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Three-Dimensional Finite Element Analysis of Posterior Fiber Reinforced Composite Fixed Partial Denture: Framework Design for Pontic

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Abstract - *This study investigated the effects of two types of loading conditions on mechanical behavior of the pontic of composite fixed partial denture (C-FPD) and fiber reinforced composite fixed partial denture (FRC-FPD). Two types of FE model of posterior bridge were developed. Two types of loading conditions, i.e. vertical 629 N, and lateral of 250 N, were used. In lateral load, displacement was showed a similar behaviours. However in vertical load, displacement of FRC-FPD was less than C-FPD. These results clarified the magnitude, distribution of stress and displacement generated in C-FPD and FRC-FPD of pontic caused by two different loading conditions.*

KEY WORDS: Fibre reinforced composite, Fixed partial denture, Finite element analysis, Framework design, Hybrid composite, Pontic

INTRODUCTION

Fibre reinforced composite (FRC) substructures in fixed partial denture (FPD) have been of interest during last years[1, 2]. The interest has focused on adhesion of veneering composite to FRC substructure as well as to the design of the substructure, which considerably affect properties of the FRC FPD[3, 4]. FRC FPD have been studied from several perspectives including mechanical properties[5-8], material development[9], biocompatibility[10], fatigue analysis[11,12], structural analysis[13,14] and optimizing their design[15-17]. For successful function of the FRC FPD for a long period of time, it is important to clarify biomechanical behaviour of posterior FPD, in terms of magnitude of stress, stress distribution pattern and displacement under functional loading. Biomechanical information related to occlusal conditions will be useful in preparing guidelines for clinical applications of FRC FPD.

This study focused to the design of the FPD, especially on the possible need of additional FRC support for the pontic. Two types of loading conditions, i.e. against vertical occlusal load, and loading the cusp in lateral movement of jaw, on mechanical behaviour of the pontic of hybrid composite fixed partial denture (C-FPD) and fibre reinforced composite fixed partial denture (FRC-FPD) were studied. Stress and displacement generated within the FPD was studied by three-dimensional (3-D) finite element (FE) method.

MATERIAL AND METHODS

Definition of structures and geometric conditions

Fig. 1 shows a three-dimensional model of three-unit FPD from mandibular second premolar to mandibular second molar replacing the mandibular first molar. To create a finite element model, a FPD replica was fabricated. The geometry of the abutment replica has been described by Wheeler[18]. Sanitary pontic design was chosen for missing mandibular first molar. The thickness and width of connectors of the FPD were followed described in other author's report[19]. A replica was measured with 0.75mm intervals using 3-D coordinate measuring machine (Micro Scribe 3D, Micro Scribe Inc., San Jose, USA), captured data was plotted on 3-D CAD (Mechanical Desktop R2.0, Auto Desk Inc., California, USA) to construct 3-D solid model. The model was uploaded into FE analysis software (ANSYS 10.0 Sp, ANSYS Inc., Houston, USA).

A 1.8mm occlusal clearance from pit and fissure, 1.0mm cervical clearance and shoulder margin were prepared for assumed jacket crown. The FRC framework used in this study was 0.7mm[17] in height and 2.1 mm in width, and consisted of three continuous curvatures of mesial connector, pontic and distal connector, having an each individual curvature[16]. The FRC framework was placed as well as from mesial side of mandibular second premolar to distal side of mandibular second molar.

Material properties, load case and data processing

Material properties used for this finite element analysis were listed in Table 1. Most of these values were determined according to a literature survey[16,20-23]. Veneering material was supposed to be hybrid composite resin (Estenia, Kuraray medical Inc., Tokyo, Japan) and it was assumed to be isotropic material. FRC framework was supposed to be unidirectional glass fibre (everStick, StickTech, Turku, Finland) and it was assumed to be anisotropic material. Hexagonal elements with 8 nodes were chosen for cross-sectionally anisotropic FRC framework, in the same way, hexagonal elements with 20 nodes were chosen for hybrid resin-dentin-pulp continuum, and a 3-D finite element model consisting of 70,393 elements with 155,070 nodes

