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Influences of metal frame design on the mechanical strength of posterior porcelain fused to metal crown

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Summary

Objectives : The purpose of this study was to find an ideal shape of the metal frame (coping) in the porcelain fused to metal (PFM) crown. The stress distribution was assessed by the load–to–fracture values and a three–dimensional finite element analysis.

Methods : Three kinds of coping designs were tested ; Design Ⅰ : Conventional type as control (traditional frame). Design Ⅱ : 1.0 mm lower than occlusal surface of coping (butterfly frame). Design Ⅲ : Straight type (flat frame). The load–to–fracture value consisted of three groups (Design Ⅰ, Ⅱ and Ⅲ) of five samples each. The loading location is selected at the area where mesial and distal of the metal frame will coincide with the projection of the occlussal surface. All samples were loaded to fracture at the rate of 0.1 mm/min using a universal–testing machine. The stress distribution was assessed in a three–dimensional finite element model, which consisted of the abutment tooth, cement, metal coping and porcelain. The loading position is the projection point of buccal–lingual transitional part of the frame mesial and distal proximal surface on the occlusal surface towards the median, in which the load is in constant value. Loading direction is vertically downward along tooth axis with a load of 2000 N.

Results : The mean load–to–fracture value for each group is as follows : Group A (DesignI) = 1823.0 N ± 132.7 (S.D.), Group B (Design Ⅱ) = 1940.4 N ± 147.4 (S.D.), Group C (Design Ⅲ) = 2333.9 N ± 180.9 (S.D.). The results of the three–dimensional finite element analysis showed that the maximum tensile stress of 84.5 MPa occurred in Design Ⅰ. The maximum tensile stress in design Ⅱ and Ⅲ were 53.8 MPa and 53.3 MPa, respectively, which were the lower than Design Ⅰ.

Conclusions : The results indicated that the butterfly and flat frame designs will increase metal support on proximal porcelain, thus effectively change the stress distribution within the coping and porcelain, optimizing stress distribution in PFM crown under perpendicular load, and enhance structural strength of porcelain of PFM crown.

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Introduction

Porcelain-fused-to-metal (PFM) crown has been widely applied in molar restorations due to its strength, the wear-proof, chemically stable, good biocompatibility and lifelike morphology and color. However, restoration failure caused by porcelain fracture is not rare in clinical practices. Clinical study shows that the percentage of porcelain fracture owing to its fragility in the total failure of PFM crown restorations is 50%-60%[1,2].

It has been a focus of both clinicians and dental material technology to find out the reasons of causing porcelain fracture, enhancing resistance strength of porcelain and reducing PFM crown restorations failure resulted from porcelain brittle fracture under low stress. The concept of combining a brittle material with an elastic material to arrive at more desirable physical properties has many engineering applications. Dental porcelains resist compressive loading but tend to succumb to tensile stress. Therefore, the metal substructure must be designed so that any tensile stresses in the porcelain are minimized[3].

The analysis on the PFM crown compressive strength for first molar made by the author[4] is showed that the porcelain strength on central occlusal surface supported by metal frame was far higher than that on the marginal area of occlusal surface without support. That means the marginal porcelain of PFM crown without metal frame support is the weakest area of PFM crown against external force, and is more probable to fracture than that on central occlusal surface.

As to this experiment, firstly, we've designed and fabricated three groups of PFM crowns with different metal framework designing by employing a mandibular first molar stainless steel standardized dies[5] without hurting facial appearance. And then the fracture strength was tested and compared through mechanical loading test. Finally, we created three-dimensional PFM crown model with computer-aided design, to simulate clinical vertical and constant static load on PFM crown model with finite element analysis method to analyze strength variation for porcelain at the mesiodistal marginal area of PFM crown with or without metal frame support. Additionally, we discussed the influence on distribution of stress in different frame design to provide theoretical basis for ideal metal frame design for molar PFM crown.

