 3 (70-80%). Both single and branched patterns appeared equally in Group 4 (50%), and the single pattern appeared most frequently in Group 5 (70%).

Specimen Group	Fracture Patterns of Secondary Crack	
	Single Pattern (Percentage)	Branched Pattern (Percentage)
Control	30	70
Group 2	20	80
Group 3	20	80
Group 4	50	50
Group 5	70	30
Average	38	62

Table 1. Fracture Patterns of Secondary Crack in Each Group.

Failure load analysis

The failure loads of every group in which posts were used, except Group 4, were statistically higher than in Group 2 (P<.05). However, there was no statistically significant difference among groups in which posts were used (Table 2). Weibull modulus values of each group were in the range of 4.7-7.6.

Specimen Group	Mean and of Failure Loads (N) ± Standard Deviations*
Con	667 ± 134.8[a]
Group 2	1058.7 ± 222.3[b]
Group 3	992.9 ± 149.9[b]
Group 4	849.5 ± 204.8[a,b]
Group 5	943.4 ± 226.0[b]

* Similar superscript letters means no statistical differences among the groups (P < 0.05)

Table 2. Mean and Standard Deviations of Failure Loads and Tukey's Comparison.

Failure probability of the specimens

A failure probability graph is shown in Figure 6. Every group had a higher failure probability when more force was applied. The control group had the highest failure probability when a low range of force was applied compared to the groups in which posts were used, followed by the groups in which posts with adhesive type bonding was used, and the groups with non-adhesive type bonding. When a force greater than 550 N was applied to the adhesive type groups, Group 4 had a higher rate of failure probability than Group 5. When a force greater than 850 N was applied to the non-adhesive type groups, Group 3 had a higher rate of failure probability than Group 2.

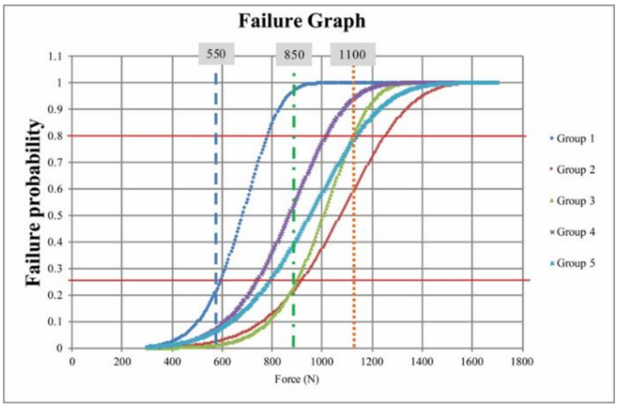


Figure 6. Comparison of Failure Probability of Structures in Each Specific Type of Post Material and Bonding Condition.

Failure rates of specimens

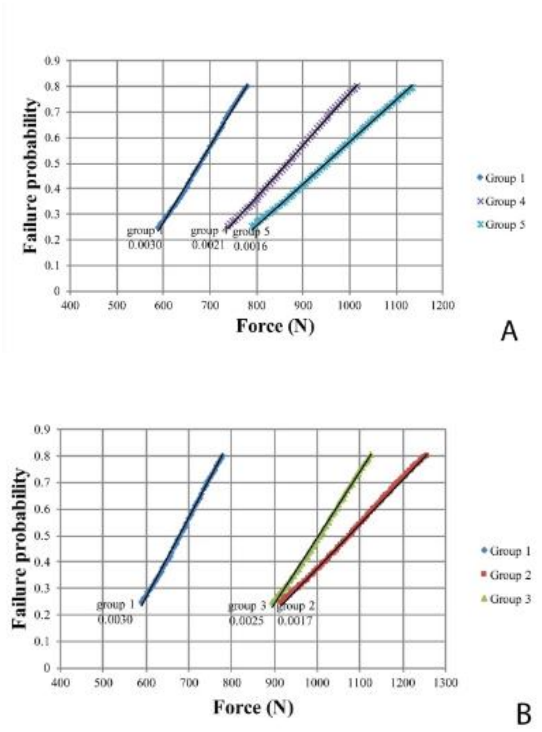
Failure rates are shown in Figure 7. Group 1 had a failure rate of 0.0030, which was higher than that in the groups in which posts were used (0.0016-0.0025). In comparing adhesive type bonding groups, Groups 4 and 5 had no significant difference in failure rate (Fig. 7a). However, in comparing non-adhesive type bonding groups, Group 3 had a failure rate of 0.0025, which was significantly higher than that in Group 2 (0.0017) (Fig. 7b). Likewise, comparison of groups in which metal posts were used showed that Group 3 had a significantly higher failure rate than did Group 5 (0.0016) (Fig. 7c). Meanwhile, both Groups 2 and 4, in which fiber posts were used, had no significant difference in failure rate (Fig. 7d).