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Table 1. *Material properties used in this study*[16, 20-23]

	Young's Modulus GPa	*Poisson's Ratio*	*Shear Modulus GPa*
Hybrid composite resin	22	0.27	-
Dentin	18.6	0.31	-
Pulp	2.1×10^{-3}	0.45	-
FRC longitudinal	46	0.29	17.8
transverse	7	0.39	2.5

Hybrid composite resin: (ESTENIA, Kuraray medical Inc., Tokyo, Japan)
FRC: Fibre reinforced composite (Unidirectional fibre: everStick, StickTech Ltd. Turku, Finland)

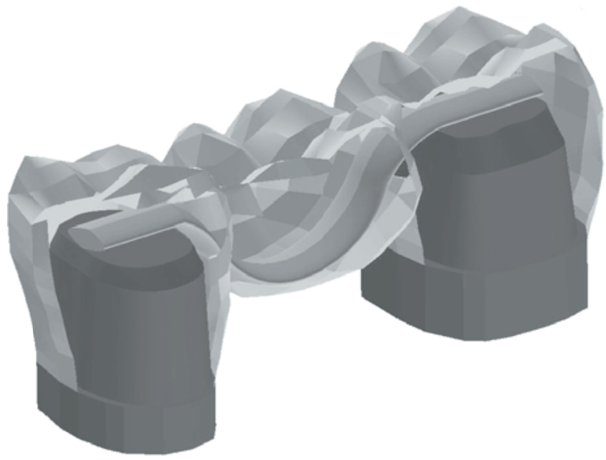

Figure 1. *Structure of the FRC-FPD used in this study*

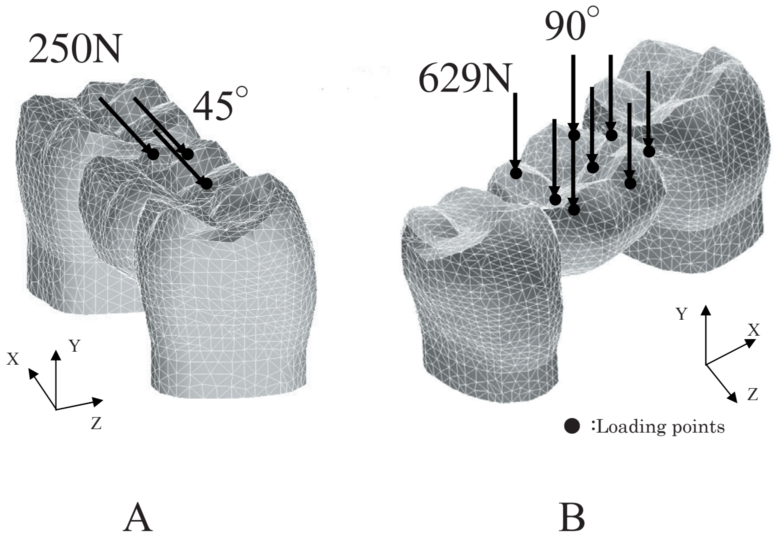

Figure 2. *Loading conditions used in this study (A; Lateral load B;Vertical load)*

was created. To define FRC framework as rectangular anisotropic material, curvature of FRC framework was to be consisted of three continuous curvatures of mesial connector, pontic and distal connector, having an each individual curvature. A new central coordinate of the circle was established for each curvature. Thus, longitudinal axes of glass fibres and 3-D FRC framework were parallel. The final element in all directions of FE model base was fixed, which was defined as boundary condition.

Two loading conditions, i.e. against vertical occlusal force referred as vertical load, and loading the cusp in lateral movement of jaw were tested in the model (Fig. 2). The latter is referred as lateral load. A total of 629N vertical load was applied to eight points on the occlusal surface of the pontic to simulate maximum occlusal force[24, 25]. To simulate loading cusp in lateral movement of jaw, a total of 250 N was applied to three points of the pontic (buccal-cusp incline) at an angle of 45 degrees from lingual direction[25-27]. FE analysis was presumed to be linear static. Finite element model construction and FE analysis were performed on PC workstation (Precision Work Station 670, Dell Inc., Texas, USA) using FE analysis software ANSYS

10.0 Sp. In considering biomechanical properties of hybrid resin, maximum principal stress and displacement were used to demonstrate the results at certain cross-sections and on the surface of the FPD.