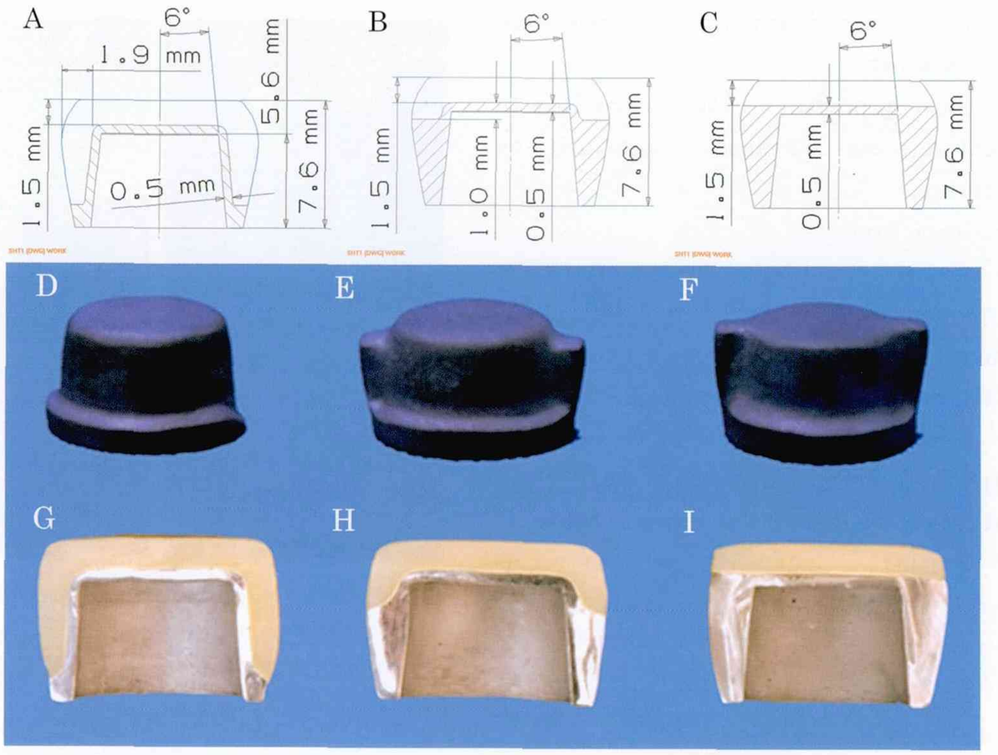
Materials & Methods

1. *Design of metal frame*

One of the basic requirements for a successful restoration is to let the dental patient have a beautiful smile. In this study, the designs of metal frame are based on the guidelines which the metal is not visible while to obtain maximum metal supporting area for the mesiodistal marginal porcelain in occlusal surface of PFM crown as possible.

Design I : Thickness of metal frame : 0.5mm[6] ; lingual metal edge height : 1.5mm, the metal junction stops at the buccal axial corner on both mesial and distal proximal surfaces, where the morphology is kept with porcelain in consistent thickness around the metal frame according to the crown shape. This is called as traditional frame. (Fig.1A)

Design II : It is based on Design I , with the metal frame mesial and distal proximal side protruding towards occlusal surface to a level of 1.0mm lower than the metal frame horizon. Since the shape looks like a butterfly, so it is called as butterfly frame. (Fig.1B)



* ▨ metal framework

Fig.1 : Design and dimensions of porcelain fused to metal crowns with different metal framework. A, B and C : Dimensions of porcelain and metal framework ; D, E and F : Designs of metal framework ; G, H and I : Mesiodistal cutaway view.

Design Ⅲ: It is based on Design Ⅰ, with the metal frame mesial and distal proximal side protruding towards occlusal surface to the metal frame level. This is called as flat frame. (Fig.1C)

2. *Mechanical load test*

2.1. Equipment and materials

1) Wirobond C (Bego, Germany).
2) IPS d. SIGN low fusion porcelain (Ivoclar Vivadent, Lischtenstein).
3) G.C. LIVCARBO cement (G.C. Corporation, Japan).
4) Stainless steel standardized die of mandibular first molar : based on Masaka[5], the die is created.
5) High frequency induction casting machine (Manfredi, Italy).
6) Porcelain furnace (Ivoclar Vivadent, Lischtenstein).
7) Instron 5882 universal testing machine (Instron, USA).
8) *in vivo* Micro-CT (R-mCT® Rigaku Co., JAPAN).