Discussion

To compare and locate a stress concentration area under a controlled loading condition, fractography has been used to identify any signs of crack formation in a two-layered resin glass model[30]. This study attempted to develop a model to compare the effects of post material and bonding condition on vertical crack formation. The models consisted simply of resin as a core with a post within it, and a glass tube as a thin external wall to detect stress and to simulate a thin clinical tooth root without a ferrule.

Hoop tensile stress-induced crack formation in glass cylinders according to fracture mechanics

The structures in this study were designed to generate wedging displacement and radial deformation, causing vertical cracks by creating hoop tensile stress, which is greatest at the thin margin of the glass tube. When stress is beyond the fracture toughness of glass cylinder, a crack starts forming and propagates vertically[30-32], as shown in Figure 8.



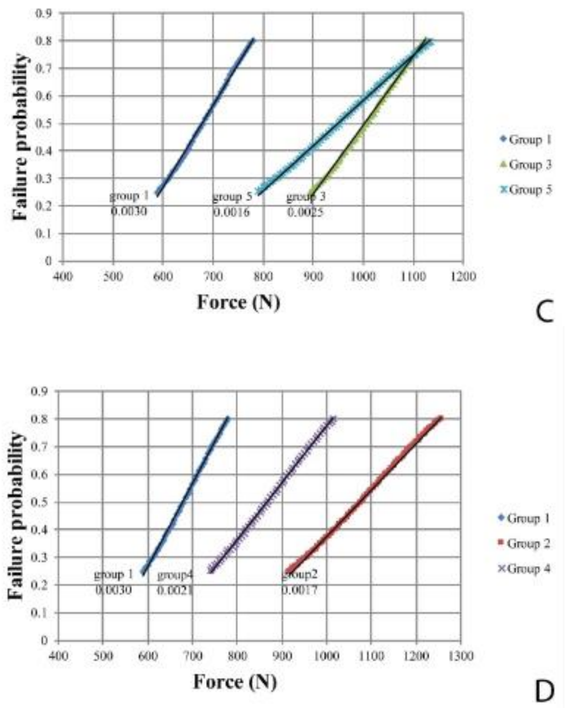
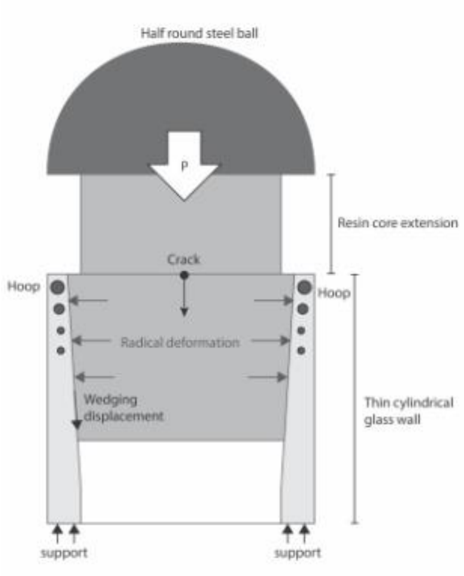


Figure 7. Comparison of Failure Rates for Different Post Materials and Bonding Conditions. Only the Linear Parts of the Curves from Figure 6 Are Displayed.

Factors affecting wedging displacement found in every group were (1) the taper of the glass cylinder, (2) the height of the tapered part of the glass cylinder, (3) the partial mechanical retention provided by the surface roughness at the glass and resin core interface, and (4) the space under the resin core. Other factors differently affecting resin deformation in each group were (1) post elasticity, (2) post wedging, which occurred in the non-adhesive groups, (3) the space around the post, also in the non-adhesive groups, and (4) the favorable bonding condition between the post and resin core, in the adhesive groups. Post wedging caused resin deformation into the space around the post, formed during the wrapping process, in the non-adhesive groups. The favorable bonding condition between the post and resin core, in the adhesive groups helped to reinforce the core component and to reduce resin deformation.



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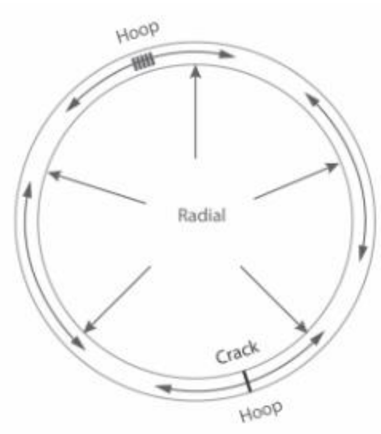

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Figure 8. Diagram of structure identifying crack formation and propagation mechanics. **A.** points and arrows are represented direction of complex stress condition developed within a cylindrical model. **B.** the hoop stress (points along the wall) across the glass wall is highlighted.

