INTRODUCTION

In conventional dental procedures, tooth preparation on enamel and dentin may cause irreversible damage to the tooth structure. Leveraging the advances in adhesive bonding technology, the conservative approach of minimally invasive dentistry allows the esthetics and function of anterior teeth to be restored with adhesive fixed partial dentures. Fueled by increasing interest in metal-free esthetic dentistry, glass fiber-reinforced composite (FRC) has been used in myriad dental applications. Of particular interest to this paper are the adhesive fixed partial dentures (AFPDs), which have been favorably reported because of their good clinical performance.

Glass fiber is a composite material with excellent mechanical properties. Being an anisotropic material, its mechanical properties are different along the orthogonal direction of each axis and that its best mechanical properties are in the direction of the fiber placement. In dental prostheses, the position and thickness of the fiber reinforcement layer also influence its reinforcing effect. In our previous report using three-dimensional (3D) finite element analysis, it was further found that stresses generated in an anterior fiber-reinforced composite (FRC) fixed partial denture (FPD) were influenced by the mechanical properties of adhesive resin cements and adhesive bond strength.

Suffice to say, the mechanical properties of the bonding interface between a fiber framework and adhesive resin cement could aggravate or alleviate the stresses generated in an anterior FRC FPD, which might eventually cause it to fracture. Using a 3D finite element method (FEM), the purpose of this study was to investigate the influence of mechanical properties of adhesive resin cements on the stress behavior of anterior FRC AFPDs under simulated clinical conditions.

MATERIALS AND METHODS

Using finite element analysis (FEA), this study investigated the effects of the mechanical properties of adhesive resin cements on stress distributions in fiber-reinforced resin composite (FRC) adhesive fixed partial dentures (AFPDs). Two adhesive resin cements were compared: Super-Bond C&B and Panavia Fluoro Cement. The AFPD consisted of a pontic to replace a maxillary right lateral incisor and retainers on a maxillary central incisor and canine. FRC framework was made of isotropic, continuous, unidirectional E-glass fibers. Maximum principal stresses were calculated using finite element method (FEM). Test results revealed that differences in the mechanical properties of adhesive resin cements led to different stress distributions at the cement interfaces between AFPD and abutment teeth. Clinical implication of these findings suggested that the safety and longevity of an AFPD depended on choosing an adhesive resin cement with the appropriate mechanical properties.

Keywords: Adhesive fixed partial dentures, Glass fiber-reinforced composite, Finite element method, Cement interface
modeled materials\textsuperscript{24,26,28}. Hybrid composite, Estenia (Kuraray Medical, Tokyo, Japan), was assumed to be an isotropic material. Two adhesive resin cements were evaluated in this study: Super-Bond C&B (Sun Medical, Shiga, Japan; SB) and Panavia Fluoro Cement (Kuraray Medical, Tokyo, Japan; PV). For the abutment teeth, the mechanical properties of enamel, dentin, and pulp were taken into account.

The FRC (everStick, Stick Tech) was assumed to be an anisotropic material. Its mechanical properties were different along different directions (longitudinal \textit{versus} transverse) of each axis (X-, Y-, or Z-axis). In the present FE analysis, orientation of the fibers was set to the X-axis, parallel to the direction along which the glass fibers exhibited exceptionally high strength and stiffness. As such, the Young’s modulus of fiber framework in the X-axis was set to a higher value (46 GPa), compared to a lower value (7 GPa) set for the Y-axis and Z-axis, thus representing the anisotropic properties.

\textit{Boundary conditions and data processing}

Ten-node tetrahedral elements were selected for the hybrid composite, abutment teeth, and adhesive resin cements. Twenty-node hexagonal elements were selected for the anisotropic fiber framework, generating a FE model which consisted of 77,157 elements with 120,084 nodes in total. Figure 3 shows the boundary and loading conditions. A concentrated load of 154 N, derived from the maximum occlusal force of healthy permanent teeth\textsuperscript{29,30}, was applied at the center of the pontic’s cutting edge at an angle of 135 degrees from the lingual side. The final element on the x and y axes of abutment base was assumed to be fixed, thereby defining the boundary conditions.

