Optimum Design for Fixed Partial Dentures Made of Hybrid Resin with Glass Fiber Reinforcement by Finite Element Analysis: Effect of Vertical Reinforced Thickness on Fiber Frame

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By means of finite element analysis, the optimal thickness of fiber framework placed in a fiber-reinforced composite bridge replacing the mandibular first molar was obtained. Test results demonstrated that more than 30% maximum principal stress was reduced by reinforcing with fiber framework in a thickness of up to 0.6 mm for 1.5-mm occlusal clearance. Indeed, maximum principal stress generated in lower embrasure of connectors was reduced from 107 MPa to 70 MPa by maximizing reinforcement effect.

Keywords: Optimum design, Finite element analysis, Glass fiber reinforcement

INTRODUCTION

Presently, a wide range of esthetic restorations are commonly used in daily dental practice – inlays, crowns, bridges, and suprastructures of implants fabricated from ceramics, composite resins. Those are also used as facing to the metal. The fiber-reinforced composite system is applicable to metal-free posterior crowns as well as full and partial coverage of fixed partial dentures, and these applications have been favorably reported with encouraging results¹⁻¹⁴. In a previous study¹⁵, the authors further demonstrated – by means of finite element analysis – that maximum principal stress applied to mandibular first molar was decreased from 106 MPa to 75 MPa (approximately 29% stress reduction) by maximizing fiber reinforcement effect.

However, the effect of fiber quantity (*i.e.*, vertical thickness of fiber framework) on magnitude and distribution of stress has not yet been fully investigated, which means there are no definite guidelines on this matter. Putting aside the lack of research and lack of guidelines, it is undeniably critical to clarify stress reduction mechanism (or stress-transferring mechanism), which is achieved by reinforcing with fiber framework placed within a limited occlusal clearance.

In the present study, preimpregnated, unidirectional, and orthotropic fiber-reinforced composite with high strength and stiffness in one direction was used to fabricate fixed partial dentures (FPDs). Then, from a structural and mechanical perspective, a finite element method was used to investigate the influence of the thickness of fiber framework on

magnitude and distribution of stress, and thereby determine the optimal thickness of fiber framework.

MATERIALS AND METHODS

Analysis of glass fiber-reinforced composite bridge using two-dimensional finite element analysis

1) Definition of structures

With a view to replacing the mandibular first molar, two-dimensional finite element models of three-unit bridge from mandibular second premolar to mandibular second molar were created. This model (GFR0) was the base model with no fiber framework reinforcement. GFR0 was to be in the middle of both buccolingual and mesiodistal distances and along the long axis of a crown. Crown contour based on anatomical measurements was obtained from Fujita¹⁶. Sanitary pontic design was used for missing mandibular first molar. A 1.5-mm occlusal clearance from pit and fissure and a deep chamfer (1.0 mm) were prepared for assumed jacket crown. Axial inclinations of abutment teeth were based on an anatomical study by Ogasawara¹⁷, while thickness and width of connectors were as per described in previous reports^{18,19}.

Figure 1 shows a finite element model of the fiber framework. The latter's continuous design consisted of a mesial connector, a pontic, and a distal connector, each having its peculiar curvature. Individual central coordinates of the circle were established for each curvature.

To optimize reinforcement effect, the shape of fiber framework was as per that described in a previous study by Shin-ya *et al.*¹⁵. Fiber framework was

Fig. 1 A finite element model of glass fiber framework.

Fig. 2 Two-dimensional models of 3-unit glass fiber-reinforced fixed partial dentures.

reinforced in the axial direction (or along y-axis). With due consideration for 1.5-mm occlusal clearance, a total of eight fiber framework models were constructed with a thickness of 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, or 1.4 mm (GFR0, GFR0.2, GFR0.4, GFR0.6, GFR0.8, GFR1.0, GFR1.2, GFR1.4) (Fig. 2). All shape information was expressed numerically, and input data were created using ANSYS 9.0 (ANSYS Inc., USA).

2) Geometric conditions

Finite element models consisting of 5,684 elements with 15,046 nodes were created for plane stress analysis. Quadrilateral elements with eight nodes were chosen because they are more regular than triangular elements. The final element on the x-y axes of abutment base was assumed fixed, thereby defining the boundary conditions. An applied force of 50 N was derived from the maximum occlusal force of

healthy permanent teeth. Two vertical loads of 25 N (y-axis) were thus applied to each cuspal tip²⁰⁾.

Figure 3 shows the outline of the model and its boundary conditions. Material properties used for this finite element analysis are listed in Table 1. Hybrid resin, which was Estenia in this study, was assumed to be an isotropic material, while glass fiber was assumed to be orthotropic material. As in all finite element models, fiber orientation was set to the x-axis. As such, material properties of fiber framework in the x-axis were set to be of the highest values.

