Finite Element Analysis of Fiber-reinforced Fixed Partial Dentures

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Two-dimensional finite element models were created for a three-unit posterior fixed partial denture. An experimental resin-impregnated glass fiber was used as the fiber-reinforced composite (FRC) for the framework. The FRC was evaluated using varying combinations of position and thickness, alongside with two types of veneering composite. A load of 50 N simulating bite force was applied at the pontic in a vertical direction. Tensile stress was examined using a finite element analysis program.

Model without FRC showed tensile stress concentrations within the veneering composite on the cervical side of the pontic – from the connector area to the bottom of the pontic. Model with FRC at the top of the pontic had almost the same stress distribution as the model without FRC. Models with 0.4–0.8 mm thick FRC positioned at the bottom of the pontic showed maximum tensile stresses reduced by 4–19% within the veneering composite.

Key words: Finite element analysis, Fiber-reinforced composite, Fixed partial denture

INTRODUCTION

Oral restorations using minimal amount of metal are in high demand due to an increasing interest in esthetics and biocompatibility^{1–3)}. To this end, metal-free restorations have come to be widely used for both the posterior and anterior regions.

On posterior fixed partial dentures (FPDs), the tooth color was generally reproduced by firing porcelain on the metal framework. In recent years, however, it has become possible to fabricate FPDs using composite materials alone – by using fiber-reinforced composite (FRC) frameworks instead of metal frameworks^{4,5)}.

The strength of composites used for dental restorations can be effectively increased by reinforcing them with fibers^{6–11)}. In particular, it has been favorably reported that FPDs with FRC framework exhibited high strength^{12,13)}. However, particulate filler composites which are to be veneered on the framework have a far lower strength than the FRC framework itself¹⁴⁾, although they are superior to conventional composites in physical properties^{15,16)}.

It has been said that the strength of FRC and veneering composite laminates can be increased by placing the FRC layer at the bottom of the appliance which is to be subjected to tensile stress¹⁷⁾. The same may also be true of FPDs using FRC. That is, if FRC is placed at the bottom of the pontic to sustain tensile stress produced during mastication, stress that will apply to the veneering composite may be decreased to reduce the risk of fracture.

This study was conducted with a view to examining stress distribution on simulated posterior FPD

models by using a FRC framework. Simulated FPDs were modeled with various FRC positions and thicknesses, and two types of veneering composite. Stress analysis was then done by using two-dimensional finite element method.

MATERIALS AND METHODS

Finite element method was used to create two-dimensional models with thickness of 1.0 mm of a three-unit FPD for a missing lower first molar (Fig. 1). Each model consisted of 708 nodes and 1263 elements. Crown thickness was 1.5 mm at the occlusal surface and 1.0 mm at the margins. Shoulder margin design was used, and the connector had a thickness of 4.0 mm. Resin cement (Panavia, Kuraray

Fig. 1 Two-dimensional finite element model of a three-unit FPD.

Fig. 2 FRC positions and thicknesses.

Medical, Tokyo, Japan) was applied at a thickness of $100\mu\text{m}$.

For the fiber-reinforced composite (FRC) of the framework, an experimental BR-100 (Kuraray) was used. The BR-100 was composed of unidirectional glass fibers with a $11\mu\text{m}$ diameter and impregnated with resin¹⁴. The FRC was placed in such a manner that it interlocked the retainer and pontic, with five varying combinations of position and thickness: 1) No FRC (Control); 2) Top of pontic, 0.8 mm; 3) Top of pontic, 0.4 mm; 4) Bottom of pontic, 0.8 mm; and 5) Bottom of pontic, 0.4 mm (Fig. 2).

For the particulate filler composite to be veneered on the framework, Estenia (Kuraray Medical) or Targis (Ivoclar Vivadent, Shaan, Liechtenstein) was used.

Table 1 shows the material properties used for analysis^{18,19}. Since BR-100 had anisotropy, *i.e.*, the quality of exhibiting different physical properties in different fiber directions, its material constants were measured in both the longitudinal and transverse directions and were used for analysis.

A vertical load of 50 N simulating bite force was applied at the center of the pontic in the same manner described in a previous report²⁰. Since the buccolingual thickness of the three-unit FPD was about 10 mm and the thickness (width) of this model was 1 mm, 50 N (*i.e.*, 1/10 of the maximum bite force of 500 N) was used²¹.