2.2. Model fabrication and experiment grouping

1) Fabrication of metal frame

Fabricate wax patterns for traditional, butterfly and flat frame respectively, build casting mold chamber through investment, heating and baking, and then melt Co-Cr alloy under high temperature to cast the frame with High Frequency Induction Casting Machine, selecting qualified metal frames from the products (Fig.1D, E and F).

2) Metal frame pretreatment before porcelain fusion

Conduct metal frame pretreatment before porcelain fusion by undergoing surface roughing, washing with organic solvent, air elimination and pre-oxidation.

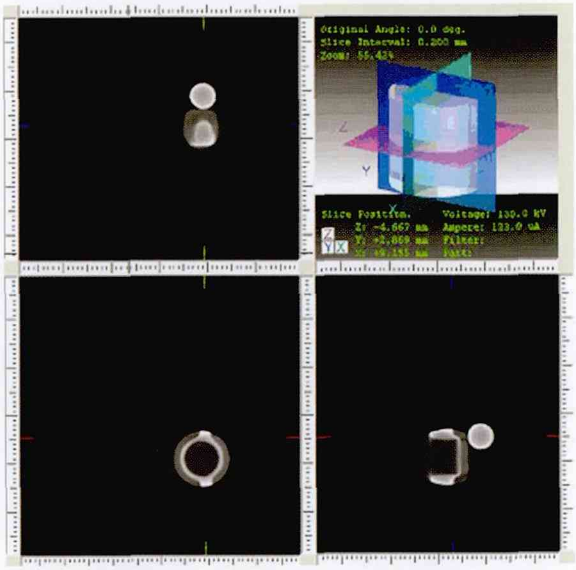
3) Porcelain overlaying on metal frame

Apply porcelain powder onto the metal frame in the order of opaque porcelain, body porcelain and incisal porcelain, and then place in the porcelain furnace for heating.

Conduct above procedures exactly according to operational process parameters provided by manufacturers.

4) Experiment grouping

Fabricate five mandibular first molar PFM crown specimens each for above three kinds of different metal frame designs respectively separately. PFM crown made with traditional frame is called as Design Ⅰ (Fig.1G) ; PFM crown made with butterfly frame is called as Design Ⅱ (Fig.1 H) ; PFM crown made with flat frame is called as Design Ⅲ (Fig.1I) ; in which Design Ⅰ was set as control group, while Design Ⅱ and Ⅲ are used as experimental groups.



Original Angle: 0.0 deg.
Slice Interval: 0.200 mm
Zoom: 55.42%
Slice Position.
Z: -4.667 mm
Y: +2.869 mm
X: [illegible] mm
Voltage: 130.0 kV
Ampere: 123.0 uA
Filter:
Part:

Fig.2 : Stereotaxic localization of load point using *in vivo* Micro-CT.

2.3. Load-to-fracture value

Seat and cemented the finished PFM crowns on to the steel dies with GC LIVCARBO cement (GC Corporation Tokyo, Japan). Store them in a chamber of 37℃ for 24 hours. The loading location is selected at the area where mesial and distal of the metal frame will coincide with the projection of the occlussal surface where the excursion will happen. Adjustment was done by means of the *in vivo* Micro-CT (Fig.2). The samples were then loaded to fracture at the rate of 0.10mm/min using an Instron (Instron 5882, USA) universal testing machine (Fig.3).