Effects of post material on crack patterns, and fracture resistance

The location of the fracture origin is where stress concentration is high enough to create a fracture. This study simulating vertical cracks, which originated from the inner surface of the thinner end of the glass cylinder, as presented in the previous studies of Øilo et al.[31] and Zhang et al.[32]. Those studies showed that fractures originating from the inner surface of thin glass tubes indicated the highest amount of hoop tensile stress[31, 32]. In this study, groups in which posts were used showed greater failure loads and greater numbers of fractures, which originated from the inner thin surface of the glass cylinder than in the groups without posts. This finding suggests that restorations with posts may increase the total modulus of elasticity of core components[33], resulting in a reduction in radial deformation of resin, hoop tensile stress at the inner surface of the glass margin, and stress in the cervical area of the specimens. The possibility that restorations with posts may increase the total modulus of elasticity of core components is in agreement with the findings of a previous study, which showed that teeth without a ferrule restored with posts have significantly higher fracture resistance[34].

The relationship between the post material and fracture probability (Fig. 6) showed that Groups 4 and 5 presented a similar increase of fracture probability when the range of applied force was lower than 550 N. Nevertheless, Group 4 presented a greater fracture probability than Group 5 when the range of applied force was higher than 550 N. This might be explained by the fact that little deformation occurred with metal posts because of the higher modulus of elasticity of metal. When force was applied, more stress was concentrated in the post material along the core and post interface in the groups with favorable bonding condition; this resulted in a reduction of wedging displacement and in reinforcement of resin core. Consequently, there was less radial deformation of resin and less hoop tensile stress at the thin margin of the glass cylinder[16, 33]. Therefore, Group 5 had greater fracture resistance than Group 4, a finding which is in agreement with the findings of laboratory experiments showing that metal posts had significantly greater fracture resistance than did fiber posts[16, 18, 20].

Effects of bonding on crack patterns, and fracture resistance

In this study, bonding may have delayed crack formation at the thinnest marginal area by changing the peak stress concentration area from the thinnest part to the middle third area of the glass tube. The groups in which bonding was used presented more fractures originating at IMid and a less-branched pattern of secondary cracks. A more-branched pattern indicates either a high stress condition or non-axial loading. The occurrence of fractures originating at IMid indicates that bonding helps to equally distribute stress to all surfaces of the bonded post[27], resulting in a reduction in stress at the thin margin of the glass cylinder and in the replacement of stress concentration to the middle part of the glass cylinder.

A comparison of fracture resistance between groups with and without bonding was inappropriate, especially by considering only aspects of failure load and fracture probability, because the bonded groups presented no space between post and resin core. When force was applied to the specimens, the resin deformed only toward the glass cylinder, resulting in greater hoop tensile stress and a less steep slope of the fracture probability graph in the groups in which bonding was used than in the groups without bonding (Fig. 6). Therefore, the linear portion of the fracture probability graph should be compared to evaluate fracture rate (Figs. 6 and 7) in order to eliminate the sources of difference in hoop tensile stress and to consider only circumstances in which the core components directly affected hoop tensile stress, inducing fracture formation.

In terms of fracture rate, Group 1, which contained a resin core with a low modulus of elasticity but no post, showed a higher fracture rate than did the groups in which posts were used. Bonding of posts and resin cores may help to reinforce the resin core; therefore, Groups 4 and 5 presented similar fracture rates (Fig. 7a). This finding is in agreement with the findings of previous studies, which showed that bonding provided by resin cement helps to distribute stress equally through the clinical root and increases fracture resistance[21, 27, 35, 36]. However, a comparison among the groups without bonding showed that Group 3 had a significantly higher rate than Group 2 (Fig. 7b). Since the metal posts had a high modulus of elasticity and were not bonded to the resin cores, wedging displacement of the posts and radial deformity of resin occurred to a greater extent than with fiber posts. However, when the metal posts were bonded to the resin core, there was no wedging displacement, helping to reinforce the resin core, resulting in the lower fracture rate in Group 5 than in Group 3 (Fig. 7c). In case of fiber posts, both Groups 2 and 4 presented similar fracture rates (Fig. 7d), since the modulus of elasticity of the fiber posts was similar to that of the resin core, resulting in no difference in radial deformity of the resin; however, in Group 2 (without bonding) wedging displacement of the post occurred.