The element coordinate system was used considering the anisotropy of the FRC. In addition, tensile stress was examined using a finite element structural analysis software (COSMOS/M Ver 2.7, Structural Research and Analysis, Santa Monica, CA, USA) since the fracture of brittle materials such as composites was chiefly due to tensile stress²².

RESULTS

The model facing Estenia and not having a FRC (*i.e.*, the Control) showed a high concentration of tensile stresses within the veneering composite on the cervical side of the pontic from the connector area to the bottom of the pontic, where a maximum tensile stress value of 48.5 MPa was observed in the distal connector area. Models which were veneered with Estenia and with 0.4-mm and 0.8-mm thick FRC positioned at the top of the pontic had almost the same stress distribution as the Control (Table 2, Fig. 3).

For the Estenia-veneered model with FRC posi-

Table 1 Material properties

Material	Product	Elastic modulus (GPa)	Poisson's ratio	Ref no.
FRC (longitudinal)	BR-100	39	0.35	*
FRC (transverse)		12	0.11	*
Veneering composite	Estenia (Kuraray)	21	0.27	19
	Targis (Ivoclar)	7.9	0.27	19
Luting cement	Panavia (Kuraray)	18	0.30	18
Pulp	—	0.01	0.49	18
Periodontal ligament	—	0.01	0.49	18
Dentin	—	14	0.15	18
Alveolar bone	—	12	0.15	18

*Data from manufacturer

Table 2 Maximum principal stress which appeared in the model (MPa)

Combination	Control (no FRC)	0.8 mm (Top)	0.8 mm (Bottom)	0.4 mm (Top)	0.4 mm (Bottom)
Estenia/ BR-100	48.5 —	49.5 17.9	46.1 24.4	49.1 17.7	46.6 25.2
Targis/ BR-100	37.6 —	37.6 13.9	30.5 39.9	37.7 13.7	31.4 42.5

Fig. 3 Tensile stress distribution of Estenia-veneered FPD. Both the Control model and the model loaded with 0.8-mm thick FRC at the top of the pontic demonstrated almost the same stress distribution.

Fig. 4 Tensile stress distribution of Targis-veneered FPD. In the case of the model loaded with 0.8-mm thick FRC at the bottom of pontic, maximum stress value within veneering composite was about 19% lower than the value obtained in the Control model.

tioned at the bottom of the pontic, stress concentration occurred at the FRC (positioned at the bottom of the pontic) as well as within the veneering composite at the cervical side of the connector. In addition, compared with the Control, the veneering composite at the cervical side of the connector showed a smaller high-stress area. The Estenia-veneered model with 0.8-mm and 0.4-mm thick FRC positioned at the bottom displayed maximum stress values of 46.1 MPa and 46.6 MPa respectively within the veneering composite in the mesial connector area (Table 2). These values were 4-5% lower than that of the Control.

Models veneered with Targis also showed the same tendency as the Estenia-veneered models. The models which were veneered with Targis and with FRC positioned at the top of the pontic (0.4 mm and 0.8 mm) had almost the same stress distribution as the Control (Table 2, Fig. 4). When FRC with thickness of 0.4 mm and 0.8 mm were positioned at the bottom of the pontic, the Targis-veneered models had a clearly smaller stress area than the Estenia models within the veneering composite at the cervical side of the connector (Fig. 4). The Control showed peak

tensile stress of 37.6 MPa within the veneering composite in the distal connector area. On the other hand, models with 0.8-mm and 0.4-mm thick FRC positioned at the bottom of the pontic showed peak tensile stresses of 39.9 MPa and 42.5 MPa respectively at the FRC-positioned area of the connector. In the case of these models, tensile stress within veneering composite was maximum at the distal connector area, or 30.5-31.4 MPa – which was about 19% (0.8 mm) or 16% (0.4 mm) lower than the Control value obtained in the same area (Table 2).

DISCUSSION

Fracture often occurs in brittle materials – such as dental ceramics and composites – when they are subjected to high tensile stress^{22,23}. All-ceramic FPDs seem to have a high risk of fracture when tensile stress concentrates in the connector area^{24,25}. Indeed, another clinical report claimed that the strength of the connector area is important for successful all-ceramic FPDs²⁶. Like all-ceramic FPDs, the models used for this study had a high concentration of

tensile stresses at the bottom of the connector.