RESULTS

Displacement

Lateral load (Fig. 3)

Surface and mesiodistal cross-section

C-FPD showed relatively large displacement of up to 0.04mm at one third of the buccal side of the pontic. The largest displacement of 0.05mm 0.07mm was observed from buccal groove to distobuccal cusp. Displacement of FRC-FPD was 0.03mm 0.04mm being slightly less than that of C-FPD. The displacement distribution between C-FPD and FRC-FPD showed similar patterns.

Buccolingual cross-section

On lingual side, displacement of 0.02mm 0.03mm at C-FPD was observed at one third of the central part of the pontic. Displacement of 0.03mm 0.04mm was observed from one third of central part of the pontic to buccal direction. Displacement of 0.04mm 0.05mm was observed from buccal one third to buccal side. The largest displacement (0.05mm 0.07mm) was found at the upper outermost surface of buccal side, buccal groove and its surrounding area. Compared displacement distribution of FRC-FPD with that of C-FPD, it showed a similar pattern.

Vertical load (Fig. 4)

Surface and mesiodistal cross-section

The largest displacement of C-FPD (0.05mm 0.07mm) was seen from buccal one third of the pontic to buccal cusp of the pontic and to pontic base. Calculation of FRC-FPD showed a similar displacement distribution than that of around the connector. However, the largest displacement (0.05mm 0.07mm) was lower in the pontic area.

Buccolingual cross-section

C-FPD showed displacement of 0.04mm 0.05mm from lingual side to the middle of the pontic. The largest displacement of 0.05mm 0.07mm was found from the middle to buccal side of the pontic. Displacement of FRC-FPD was 0.04mm 0.05mm was seen through the whole pontic.

Maximum principal stress

Lateral load (Fig. 5)

Surface and mesiodistal cross-section

In calculation of maximum principal stress of C-FPD, 70mm 80 MPa was distributed to areas including pontic base of distal connector and within a pontic. Maximum principal stress of the FRC-FPD, i.e. 80mm 90 MPa was distributed to the FRC framework of distal connector.

