INTRODUCTION

Endodontically-treated teeth that present minimal remaining dental structures, require the use of post and cores to improve the retention of crown restorations. Metallic cast post and cores have been used for many years. However, they present poor aesthetic features and have much higher elastic moduli compared to dentin, causing catastrophic root fractures because of stress concentrations at the post end. Ideally, post and core materials should have physical properties similar to dentin, so they are able to bond to tooth structures and distribute torqueing forces to radicular dentin, protecting root integrity. If post and core materials have similar elastic moduli to dentin, they avoid the stress concentrations at the post end and reduces root fractures, compared with cast or prefabricated metallic posts.

Resin post and cores fabricated with fiber posts have become widely used due to the development of new adhesive materials. Adhesion of resin post and cores to remaining dentin substrate is important for the integrity of resin core built-up teeth, and it is reported that the bonding loss at the interface between resin core and dentin could increase the risk of root fracture in that the bonding loss at the interface between resin core and dentin regardless of fiber post insertion. Regardless of fiber post insertion, the shear stress on the cervical surface of resin core decreased as the E of resin composites increased. Insertion of fiber posts increased the shear stress on the post surface of resin core, with increases in the E of resin composites. In conclusion, using resin core materials with higher E decreased the shear stress at cervical interface between resin core and dentin regardless of fiber post insertion.

Keywords: Debonding, Elastic modulus, Fiber post, Finite element analysis, Resin composite
stress distributions in root/resin post and core, and shear stress distribution at the adhesive interface in resin built-up teeth with resin core materials of different elastic moduli, considering the effect of the placement of fiber posts, using FEA, and to investigate optimal elastic moduli in resin core materials.

MATERIALS AND METHODS

The finite element model used in this study consisted of a mandibular second premolar tooth with a root filling, periodontal ligament and surrounding alveolar bone. A three-dimensional intact tooth model (Fig. 1-1) was constructed, based on the anatomical image of an adult tooth (Dental Anatomy & Interactive 3-D Tooth Atlas, Brown & Herbranson Imaging, Portola Valley, CA, USA). The mandibular bone was modelled as a cancellous block with 2.0-mm-thick cortical bone. The post preparation was modelled with a simplified circular external cross-section 2.0 mm in diameter at the cervical area, 1.8 mm in diameter at the post end area, and 6.0 mm in depth in the root. Part of the tooth structure was replaced by a full coverage ceramic crown 6.0 mm in height, with no ferrule around the cervical region of the root. For both the post and core, resin composites were used with three different elastic moduli: 12,000, 18,000 and 24,000 MPa, with or without a fiber post 1.7 mm in diameter, which was completely embedded in the resin composite.

Each model had symmetrical mesiodistal boundary conditions applied, and was meshed by approximately 125,000 hexahedral elements, determined by preliminary convergence tests (ANSYS 11.0, ANSYS, Canonsburg, PA, USA). All materials were considered homogenous, linearly elastic and isotropic, except for the orthotropic glass fiber post (Table 1). All materials were assumed to be perfectly bonded, and the simulations of this study were performed based on linear elastic analysis. A total axial load of 400 N was applied to the tip of the buccal cusp at an angle of 45° obliquely from buccal to lingual (Fig. 1-2). In each model, the movement of the outer surface bone was restricted by cortical bone.

The equivalent stress distributions in the root

![Fig. 1 Three-dimensional finite element model of the mandibular second premolar tooth.](image)

(1) Tooth model: root (r), post and core foundation (f), the crown restoration (c), Gutta-percha (gp), the periodontal ligament (pdl), and fiber post (fp) was modeled for support of the tooth structures.

(2) The loading and boundary conditions of a mesiodistal slice of the tooth model with symmetric boundary conditions and meshes. Arrow indicates an off-axis 45° oblique load of 400 N applied to the buccal cusp. The triangles represent the fixation of the lower surface of bone. This figure was modified from Kainose et al.