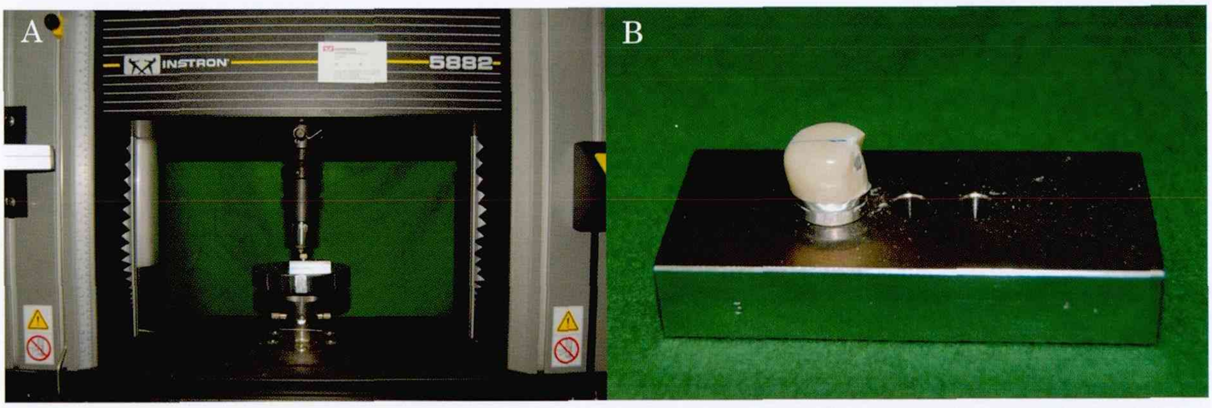


Fig.3 : Load-to-fracture test. A : An Instron (Instron Corporation, Norwood, USA) universal testing machine ; B : Fractured crown on steel die.

3. *Three-dimensional finite element analysis*

3.1. Model analysis

1) Design of metal framework

Create three-dimensional models for Design Ⅰ (traditional frame), Design Ⅱ (butterfly frame) and Design Ⅲ (flat frame) respectively on the basis of metal frame geometric parameters used in load to fracture value.

2) Mandibular first molar PFM crown model

Modify parameters of metal frame morphology and porcelain without changing the PFM crown

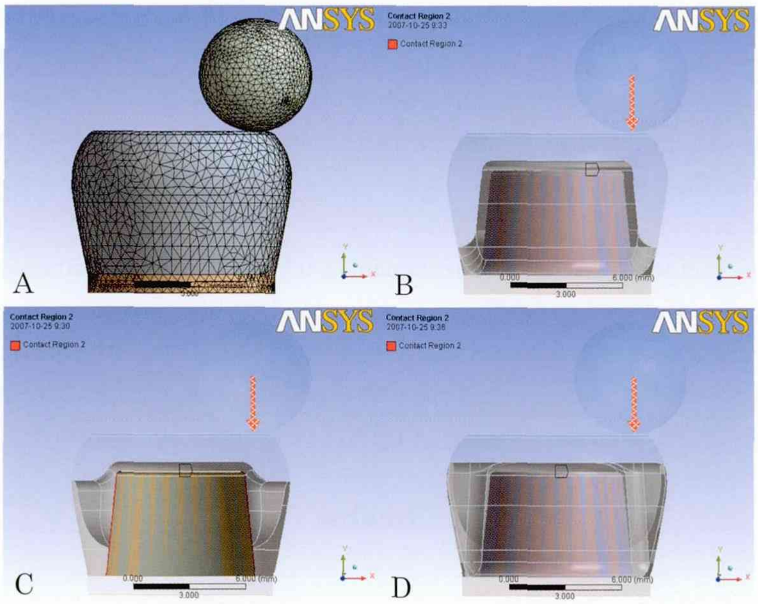


Fig.4 : Finite element model for PFM crowns and perspective view of metal framework. A : Standard configuration of finite element model for PFM crowns, nodes : 72804 ; elements : 37903. B : Design Ⅰ. C : Design Ⅱ. D : Design Ⅲ. Arrow pointing direction : load point on crowns, load forecast 2000 N.

shape according to major geometric parameters in fabricating PFM crown during mechanical load test. Experimental mandibular first molar PFM crown model consists of the abutment tooth, cement, metal coping and porcelain, in which the cement thickness is set as 0.06mm(7), porcelain thickness on occlusal surface is of 1.5mm consistently (Fig.4).

Besides variations among the three model structures, there're also minor differences in the number of elements and nodes of the 10-node tetrahedral element obtained from the models, in which Design Ⅰ is of 37903 elements and 72804 nodes, while Design Ⅱ is of 39442/75528, and Design Ⅲ is of 39296/74920 respectively.