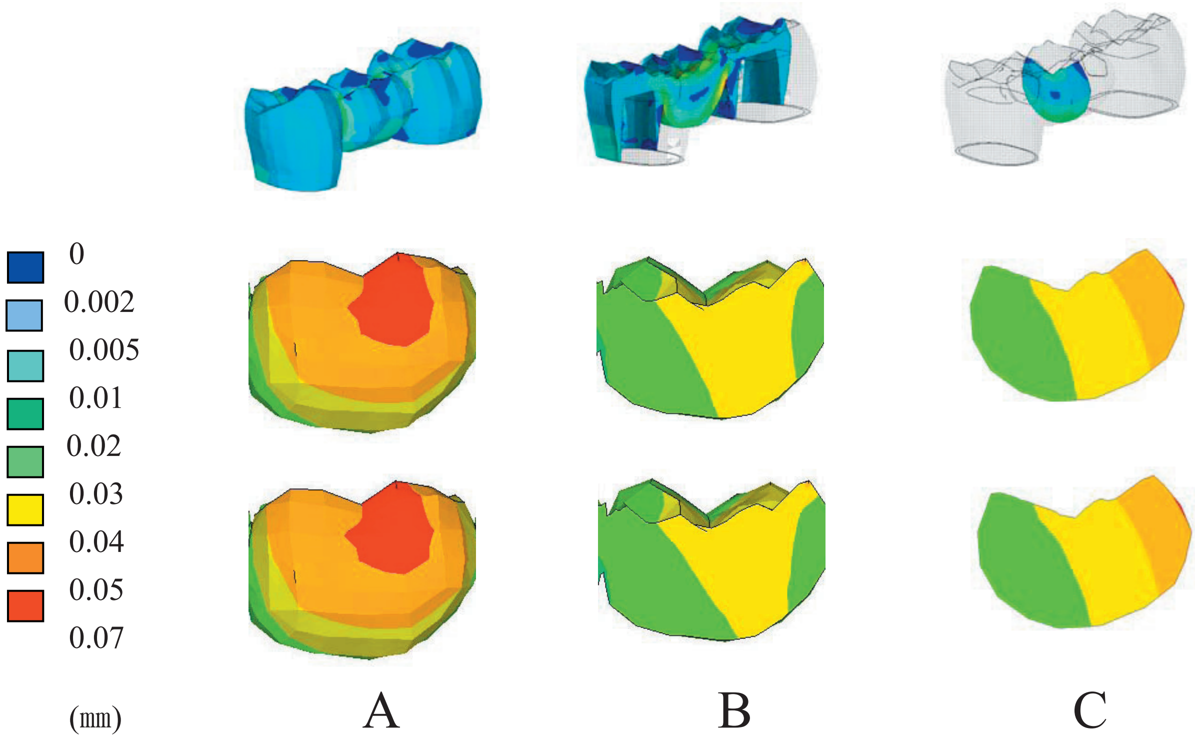

Figure 3. *Displacement of the pontic against lateral load*

Upper: C-FPD. Lower: FRC-FPD.
A; Surface view of buccal side. B; Mesiodistal section. C; Buccolingual section

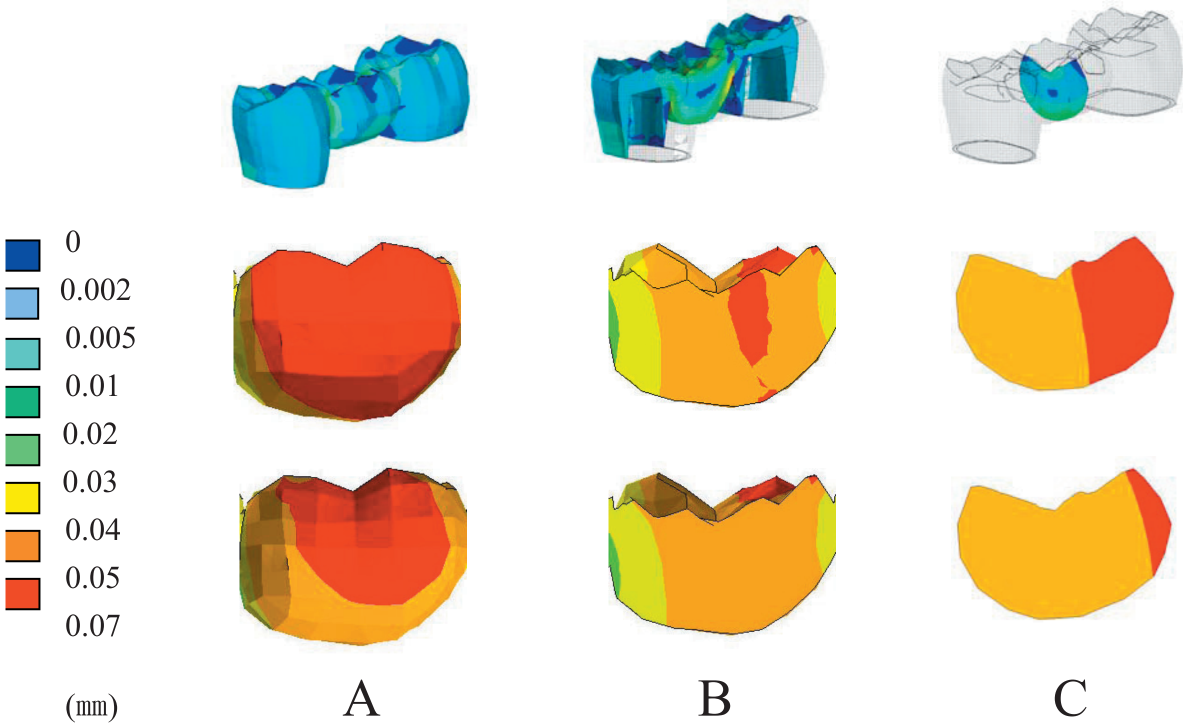

Figure 4. *Displacement of the pontic against vertical load*

Upper: C-FPD. Lower: FRC-FPD
A; Surface view of buccal side. B; Mesiodistal section. C; Buccolingual section