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Table 1  Material properties used in the study and their elastic moduli

| Material                  | Elastic modulus (MPa) | Poison’s ratio | References |
|---------------------------|-----------------------|----------------|------------|
| Dentin                    | 18,000                | 0.31           | Kinney et al. |
| Porcelain                 | 70,000                | 0.19           | Käse et al. |
| Cortical bone             | 14,700                | 0.3            | Moroi et al. |
| Cancellous bone           | 490                   | 0.3            | Moroi et al. |
| Gutta-percha              | 140                   | 0.49           | Friedman et al. |
| Periodontal ligament      | 800                   | 0.45           | Farah et al. |
| Resin composite           | 12,000                | 0.33           | Lanza et al. |
|                           | 18,000                |                |            |
|                           | 24,000                |                |            |
| Glass fiber               |                       |                |            |
| Transverse                | 9,500                 | 0.27           | Lanza et al. |
| Longitudinal              | 37,000                | 0.34           |            |
RESULTS

Figure 3 shows the equivalent stress distribution in buccolingual cross-sections and at the cervical area in resin post and core. The equivalent stress concentrations were observed at the cervical area on the lingual (non-loading) side, in which the magnitude of maximum equivalent stress were almost similar with and without fiber posts, and between the different elastic moduli of resin composites (Fig. 3-1). On the other hand, the area with high equivalent stress increased as the elastic moduli of resin composites increased (Fig. 3). Additionally, in the models with fiber posts, the equivalent stress was concentrated at the fiber post-side.

dentin, and in the post and core were investigated and the maximum equivalent stress at the cervical area, and at the top of the alveolar bone area, and at the end of the posts, were highlighted and analyzed. Additionally, the shear stress distributions in the post and cores were investigated in the XY, XZ and YZ planes (Fig. 2). The maximum shear stress on the post surface in the XY and YZ planes, and on the cervical surface of core in the XZ plane were highlighted and analyzed.

Fig. 3 The equivalent stress distribution (a) in a buccolingual cross-section of the resin cores with fiber posts (fiber posts were removed from the graphic for viewing), (b) in the resin cores without fiber posts using a resin composite with an elastic modulus of 18,000 MPa. (a-1)(b-1)12,000 MPa, (a-2)(b-2)18,000 MPa, (a-3)(b-3)24,000 MPa. Red areas represent the highest stress, as indicated by the color legend. The letters ‘B’ and ‘L’ in the figures indicate buccal and lingual sides. In the buccolingual cross-section, the equivalent stress concentration was observed at cervical area on lingual side. Additionally, the stress was also concentrated at the fiber post-side surface in the middle part of resin core in the models with fiber posts (arrow). At cervical area surface, the high equivalent stress area (red and orange) increased as the elastic moduli of resin composites increased. The bar charts of maximum equivalent stress (1) at the cervical area on the lingual (non-loading) side in resin composites of 12,000, 18,000 and 24,000 MPa, respectively.
The equivalent stress distribution in root dentin with a resin composite elastic modulus of 18,000 MPa with fiber post.

Red areas represent the highest stress, as indicated by the color legend. The letters 'B' and 'L' in the figures indicate buccal and lingual sides. The equivalent stress concentration was observed at the top of alveolar bone level at the lingual side. The bar chart of maximum equivalent stress (1) at the bottom of post cavity, (2) at the top of alveolar bone area on the lingual (non-loading) side of the root with resin composites of 12,000, 18,000 and 24,000 MPa, respectively.

Figure 4 shows the equivalent stress distribution in root dentin. The equivalent stress concentrations were located at the alveolar bone level on the lingual (non-loading) side of dentin in all models, in which the magnitude of stress increased with the insertion of fiber posts, and it decreased with increases of the elastic moduli of resin composites (Fig. 4-2). At the bottom of the post cavity, the equivalent stress was similar with and without insertion of fiber post, and between the different elastic moduli of resin composite (Fig. 4-1).

Figure 5 shows the shear stress distribution in the XY plane on the post surface of resin post and core with and without fiber posts (Fig. 5-a and b). The insertion of fiber posts increased the maximum shear stress at the basal part of the post, and the middle part of the post on the mesiodistal side, with increases of the elastic moduli of resin composites (Fig. 5-1 and -2). On the other hand, in the YZ plane on the post surface, differences of shear stress distribution were not observed between with and without fiber posts, and between the different elastic moduli of resin composites (not shown).