Analysis was presumed to be linear static. Finite element model construction and FE analysis were then performed on a PC workstation (Precision Work Station 670, Dell Computer) using a commercially available FEM software, ANSYS 9.0 (ANSYS Inc., USA).

Fig. 3 Boundary conditions of finite element models (GFR1.0).

Table 1 Material properties

	Young's modulus (MPa)	Poisson's ratio	Shear modulus (MPa)
Hybrid composite resin	2.20×10^4	0.27	
Dentin	1.80×10^4	0.31	
Pulp	2.10	0.45	
Glass fiber			
Longitudinal	3.90×10^4	0.35	1.40×10^4
Transverse	1.20×10^4	0.11	0.54×10^4

RESULTS

Stress analysis of GFR FPD models

1) Maximum principal stress distribution

Figure 4 shows the maximum principal stress distribution patterns from GFR0 to GFR1.4. With GFR0, maximum principal stresses of 3–7 MPa were observed in the mesial margin of second premolar, occlusal surface of abutment teeth, connector areas, one half of pontic base, and loading points. Maximum principal stresses of 7–10 MPa were distributed to gingival connector, pontic base, as well as pit and fissure of both abutment teeth. Maximum principal stresses exceeding 20 MPa were distributed to gingival connector, and a localized high stress of 107 MPa was observed at lower embrasure on pontic of mesial connector.

In terms of the influence of fiber reinforcement, significant differences were noted in the maximum principal stress patterns of GFR0.2–GFR1.4. With GFR0.2, maximum principal stress (103 MPa) was distributed to the fiber framework. However, maxi-

um principal stress mostly concentrated in a limited area of fiber framework, not showing a uniform stress distribution pattern as compared with GFR0.6–GFR1.4.

Disparity in maximum principal stress was apparently observed at the interface between fiber framework and resin matrix. However, more disconcertingly, high stress concentration (84 MPa) was observed in regions pertaining to lower embrasure of the connectors, indicating that fiber framework bore little load. It should be re-emphasized that fiber reinforcement was deemed effective only if the stress were transferred from resin matrix to the fiber framework.

Concerning stress distribution pattern of pontic in all the finite element models, maximum principal stress was extensively distributed to the pontic. With increase in the fiber framework quantity (*i.e.*, vertical reinforcement), maximum principal stress—which had been concentrated in connector area—was transferred to the fiber framework, whereby maximum principal stresses of 20–30 MPa were gradually

Fig. 4 Distributions of maximum principal stress.

distributed to the whole fiber framework.

2) Quantified displacement distribution

Figure 5 shows the quantified displacement distributions of GFR FPD models. With GFR0, displacement exceeding 0.017 mm was extensively observed at the center of the pontic, from the occlusal surface to

pontic base, peaking at a value of 0.02 mm.

Displacement area exceeding 0.017 mm, however, decreased with increase in the quantity of fiber framework. Starting from GFR0.2, this high displacement area already vanished from the pontic base.

Fig. 5 Distributions of displacement.

FPDs

GFR FPDs

Fig. 6 Depiction of stress vectors.

Moving on to GFR0.8, displacement area exceeding 0.017 mm was decreased to one third of pontic height. It remained so in GFR1.0, GFR1.2, and GFR1.4, such that it was observed only at the occlusal surface and its surrounding area.

3) Principal stress direction

Figure 6 shows the directions of maximum principal stress. With GFR0, maximum principal stress was oriented from the lower embrasure of connector to the occlusal surface of abutment teeth, and then to the marginal area parallel to the external form of bridge. At pontic, maximum principal stress was oriented from the upper embrasure of connector (or marginal ridge of pontic) to the pontic base, showing a curvature along the external form of pontic base.

On the whole, maximum principal stress showed a M-shaped stress distribution pattern, *i.e.*, connecting the proximal margins of both abutment teeth and being oriented parallel to the external form of bridge near the outer surface.

With GFR1.4, maximum principal stress was oriented uniformly along the orientation of fibers, presenting a striking contrast to GFR0, of which the principal stress was oriented randomly at the mesial connector.

Stress reduction with vertical reinforcement

Figure 7 represents the change in maximum principal stress value of high stress concentration area observed from second premolar distal margin to pontic

Fig. 7 Path plots of maximum principal stress on the bottom surface in all models.