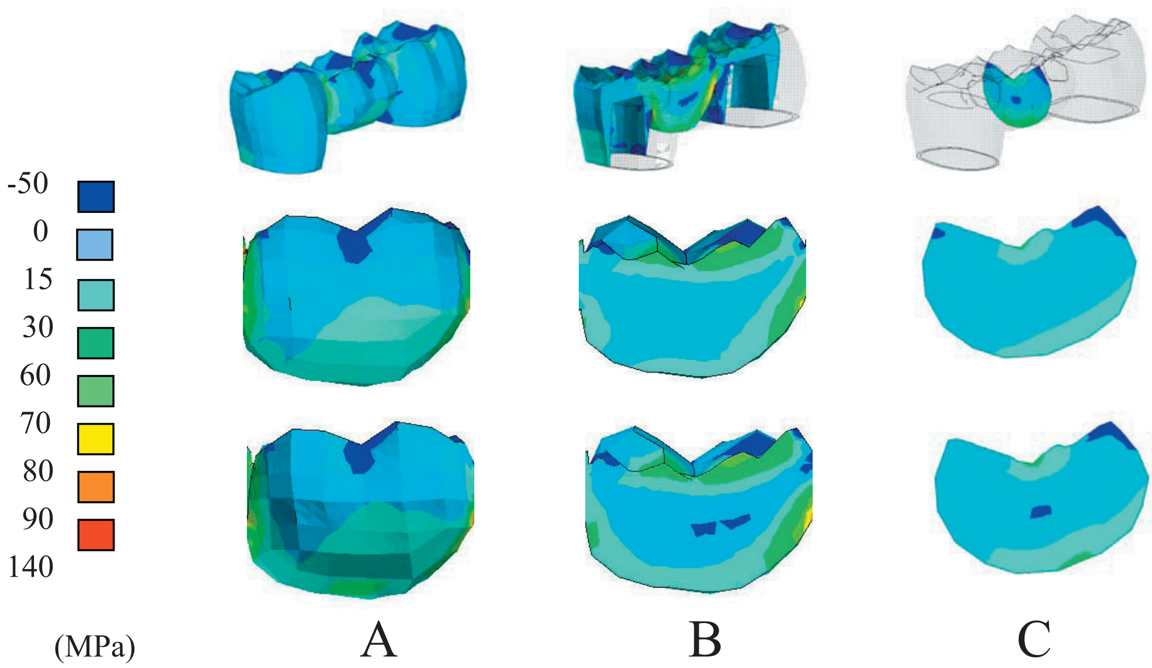

Figure 5. *Maximum principal stress of the pontic against lateral load*

Upper: C-FPD. Lower: FRC-FPD
A; Surface view of buccal side. B; Mesiodistal section. C; Buccolingual section