Figure 6 shows the shear stress distribution in the XZ plane on the cervical surface of resin post and core with and without fiber posts (Fig. 6-a and b). The shear stress concentrations were located at the cervical surface on the mesiodistal side in all models, regardless of fiber posts insertion, and the magnitude of maximum shear stress decreased as the elastic moduli of resin composites increased (Fig. 6-1).

**DISCUSSION**

Many studies have reported that using the resin composite built-up method with fiber posts can decrease the risk of catastrophic root fracture, because stress concentration at the post-end can be reduced if the elastic moduli of the resin composite and fiber post are similar to dentin. Over the past 50 years, there has been much variation (12,000–25,000 MPa) in elastic moduli of dentin due to different measurement techniques, such as bending, indentation and ultrasound, and measurement conditions of specimens. Kinney et al. reevaluated those data and suggested that 18,000–20,000 MPa is appropriate for the elastic modulus of dentin at strain rates encountered with physiologic loading. In this study, the elastic modulus of dentin was fixed at 18,000 MPa, which has been used...
Fig. 5  The shear stress distribution in the XY plane on the post area of the resin core and post using a resin composite with an elastic modulus of 18,000 MPa.

(a) resin core with fiber post, (b) resin core without fiber post. The highest shear stress was indicated as red or blue depending on whether one follows the shear stress in clockwise or counterclockwise directions. The letters ‘B’ and ‘L’ in the figures indicate buccal and lingual sides. The shear stress concentrations were observed at basal part of post (arrow) and middle part of post (pointing index) on mesiodistal side. The bar charts of shear stress (1) at basal part of post on mesiodistal side (2) at the middle part of post on mesiodistal side in resin composites of 12,000, 18,000 and 24,000 MPa, respectively.

In many FEA studies\(^{21-25}\). Conversely, the elastic moduli of resin core materials have been reported to be between 6,000–17,000 MPa\(^{19,20}\). Therefore, many FEA studies have used 12,000–16,000 MPa as elastic moduli of resin core materials\(^{21,22,30,38,39}\), which are lower than that of dentin. In our FEA study, to evaluate the effects of lower vs. higher elastic moduli of resin composites compare to that of dentin, on stress distribution in resin built-up teeth, the elastic moduli of resin composites were 12,000, 18,000 and 24,000 MPa.

For resin core built-up teeth, resin post and cores would cause elastic deformation and/or hold the stress internally when loads are applied to crown restorations. Moreover, the load from the buccal cusp at an angle of 45° obliquely would induce the movement that would overturn the crown restoration to the lingual side apart from the deformation in resin core, because the crown material has much higher elastic modulus than resin composite material. In our study, the equivalent stress concentrations in resin cores were observed at the cervical area on the lingual (non-loading) side (Fig. 3), in which the magnitudes of maximum equivalent stress was similar among all models (Fig. 3-1). Presumably, the crown movement would play a significant role in the stress concentration at the cervical area on the lingual (non-loading) side. Conversely, the area with high stress concentration increased with increases of the elastic moduli of resin composites (Fig. 3). This may have been due to the fact that the resin core materials with higher elastic moduli could restrain the elastic deformation and hold the larger stress internally. Additionally, in the models with fiber posts, the stress concentration was observed in the fiber post-side surface at the middle part of the resin core (Fig. 3). This would indicate that different distortion was produced between fiber posts and resin core materials.