Limitations of this study and suggestions for further study

Although the standard deviations were high due to the brittleness of the glass and the size and distribution of flaws, statistical analysis showed that the values of the failure loads had a normal distribution. Moreover, considering the Weibull distribution, which is usually used to analyze the failure load distribution of brittle materials, this study showed that the Weibull modulus of the model was approximately in the range of 5-10, indicating that the distribution was both valid and reliable[37, 38].

The rapid cooling process used in the formation of borosilicate glass results in clarity of the glass. The process of devitrification may help to produce its crystalline structure and adding boron trioxide decreases the coefficient of thermal expansion, resulting in resistance to thermal change, rigidity, and brittleness[39]. This kind of glass is both similar and different from the structure of human clinical root in many respects.

There are many similarities between borosilicate glass and clinical tooth root. (1) The fracture patterns are elastic. The range of plastic deformation is short before fracture formation, and the fracture is well-defined and is easy to analyze. (2) Damage to the structures is caused by the stress intensity factor from flaws in the structure, such as trapped air bubbles and cracks from the preparation process in the glass cylinder, and lamellae and enamel tufts at the cemento-enamel junction in the root structure. (3) Expansion of structural flaws caused by applied force, results in mostly single fracture origins and primary cracks[40].

There are also differences between borosilicate glass and clinical tooth root. (1) Whereas the the glass has a partially crystalline structure, the microstructure of clinical root is complex. The clinical root consists of a synchronized pattern of dentinal tubules and other organic substances, such as collagen type I and glycosaminoglycan (GAG), resulting in root structure having twice the fracture resistance of borosilicate glass (1.7 MPa√m for clinical root[41] and 0.77 MPa√m for glass)[42]. (2) The coefficient of thermal expansion of dentin is twice that of borosilicate glass (6.8×10-6 K-1 for dentin[43] and 3.3 ×10-6 K-1 for glass)[42].

However, the objective of using glass cylinders was not to simulate the microbiostructure of clinical root, but to utilize some properties of the glass. Using glass cylinders provided the ability to detect stress pattern formation in the structure when the glass and resin core were not bonded to one another. Since the modulus of elasticity of the resin core was similar to that of dentin[21], different patterns of deformation from different types of post restoration occurred, along with hoop tensile stress when the post and resin touched the glass inner surface, resulting in the hoop tensile stress being conveyed to the glass outer surface. Therefore, it was possible to detect the primary-crack origins, which showed the relationships between the locations of hoop tensile stress in the specimens. Moreover, the preparation of the glass inner surface to a tapered form created structural flaws, which helped the propagation of vertical cracks, caused by stress from the conical shape of the resin core, as in a flared, single, conical root. More complex analytical models are needed to analyze fracture propagation in different stress conditions using finite element analysis. Such models may eventually be applied to fracture analysis in clinical roots.

Clinical implications

Vertical root fractures have been reported in root-canal-treated teeth, which had a thin margin at the cervical area of the tooth structure and no ferrule. This study showed that restoration with post and core material reinforcement might reduce a chance of cervical crack development when axial force was applied. This reduction was because of higher hoop tensile stress resistance at the thin margin, resulting in a reduction of fracture formation originating from this area. The treatment option for the root-canal-treated tooth with thin cervical tooth structure may be a bonded rigid post. This option might increase the fracture resistance of the tooth and equally distribute stress along the root.

However, in the case of a tooth with a thicker root wall in the middle of the root, restoring the tooth with a bonded fiber post may reduce the incidence of vertical root fracture, since the bonding could change the location of the peak stress concentration area from the thinnest part to the middle area of the structure.

Conclusion

Within the limitations of this study, it can be concluded as follows:

1. Posts significantly increased the vertical fracture resistance of the glass cylinders, and reduced crack formation at the inner surface of the thin margin of the glass cylinders.
2. The type of post material had an effect on fracture resistance. Metal and fiber posts had similar fracture rates when bonding was used; however, fiber posts presented a lower fracture rate than unbonded metal posts.
3. Bonded fiber posts reduced the number of cracks at the inner surface of the thin margin of the glass cylinders.
4. Bonding reduced the number of fractures at the inner surface of the thin margin of the glass cylinders by distributing stress along the bonded interface and by changing the location of stress concentration to the middle of the glass cylinders.

Acknowledgments

This study was funded by Chiang Mai University and the Faculty of Dentistry, Chiang Mai University. The authors wish to thank Dr. Thanapat Sastraruji for his statistical advice. We also wish to thank Unity Dental Company for providing the materials and Hexa Ceram Company for laboratory technical advice. The authors wish to thank Dr. M. Kevin O Carroll, Professor Emeritus of the University of Mississippi School of Dentistry, USA and Faculty Consultant at Chiang Mai University Faculty of Dentistry, Thailand, for his assistance in the preparation of the manuscript.

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