Fig. 8 Reduction ratios of maximum principal stress values observed at mesial connector.

base to second molar mesial margin. Peak value was detected in the lower embrasure of both mesial and distal connectors, although the peak values differed from each other. Apart from the peak values, maximum principal stress value increased slightly at the center of pontic base. FE models reinforced with fiber framework demonstrated a sharp decline in principal stress value, compared with FE model with no fiber framework reinforcement.

Concerning GFR0.6–GFR1.4, stress reduction ratio tended to gradually decrease with increasing quantity of fiber framework. Stress reduction ratio was calculated based on the difference between maximum principal stress values of GFR0 and GFR0.2–GFR1.4 observed at lower embrasure of mesial connector. On this note, Fig. 8 shows the stress reduction ratios observed at mesial connector. Compared with GFR0 (107 MPa), GFR1.4 demonstrated the highest reduction ratio of 34% (70 MPa), while GFR0.2 demonstrated the lowest reduction ratio of 21% (84 MPa).

DISCUSSION

Study method

It is difficult to evaluate the influence of fiber framework quantity on magnitude and distribution of stress, because test specimens and clinical bridges are different in terms of structure, shape, dimension, and fabrication process. In particular, it is almost an impossible task to prepare test specimens with the same fabrication process as the clinical bridges. To complicate matters, factors such as degree of polymerization, adhesion, and minute surface scratch also threaten to affect test results^{21–25}. However, with finite element method, this approach puts to rest all the disagreements arising from dimensions and material properties of structures. Although constructing finite element models is difficult, there is the undeniable and concrete benefit of precise calculation of inner stress. With the advantages outweighing the disadvantages, finite element study was chosen for this research. Moreover, finite element analysis allowed the form and structure of bridge to remain unchanged and unaffected by the quantity of fiber framework, to the end of evaluating only the influence of the thickness of fiber framework.

Since fiber framework is a composite material of preimpregnated fiber embedded in a resin matrix, analysis in this study focused only on the macroscopic behavior, following the method suggested by Shin-ya *et al.*¹⁵. To examine the intrinsic material properties of glass fiber, a new local coordinate system—in addition to the rectangular coordinate system—with a different point of origin would need to be established.

Stress analysis of GFR FPDs with different quantities of fiber framework

1) Maximum principal stress distribution

Stress analysis with different quantities of fiber framework revealed that the value of maximum principal stress peaked at the lower embrasure of connectors. With a three-point bending test using bridge specimens, Vallittu²⁾ demonstrated that a crack which was initiated at lower embrasure of connectors propagated to the loading points. Further, it was commented that high stress concentration in connector area was closely related to bridge design—a suggestion in cordial agreement with the results of this study, which also showed high stress concentration in lower embrasure of connectors.

However, high stress concentration in connector area is mainly due to intrinsic morphology of a bridge. On this matter, Shin-ya *et al.*¹⁵⁾ commented that from a biomechanical perspective on the intrinsic morphology of a bridge, it was difficult to obtain an optimum design to achieve uniform stress distribution.

As for the stress distribution pattern in pontic, maximum principal stress was efficiently transferred from resin matrix to fiber framework with increasing quantity of fiber framework. This was probably due to the excellent tensile properties of glass fiber to bear more tensile stress, thus causing less tensile stress to be generated in the resin matrix.

As for the stress distribution patterns in connectors, they showed a similar behavior as that of pontic, *i.e.*, stress was transferred reliably from resin matrix to fiber framework with increasing quantity of fiber framework. Compared with GFR0, GFR0.2 demonstrated that stresses exceeding 78 MPa were extensively distributed along the orientation of fibers, and that maximum principal stress value at lower embrasure of connectors was reduced to 84 MPa (approximately 21% stress reduction). With increasing quantity of fiber framework (GFR0.4–GFR1.4), maximum principal stress was gradually transferred from resin matrix to fiber framework, such that stresses exceeding 78 MPa were no longer observed in resin matrix from GFR0.6.

With increase in the quantity of fiber framework, the value of maximum principal stress in connectors tended to decrease. This was probably due to the exceptionally high elastic modulus of the fiber framework along the orientation of fibers. As a result, the enhanced tensile properties enabled glass fibers to bear more tensile stress generated in the connectors, thus reducing the stress in resin matrix.

In this research, GFR1.4 achieved the highest stress reduction ratio, demonstrating a uniform stress distribution pattern without any high stress concentration in the fiber framework. Indeed, Fig. 7 confirmed that fiber framework had enough stress-

bearing capacity to withstand occlusal force generated in bridge.

2) Quantified displacement distribution

Upon examining the relationship between quantified displacement distribution and fiber framework quantity, the following were noted. With GFR0, displacement area exceeding 0.017 mm was extensively distributed from occlusal surface to pontic base. With GFR0.2, the same displacement area was confined to the upper portion of pontic. Then, with GFR1.4, it was reduced to a limited area of occlusal surface.