FEA was presumed to be linear static. FE model construction and FEA were performed on a PC workstation (Precision Workstation 670, Dell) using an FEA software, ANSYS 11.0.

\begin{table}
\centering
\begin{tabular}{l|c|c|c}
\hline
 & Young’s modulus (MPa) & Poisson’s ratio & Shear modulus (MPa) \\
\hline
Hybrid composite & 2.20×10\textsuperscript{4} & 0.27 & \\
Dentin & 1.80×10\textsuperscript{4} & 0.31 & \\
Enamel & 4.80×10\textsuperscript{4} & 0.23 & \\
Pulp & 2.1 & 0.45 & \\
Super-Bond C&B (SB) & 2,000 & 0.3 & \\
Panavia Fluoro Cement (PV) & 1.70×10\textsuperscript{4} & 0.3 & \\
 & Longitudinal & X 3.90×10\textsuperscript{4} & X 0.35 & X 1.40×10\textsuperscript{4} \\
Glass fiber & Transverse & Y 1.20×10\textsuperscript{4} & Y 0.11 & Y 0.54×10\textsuperscript{4} \\
 & Transverse & Z 1.20×10\textsuperscript{4} & Z 0.11 & Z 0.54×10\textsuperscript{4} \\
\hline
\end{tabular}
\caption{Material properties}
\end{table}

\textit{RESULTS}

\textit{Maximum principal stress distributions and stress values in FRC AFPD}

Figure 4 shows that maximum principal stress was generated in the upper embrasures of both connectors. FEA revealed that the maximum principal stresses of SB and PV were found in the mesial and distal connectors of upper embrasures. At the mesial connector, the stress values produced with SB and PV were 102.7 MPa and 96.6 MPa respectively. At the distal connector, the stress values produced with SB and PV were 120.3 MPa and 113.5 MPa respectively.

\textit{Stresses at the bonding interfaces of retainers}

Figure 5 shows the stress distributions and stress values found at the bonding interfaces of mesial and distal
Areas of high stress concentration were observed at the retainers. At the mesial bonding interface, maximum principal stresses produced with SB and PV were 44.4 MPa and 35.4 MPa respectively. At the distal bonding interface, maximum principal stresses produced with SB and PV were 39.6 MPa and 27.5 MPa respectively.

At the bonding interfaces of both mesial and distal retainers, results of this study revealed that SB exhibited higher stress concentration and higher stress values than PV.

**Stresses at the bonding interfaces on abutment teeth**

Figure 6 shows the stress distributions for abutment teeth. Analysis of maximum principal stress distributions revealed that high stresses were localized in the cingulum, distolingual marginal ridge, and distoproximal surface of the central incisor, and in the mesiolingual marginal ridge and mesioproximal surface of the canine, forming V-shaped stress concentration patterns. At the central incisor, maximum principal stresses produced with SB and PV were 17.4 MPa and 28.2 MPa respectively. At the canine, maximum principal stresses produced with SB and PV were 22.6 MPa and 30.2 MPa respectively.

At both the central incisor and canine, results of this study revealed that PV exhibited higher stress concentration and higher stress value than SB.

**Stresses in the adhesive resin cement layer**

Figure 7 shows the stress distributions generated within the adhesive resin cement layer. Maximum principal stresses concentrated within the lute periphery of distoproximal surface of central incisor, and within the lute periphery of mesioproximal surface of the canine. At the central incisor, maximum principal stresses
**Fig. 4** Maximum principal stress distribution patterns in upper embrasures of both connectors.

**Fig. 5** Stresses at the bonding interfaces of retainers:
(A) Stress distribution pattern with SB at mesial interface of retainer;
(B) Stress distribution pattern with SB at distal interface of retainer;
(C) Stress distribution pattern with PV at mesial interface of retainer; and
(D) Stress distribution pattern with PV at distal interface of retainer.
produced with SB and PV were 16.1 MPa and 31.3 MPa respectively. At the canine, maximum principal stresses produced with SB and PV were 20.7 MPa and 30.7 MPa respectively.

At both the central incisor and canine, results of this study revealed that PV exhibited higher stress concentration and higher stress value than SB.

**DISCUSSION**

For adhesive resin cements luted to an anterior FRC AFPD, this study evaluated the influence of their mechanical properties on the latter’s stress behavior based on FEA outcome. In clinical situations, it is extremely difficult to calculate stresses generated within and around the adhesive resin cement with a film thickness of only 50–140 µm. Therefore, stress analysis using FEA seemed to be an ideal approach to evaluate stresses in an FRC AFPD under simulated clinical conditions and taking into account the position of fiber framework placement and adhesive cement layer thickness.