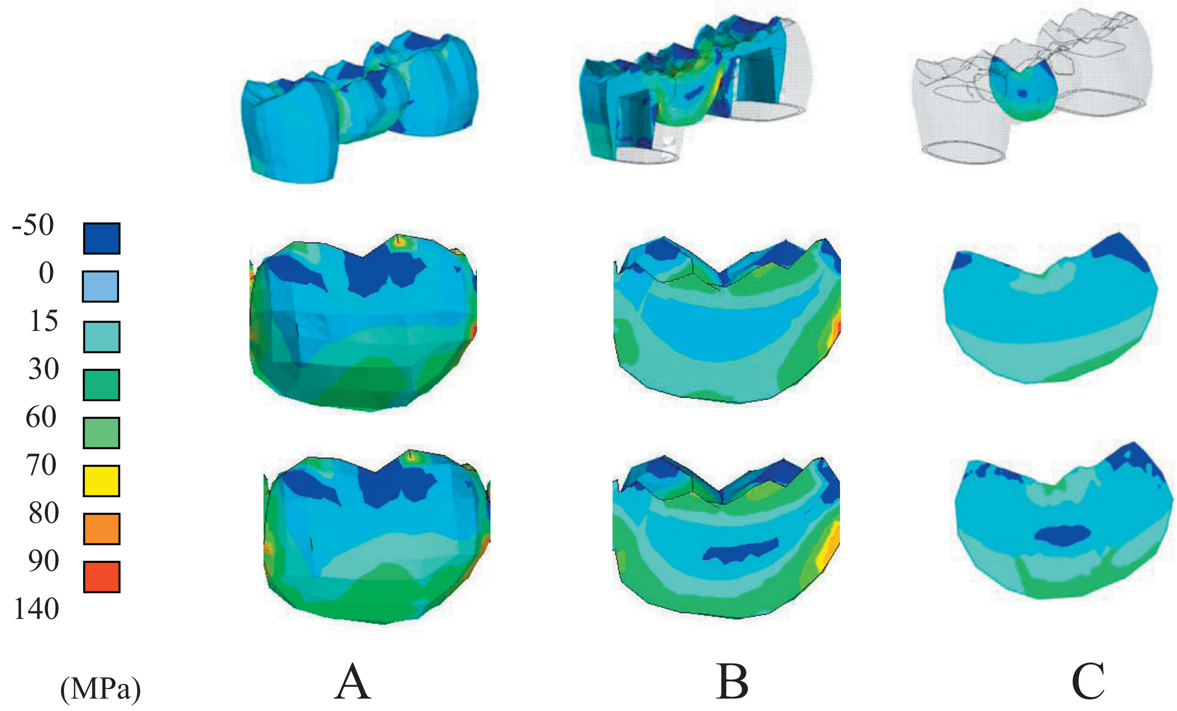

Figure 6. *Maximum principal stress of the pontic against vertical load*

Upper: C-FPD. Lower: FRC-FPD
A; Surface view of buccal side. B; Mesiodistal section. C; Buccolingual section

Buccolingual cross-section

In C-FPD, 15mm 30 MPa principal stresses were distributed to the area from the middle of the pontic to the buccal direction as well as to cusp and fossa on the occlusal surface.

Maximum principal stress of FRC-FPD, 15mm 30 MPa was distributed to the areas from one third of thr pontic to the buccal direction of the pontic. Higher than 30 MPa stresses were exclusively found in FRC framework surrounded by around buccal side of pontic base. Compressive stresses were observed in the center of the pontic.

Vertical load (Fig. 6)

Surface and mesiodistal cross-section

Maximum principal stress of C-FPD, higher than 90 MPa was distributed to the area including pontic's of distal connector as well as to the inner portion of the pontic. In FRC-FPD, higher than 90 MPa principal stresses were found in the FRC framework surrounded by the pontic side of lower embrasure of distal connector, but its area was reduced compared with C-FPD. In a buccoligal section of C-FPD, 15mm 30 MPa principal stresses were distributed to the area from the middle to the lower one third of the pontic, and to cusp and fossa in the occlusal surface. Maximum principal stress of FRC-FPD was 15mm 30 MPa in the middle to lower one third of the pontic, in the cusp and fossa, demonstrating similar stress distribution pattern of that of C-FPD. Compressive stress was observed in the middle of the pontic.

DISCUSSION

In this modelling study, it was demonstrated that there are some differences in mechanical behaviour of isotropic particulate composite resin and anisotropic FRC FPDs. Also, the stress distribution variation by changing the loading condition was seen. This is important because it has been reported that there might occur delamination of veneering composite from the FRC framework because at undesirable loading conditions (lateral load) with some framework design.

Mechanical behaviour of the FPD under lateral load

When taking into consideration the displacement distribution, no significant difference was found between C-FPD and FRC-FPD, showing a similar distribution pattern in all reference cross sections. Lateral load applied to incline of buccal-cusp from lingual direction caused bending force and it was concentrated at buccal side of the pontic. This is probably due to FRC framework placed on the bottom of the pontic could not exhibit good load-bearing capability and buccal-cusp was not veneered with high enough quantity of hybrid resin (insufficient thickness), which is most likely inducing delamination of the composite veneers. When compared maximum principal stress distribution of C-FPD with that of FRC-FPD, higher stress concentrations were not found at the pontics. Stress generated in the pontic of C-FPD was transferred from the areas to the bottom of the FRC framework with higher Young's modulus material (horizontal cross-section) in the FRC-FPD. No significant difference in the displacement distribution pattern was noted between C-FPD and FRC-FPD. This may suggest that longitudinal FRC along the direction of framework does not provide any support for the veneer over the regular veneering composite. Similar finding was reported by Xie et al with experimental biomechanical tools of FRC-FPDs[28]).