With GFR0.6–GFR1.4, no sudden change in quantified displacement was found between isotropic composite resin and orthotropic fiber framework, and neither was any similar behavior found at the interface between them. However, with GFR0–GFR0.4, high stress concentration was observed in fiber framework adjacent to connectors. Moreover, these observed high stresses tended to extend along the orientation of fibers, which was associated with stress reduction ratio.

Thus, these test results revealed that the rigidity and strength of a bridge were improved with increasing quantity of fiber framework.

3) Principal stress direction

Maximum principal stress was oriented from marginal ridge of both abutment teeth to pontic base, showing a curve-like stress distribution pattern along the external form of pontic base.

On the whole, maximum principal stress distribution showed a M-shaped pattern, *i.e.*, connecting the cervical regions of both abutment teeth. With increasing reinforcement effect of fiber framework, principal stress became more systematically oriented along the major axis of fiber framework. As a result, excellent stress-bearing capacity along the orientation of fibers led to enhanced tensile strength.

Optimum fiber framework design for GFR FPDs

In several clinical studies of fiber-reinforced FPDs, it has been favorably reported that fiber frameworks possess adequate mechanical properties to reduce tensile stress generated in high stress concentration area of connectors^{26–28)}.

The effectiveness of fiber reinforcement is dependent on many variables, including the quantity of fibers, location of fiber placement, fiber form, fiber type, pretreatment of fibers with silane coupling agent, as well as fatigue properties.

To determine the optimal reinforcement effect of a fiber framework, various tests such as three-point bending test, fatigue test, and finite element analysis have been performed^{4,5,9,10,15)}. Highest test results⁴⁾ were obtained under the following conditions—fiber quantity for reinforcement: 16 wt%; fiber placement location: bottom of pontic; fiber length: maximum

mesiodistal length; fiber diameter: 11 μm ; filler particle content of bonding agent: 30 wt%.

In the current study, FEM analysis results showed that principal stress was reduced by 29%, as compared with no fiber reinforcement at the bottom of pontic. In clinical scenarios with a typically limited occlusal clearance, it is highly critical that reinforcement effect be optimized with a relatively small quantity of fiber framework. In this connection, it has been reported—from a structural and mechanical perspective—that fiber framework be reinforced with 0.6–1.4 mm thickness for 1.5-mm occlusal clearance. Moreover, the higher the quantity of fiber framework, the greater was the reinforcement effect.

However, when reinforcement exceeded 0.6 mm, stress-bearing capacity did not improve significantly; on the contrary, a lower stress reduction ratio was yielded. Therefore, it did not seem necessary for fiber framework thickness to be more than 0.6 mm to withstand an average adult's masticatory force in the molar region. Moreover, from esthetic and biomechanical standpoints, at least 0.5 mm of occlusal surface must be overlaid with a veneering composite with highly filled ceramic particles—otherwise, esthetics will be compromised. Putting both stress reduction findings and esthetic/biomechanical considerations together, 0.6–1.0 mm thickness seemed to be both adequate and appropriate to achieve the desired reinforcement effect, with more than one third of occlusal clearance placed with fiber framework.

CONCLUSIONS

To the end of replacing the mandibular first molar, two-dimensional finite element models of fiber-reinforced composite FPDs from mandibular second premolar to mandibular second molar were created.

By means of finite element analysis, the influence of the thickness of fiber framework on magnitude and distribution of stress from a structural and mechanical perspective was investigated. Within the limitations of this *in vitro* study, the following conclusions were drawn:

1. Results of finite element analysis showed that for all fiber-reinforced models, the fiber framework bore the maximum principal stress. With GFR0, maximum principal stress of 107 MPa was observed at lower embrasure of connectors. With GFR1.4, on the other hand, only a maximum principal stress of 70 MPa was observed, indicating approximately 34% stress reduction.
2. In terms of quantified displacement, an area of displacement peaking at 0.02 mm was distributed extensively from occlusal surface to pontic base in GFR0, but which was reduced to a limited area of occlusal surface in GFR1.4. By

increasing the quantity of fiber framework, quantified displacement at pontic was reduced, thereby improving significantly the rigidity of bridge.

3. Significant stress reduction was found in GFR0.2–GFR0.6 models, but stress reduction seemingly remained unchanged in GFR0.6–GFR1.4.

The present test results revealed that magnitude and distribution of stress were influenced by the thickness of fiber framework, whereby 0.6 mm of vertical reinforcement was deemed both necessary and adequate from a structural and mechanical perspective.

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