In root dentin, the equivalent stress at the bottom of the post cavity was very low (approximately 20 MPa), and there were no significant differences between any elastic moduli of resin composites, with and without fiber posts (Fig. 4-1). These results indicated that, regardless of the insertion of fiber post, increasing the elastic moduli of resin composites does not raise the risk of catastrophic root fractures, even if the elastic modulus of...
The shear stress distribution in the XZ plane at cervical area in the resin core and post using a resin composite with an elastic modulus of 18,000 MPa. (a) resin core with fiber post, (b) resin core without fiber post. The highest shear stress was indicated as red or blue depending on whether one follows the shear stress in clockwise or counterclockwise directions. The letters 'B' and 'L' in the figures indicate buccal and lingual sides. The shear stress concentration was observed at cervical edge on mesiodistal side. The bar charts of shear stress (1) at the cervical edge on mesiodistal side in resin composites of 12,000, 18,000 and 24,000 MPa, respectively.

Fig. 6

In this study, the shear stress distribution on the surface of post and core were investigated to elucidate the debonding stress on the interface between post and core and dentin. On the post surface of resin post and core, the shear stress concentrations were observed at the basal part of post and the middle part of post on the mesiodistal side (Fig. 5-a). The insertion of fiber posts had a larger effect on shear stress concentration at the post surface, with increases of the elastic moduli of resin composites (Fig. 5-1 and -2). When using fiber posts, which have much higher elastic moduli than dentin and resin composites longitudinally (Table 1), the force applied to the crown restoration would be stored in the fiber posts and transmitted apically. Additionally, the fiber posts would attempt to reduce the distortion of resin posts due to the strut reinforcing effect which prevents bending stress. Consequently, the insertion of fiber posts might increase the shear stress between resin post and root dentin.

For resin post and core building-up methods, it is essential to establish strong adhesion between the post-resin-dentin interfaces. It has been demonstrated that adhesion to the cervical interface plays a critical role in maintaining the integrity of resin built-up teeth. 

Resin composite is 24,000 MPa which is higher than that of dentin. On the other hand, at the top of the alveolar bone level in the root, the equivalent stress decreased as the elastic moduli of resin composites increased (Fig. 4-2). When using resin composite core materials with higher elastic moduli than that of dentin, the resin core part would hold greater stress internally with smaller distortion, leading to smaller stress in the root dentin. In contrast, using resin composite core materials with lower elastic moduli would increase the stress in the root dentin in order to support the resin core with larger distortion. Additionally, the insertion of fiber posts slightly increased the equivalent stress in the root at the top alveolar bone level. These results indicated that the insertion of fiber posts does not reduce the stress in restored root dentin. The load applied to the crown restoration would induce bending deformation and/or rotation movement of fiber post within resin post and cores, which would deliver the stress to the restored-root. This behavior would lead to slight increases of equivalent stress in the root at the top alveolar bone level.

In this study, the shear stress distribution on the
Larger shear stress at the cervical adhesive interface would raise the probability of initial debonding in resin built-up teeth. In our study, the maximum shear stress at the cervical area was observed at the mesiodistal edge (Fig. 6-a and b) and decreased with increases of the elastic moduli of resin composites (Fig. 6-1). These results would be due to the diminishment of the distortion within resin cores with higher elastic moduli. In contrast, the insertion of fiber post scarcely affected the maximum shear stress (Fig. 6-1). This might indicate that the insertion of fiber posts does not decrease the risk of debonding of resin core part at the cervical area.

In this study, ferrule extensions were not simulated in the resin built-up teeth models, because the mechanical properties of post and core materials would hardly affect the stress distribution of restored teeth with ferrule extensions. A recent FEA study reported that, when absolute debonding occurred at the adhesive interface of resin post and cores, the stress distribution changed dramatically. Under debonding situations at the adhesive interface, there might be different behaviors on the stress distribution in resin built-up teeth with various mechanical properties of resin core materials. Additionally, initial debonding at the adhesive interface may occur partially in clinical situations. Further FEA research is required to consider the effects of elastic moduli of resin core materials on stress distribution in resin built-up teeth, with and without ferrule extensions, under partial debonding situations at the adhesive interface.

CONCLUSION

Within the limitation of this FEA study, it was concluded that using resin core materials with higher elastic moduli could decrease the shear stress at the cervical adhesive interface and equivalent stress in the restored root. On the other hand, the insertion of fiber post could not improve the shear stress at the cervical adhesive interface and the post surface of resin core, and the equivalent stress in the restored root.

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