The fiber framework was made of a composite material comprising pre-impregnated E-glass fibers embedded in a resin matrix. The glass fiber is an anisotropic material in which fiber orientation, but not fiber layer thickness, has a significant influence on its mechanical properties. Thus, it features exceptionally high Young’s modulus and enhanced tensile strength along fiber orientation, thereby enabling the fiber framework in this study to exhibit an excellent stress-bearing capacity.

To exploit the optimum mechanical properties because of the anisotropic behavior of glass fibers, fiber orientation was set to X-axis for FEA in this study, along which the highest mechanical properties were exhibited (Table 1). Apart from the rectangular coordinate system, a second local coordinate system with a different point of origin was established. This ensured that fiber orientation coincided with the axial direction of the
element coordinate system, and hence in full agreement with the mechanical properties that the fiber framework possessed.

In clinical practice, numerous treatment options are available for anterior single-tooth replacement. Amongst which, AFPDs make use of adhesive techniques to replace a missing anterior tooth with minimal or no tooth preparation. On the other hand, the use of AFPDs was plagued with numerous problems. Amongst which were degradation of the luting agent, disintegration of the interface between framework and veneering resin composite, and fracture of thin connector areas and the low bulk retainers.

In Fig. 4, FEA revealed localized high stress concentration in the connector area despite the use of an FRC APFD. This result pointedly illustrated that the inevitable notch in the shape and geometry of fixed partial dentures was responsible for the exceptionally high values of maximum principal stresses in the upper and lower embrasures of the connector, which were probably caused by a combined effect of bending and twisting forces. When a load was applied to the pontic’s cutting edge, it generated a bending deformation toward the labial side, further inducing a twisting moment with the connector as a fixed point. The mechanical properties of the adhesive resin cements also contributed to the stress distribution pattern of fixed partial denture-abutment teeth continuum. Maximum principal stress values obtained with SB were higher than those of PV.

In Figs. 5–7, FEA revealed areas of high stress concentration at the wing retainer and the proximal surfaces (defect side) of abutment teeth, and within the luted adhesive resin cement layer. From a biomechanical perspective, these results pointedly confirmed that the most critical area in the retention of a fixed partial denture is the wing retainer.

At the bonding interfaces of both mesial and distal retainers, the maximum principal stresses obtained with SB were higher than those of PV. PV had a Young’s modulus approximating to that of the hybrid composite.
and 200 µm, thereby resulting in a more homogeneous and regular distribution of stress at the bonding interfaces. However, SB had a Young's modulus different from that of the hybrid composite (Table 1), thereby resulting in a less homogeneous stress distribution pattern and higher maximum principal stress values.

There were also other inherent differences between PV and SB. PV was a composite resin whereas SB was a PMMA-based resin. Although both PV and SB had good adhesive properties, they had different adhesion mechanisms\(^\text{17,30}\). The fracture toughness of both PV and SB were also influenced by their adhesive layer thickness. Nonetheless, it was reported that there were no significant differences in fracture toughness between PV and SB at adhesive layer thickness ranging between 100 and 200 µm\(^\text{39}\). For this reason, cement thickness was set at 100 µm for both PV and SB in this study to preclude the influence of adhesive layer thickness on the mechanical properties of adhesive resin cements.

Within the limits of an FRC AFPD chosen for FEA in this study, PV was found to exhibit more excellent stress distribution than SB. First, PV could reduce stress at the connector area, thereby ensuring a stable structure for the bridge connector. Second, PV did not create sharp differences in stress values at the bonding interfaces of the retainers, which was a striking contrast to the stress distribution patterns created by SB. Therefore, PV ensured gradual transition for optimal stress distribution and a stable bonding interface for the retainers.

Suffice to say, the mechanical properties of adhesive resin cements in this study played a contributing role to the stress distribution patterns of FRC AFPD. This meant that in clinical situations, the selection of an adhesive resin cement for an AFPD should involve multifactorial considerations to ensure the latter’s efficacy and longevity.

**CONCLUSIONS**

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

1. Areas of high stress concentration were observed at the bonding interfaces of mesial and distal retainers. Maximum principal stress values of Super-Bond C&B were higher than those of Panavia Fluoro cement.
2. Areas of high stress concentration were observed at the bonding interfaces of abutment teeth. Maximum principal stress values of Panavia Fluoro cement were higher than those of Super-Bond C&B.
3. Areas of high stress concentration were observed at the wing retainer and proximal surfaces (defect side) of abutment teeth and within the luted adhesive resin cement. Maximum principal stress values of Panavia Fluoro cement were higher than those of Super-Bond C&B.

**REFERENCES**