Mechanical behaviour of the FPD under vertical load

Viewed from buccolingual cross section, the stress found in the side and the bottom of the pontic was transferred to the FRC framework, and relatively low stress of 30mm60 MPa was found in the buccal side of the pontic base which was transferred to FRC framework, demonstrating good load-bearing capacity that FRC framework can withstand.

Occlusal contact of a pontic and guideline for FRC framework design

In this analysis, a total of 629N vertical load was applied to eight points on the occlusal surface of the pontic to simulate maximum occlusal force, and a total of 250N lateral load was applied to three points on buccal-cusp incline of the pontic at an angle of 45 degrees from lingual direction to simulate lateral movement of jaw. This can be considered as worst-case scenario loading condition when there is no cuspid protection available and teeth are loaded laterally.

The most effective way to reduce stress concentration in mesiodistal connectors and buccal side of the pontic is to decrease magnitude or avoid occlusal contacts of buccal side of the pontic. Technically, the pontic can be reinforced by additional fibres on the main framework. It was suggested that in order to get better stress distribution to the FRC-FPD, the framework design should contain FRC perpendicular to that of main framework. To obtain optimal hygiene, function and aesthetics, a wide variety of pontic design are proposed. As for occlusal morphology, buccolingual diameter of a pontic should be 2/3mm3/4 smaller than that of a missing tooth, and as for occlusal contact, centric stop is defined as an important occlusal contact. Rudo[15] et al suggested in his study that to resist twisting force generated in pontic, orthotropic FRC framework is more effective to anisotropic, unidirectional FRC framework with high strength and stiffness in one direction. Rudo[15] et al also suggested the placement of FRC on the outermost surface of a bridge where crack might initiate. In considering plaque accumulation and aesthetics, however, placing FRC on the outermost surface of a bridge can be difficult. There are evidence that exposed fibres, especially polyethylene fibres adheres significant quantities of oral pathogens on the surface[29-32]). The authors suggest that it is more appropriate to place FRC framework to the bottom of the pontic, where crack might initiate. The results of this study indicate that high stress concentration in the connectors can be reduced by weakening contacts of buccal cusp. When applied 250 N lateral loads to simulate loading the cusp in lateral movement of jaw, localized high stress concentrated in upper line angle of buccal side of mesial connector in C-FPD was eliminated by the reinforcement of FRC framework, avoiding high stress concentration. Peak stress value of 80 MPa is not likely to cause fracture or delamination of the veneer. When applying 629 N vertical load to simulate maximum occlusal force, higher than 90MPa stress were concentrated in upper line angle of the buccal side of the mesial connector and from lingual side to the bottom of the distal connector in C-FPD. The high stress concentration in the mesiodistal connectors was thought to have been caused by twisting moment imposed on the pontic. With the FRC-FPD, this localized high stress concentration area was subsequently transferred to be carried by the FRC framework, and thus avoiding the high stress concentrations. In addition to stress-transfer mechanism, the FRC framework reinforcement also improved the rigidity of the FPD. FRC framework bore more than 90MPa of stress, but considering superb flexure strength and load-bearing capacity of the FRC framework, it corresponds to one seventh of flexure strength FRC framework exhibits. These test results confirmed that correctly designed FRC reinforced composite system possesses adequate strength and safety to withstand maximum occlusal force.

CONCLUSION

These results clarified the magnitude, distribution of stress and displacement generated in C-FPD and FRC-FPD of pontic caused by two different loading conditions. The results suggested that in order to get better stress distribution to the FRC-FPD, the framework design should contain additional pontic FRC perpendicular to that of main framework.

ADDRESS FOR CORRESPONDENCE

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