3.2. Presumptions and material parameters

In this experiment, we assume that the models consisting of uniform, continuous and isotropic linear elastic materials, which meet small deformation conditions. The elastic modulus and Poisson's ratio of the materials for all components are listed in Table 1. In order to better simulate the situations under mechanical load test and clinical conditions for PFM crown, we have placed two sets of parameters for structural steel and natural tooth (dentin) on abutment tooth.

Table 1 : Elastic properties of materials modeled

Material	Modulus of elasticity (GPa)	Poisson's ratio
Porcelain	68.9(8)	0.28
Co-Cr alloy	218.0(8)	0.33
Cement	22.4(9)	0.35
Dentin	18.6(9)	0.31
Steel	200.0*	0.30

* From Ansys workbench 11.0

3.3. Marginally restricted condition and additional load condition

The major observation of this experiment is stress distribution of the PFM crown after vertical load application, so all the freedom of the lower surface of abutment tooth model would be limited.

Restriction loading sphere (Dia. 6mm) is parallel to the two load freedom on PFM surface to ensure vertical load application. The loading position is the projection point of buccal-lingual transitional part of the frame mesial and distal proximal surface on the occlusal surface towards the median, in which the load is in constant value. Loading direction is vertically downward along the tooth axis with a load of 2000 N (Fig.4B, C and D).

3.4. Stress analysis

Stress analysis is executed by ANSYS Workbench 11.0 FEM analytical software (US. Ansys Inc.).

Dental porcelains are featured resisted compressive loading but tend to succumb to tensile stress, while compressive and tensile strength for metal is quite close. Therefore the major observation for stress indicators of this experiment is the first principal stress (maximum tension stress) in porcelain and von-Misses stress (equivalent stress) in the metal coping and abutment tooth.

Results

1. *Load-to-fracture value*

In this study fifteen PFM crowns were divided into three groups of five samples each based upon its coping type. The crowns were luted to steel dies using G.C. LIVCARBO cement. The crowns were loaded to fracture and the load-to-fracture value was obtained for each sample. The mean load-to-fracture value for each group is as follows : (Fig.5)

- Group A (Design Ⅰ) = 1823.0 N±132.7 (S.D.)
- Group B (Design Ⅱ) = 1940.4 N±147.4 (S.D.)
- Group C (Design Ⅲ) = 2333.9 N±180.9 (S.D.)

The unpaired t-test was applied to the data, which indicated there was a statistical difference between Group C (Design Ⅲ) and all of the other groups.

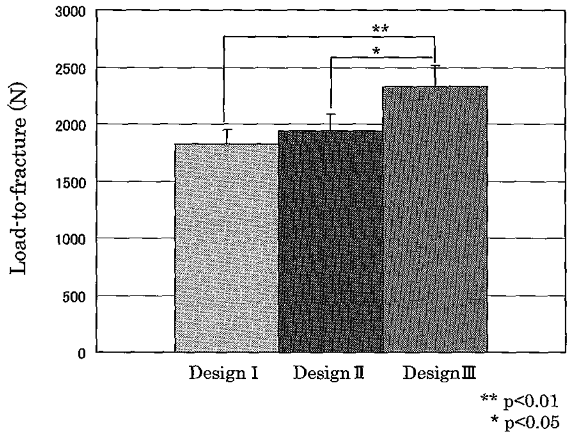


Fig.5 : Plot of the fracture strength test results in load at fracture (*N*)

2. *Stress distribution in model*

In all distribution graphs, the stresses mainly concentrates in the proximity of intersection of proximal and occlusal surface on loading area, however, the maximum stress and the position where it occurs are varied from different metal frame designs.

1) Stress distribution in porcelain

Stress concentration is distinctly visible around the loading area (Fig.6), while the stress distribution is similar for steel and natural abutment tooth. At the proximal-occlusal transitional part of porcelain of Design Ⅰ (traditional frame), the maximum tensile stress occurred on steel abutment tooth model is 84.7 MPa, while a maximum tensile is 79.5 MPa in dentin abutment tooth model. The maximum tensile stress is 1/3 higher than that in the porcelain of Design Ⅱ (butterfly frame) and Design Ⅲ (flat frame), moreover the stress concentration is far more distinct in the porcelain internal proximal-occlusal transitional part. The maximum tensile stress values of porcelain for different models are shown in Figure 7.