For all-ceramic FPDs, the strength of the connector area is usually secured by using materials with a high strength or modulus of elasticity, such as alumina or zirconia, for the inner part of the restoration where high tensile stress is induced¹⁸⁾. When using glass fiber-reinforced composite materials for this purpose, those consisting of unidirectional fibers are employed for the inner part of the appliance because they have a greater strength than composite materials reinforced with woven fibers¹³⁾. However, the use of bundled fibers makes it difficult to mold the material in the same manner as it is done for metals or ceramics, thus limiting the degree of freedom in shape molding. For this reason, it is necessary to incorporate fibers in a manner that will best improve the strength of the entire FPD.

In this study, the Control model (which was not reinforced with FRC) exhibited tensile stress concentrations in the connector area and at the bottom of the pontic. These tensile stresses seemed to be induced by the load applied to the occlusal surface of the pontic, and probably concentrated in the connector area which was thinner than the pontic.

Models with FRC positioned at the top of the pontic showed almost the same stress distribution as the Control, suggesting that stress induced in the FPD could not be alleviated by reinforcing the top of the pontic with FRC.

In contrast, when models were reinforced with FRC at the bottom of the pontic, stress within the veneering composite decreased. In other words, it was likely that strength of FPD could be improved by reinforcing the area from the retainer to the bottom of the pontic.

There was a difference in stress values between Targis and Estenia. This was probably because Targis has a lower modulus of elasticity than Estenia. Estenia has a high modulus of elasticity for a veneering composite, a value close to that of the FRC¹⁴⁾. As a result, not-so-high tensile stress was induced in FRC, thereby reducing the risk of fracture.

Loose *et al.*²⁷⁾ reported that FPDs reinforced with FRC showed a higher strength than all-ceramic FPDs. However, in actual clinical situations, fiber-reinforced composite FPDs often pose a problem of poor strength in the veneering composite area²⁸⁾. Thus, it is required to veneer the appliance with a composite material having as high strength as possible. From this viewpoint, Rosentritt *et al.*²⁹⁾ have reported on the use of hybrid FPDs where ceramics — instead of FRCs — were used for veneering.

This study was performed under static loading conditions. In actual clinical settings, bite force is repeatedly applied and the appliance needs to withstand such a severe condition. It has been reported that FRC has good fatigue resistance^{30,31)}. Thus, if a

stronger and more durable veneering composite were used, this method of utilizing FRC would become more reliable.

REFERENCES

- 1) Wataha JC, Lockwood PE, Noda M, Nelson SK, Mettenberg DJ. Effect of toothbrushing on the toxicity of casting alloys. *J Prosthet Dent* 2002; 87: 94-98.
- 2) Al-Hiyasat AS, Bashabsheh OM, Darmani H. An investigation of the cytotoxic effects of dental casting alloys. *Int J Prosthodont* 2003; 16: 8-12.
- 3) Aoyagi H, Katagiri M. Long-term effects of Ag-containing alloys on mucous tissue present in biopsy samples. *Dent Mater J* 2004; 23: 340-347.
- 4) Freilich MA, Karmaker AC, Burstone CJ, Goldberg AJ. Development and clinical applications of a light-polymerized fiber-reinforced composite. *J Prosthet Dent* 1998; 80: 311-318.
- 5) Krejci I, Boretto R, Giezendanner P, Lutz F. Adhesive crowns and fixed partial dentures fabricated of ceromer/FRC: Clinical and laboratory procedures. *Pract Periodontics Aesthet Dent* 1998; 10: 487-498.
- 6) Vallittu PK. Flexural properties of acrylic resin polymers reinforced with unidirectional and woven glass fibers. *J Prosthet Dent* 1999; 81: 318-326.
- 7) Bae JM, Kim KN, Hattori M, Hasegawa K, Yoshinari M, Kawada E, Oda Y. The flexural properties of fiber-reinforced composite with light-polymerized polymer matrix. *Int J Prosthodont* 2001; 14: 33-39.
- 8) Kanie T, Arikawa H, Fujii K, Ban S. Impact strength of acrylic denture base resin reinforced with woven glass fiber. *Dent Mater J* 2003; 22: 30-38.
- 9) Ozdemir AK, Polat NT. The effect of glass fiber distribution on the transverse strength and surface smoothness of the two denture resins. *Dent Mater J* 2003; 22: 600-609.
- 10) Kanie T, Arikawa H, Fujii K, Ban S. Light-curing reinforcement for denture base resin using a glass fiber cloth pre-impregnated with various urethane oligomers. *Dent Mater J* 2004; 23: 291-296.
- 11) Kishita C, Hamano T, Tsuru K, Nishi Y, Nagaoka E. Application of a glass fiber-reinforced composite material to clasps — The effects of immersion and repeated loading. *Dent Mater J* 2004; 23: 528-532.
- 12) Behr M, Rosentritt M, Lang R, Handel G. Flexural properties of fiber reinforced composite using a vacuum/pressure or a manual adaptation manufacturing process. *J Dent* 2000; 28: 509-514.
- 13) Chong KH, Chai J. Strength and mode of failure of unidirectional and bi-directional glass fiber-reinforced composite materials. *Int J Prosthodont* 2003; 16: 161-166.
- 14) Nakamura T, Waki T, Kinuta S, Tanaka H. Strength and elastic modulus of fiber-reinforced composites used for fabricating fixed partial dentures. *Int J Prosthodont* 2003; 16: 549-553.
- 15) Tanoue N, Matsumura H, Atsuta M. Wear and surface roughness of current prosthetic composite after toothbrush/dentifrice abrasion. *J Prosthet Dent* 2000; 84: 93-

- 97.
- 16) Kawano F, Ohguri T, Ichikawa T, Matsumoto N. Influence of thermal cycles in water on flexural strength of laboratory-processed composite resin. *J Oral Rehabil* 2001; 28: 703-707.
- 17) Ellakwa AE, Shortall AC, Shehata MK, Marquis PM. The influence of fiber placement and position on the efficiency of reinforcement of fiber reinforced composite bridgework. *J Oral Rehabil* 2001; 28: 785-791.
- 18) Hino T. A mechanical study on new ceramic crowns and bridges for clinical use. *J Osaka Univ Dent Soc* 1990; 35: 240-267.
- 19) Sugita T, Nakamura T, Ko T, Maruyama T. Physical properties and clinical application of newly developed highly filler filled material for posterior prosthesis. *Jpn J Esthet Dent* 1998; 11: 107-114.
- 20) Magne P, Parakis N, Belser UC, Krejci I. Stress distribution of inlay-anchored adhesive fixed partial dentures: A finite element analysis of the influence of restorative materials and abutment preparation design. *J Prosthet Dent* 2002; 87: 516-527.
- 21) Nishimoto K, Takashima F, Tada S, Miyauchi S, Tsutsumi S, Maruyama T. A study of stress analysis on tetrasilic fluormica crystal by finite element method. *J Jpn Prosthodont Soc* 1987; 31: 819-829.
- 22) Brosh T, Garnor Y, Belov I, Pilo R. Analysis of strength properties of light-cured resin composites. *Dent Mater* 1999; 15: 174-179.
- 23) Peterson IM, Pajares A, Lawn BR, Thompson VP, Rekow ED. Mechanical characterization of dental ceramics by hertzian contacts. *J Dent Res* 1998; 77: 589-602.
- 24) Kelly JR, Tesk JA, Sorensen JA. Failure of all-ceramic fixed partial dentures *in vitro* and *in vivo*: Analysis and modeling. *J Dent Res* 1995; 74: 1253-1258.
- 25) Kamposiora P, Papavasiliou G, Bayne SC, Felton DA. Stress concentration in all-ceramic posterior fixed partial dentures. *Quintessence Int* 1996; 27: 701-706.
- 26) Sorensen JA, Cruz M, Mito WT, Raffener O, Meredith HR, Foser HP. A clinical investigation on three-unit fixed partial dentures fabricated with a lithium disilicate glass-ceramic. *Pract Periodontics Aesthet Dent* 1999; 11: 95-106.
- 27) Loose M, Rosentritt M, Leibrock A, Behr M, Handel G. *In vitro* study of fracture strength and marginal adaptation of fiber-reinforced-composite versus all-ceramic fixed partial dentures. *Eur J Prosthodont Restor Dent* 1998; 6: 55-62.
- 28) Behr M, Rosentritt M, Handel G. Fiber-reinforced composite crowns and FPDs: A clinical report. *Int J Prosthodont* 2003; 16: 239-243.
- 29) Rosentritt M, Behr M, Lang R, Handel G. Experimental design of FPD made of all-ceramics and fiber-reinforced composite. *Dent Mater* 2000; 16: 159-165.
- 30) Vallittu PK. Comparison of the *in vitro* fatigue resistance of an acrylic resin removable partial denture reinforced with continuous glass fibers or metal wires. *J Prosthodont* 1996; 5: 115-121.
- 31) Bae JM, Kim KN, Hattori M, Hasegawa K, Yoshinari M, Kawada E, Oda Y. Fatigue strength of particulate filler composites reinforced with fibers. *Dent Mater J* 2004; 23: 166-174.