2) Stress distribution within metal coping

All kinds of stress within the metal frame concentrate on the loading side, similar as the stress

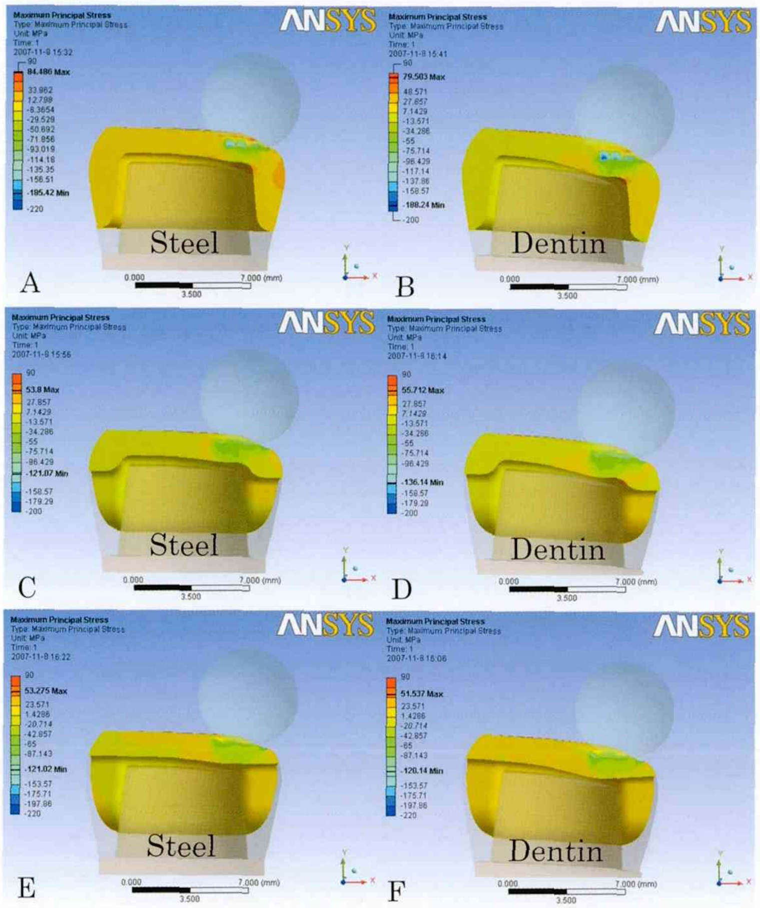


Fig.6 : Distribution of maximum principal stress on porcelain area and deformation of PFM crowns at a magnification of 150. A and B : Design Ⅰ; C and D : Design Ⅱ; E and F : Design Ⅲ. A, C and E : Steel abutment ; B, D and F : Dentin abutment.

distribution for porcelain. Stress concentration for metal frame of Design Ⅰ is more distinct at the proximal-occlusal line angle (Fig.8). The maximum equivalent stress is 310.9 MPa for steel abutment tooth model, while is 317.3 MPa for dentine abutment tooth on coping of Design Ⅰ. Equivalent stress was found out in coping of Design Ⅱ and Ⅲ, which are much lower than that of Design Ⅰ. Equivalent stress values for different types of metal copings are listed in Figure 9.

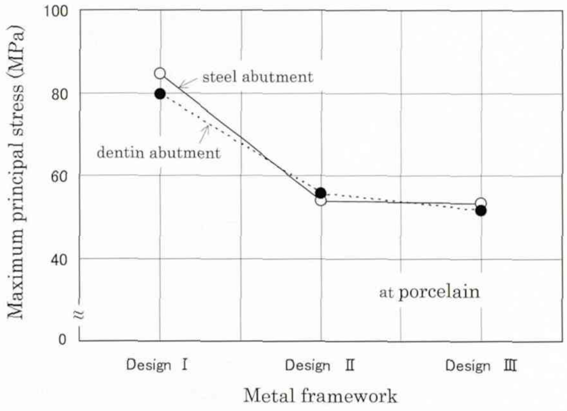


Fig.7 : Relationship between metal framework and maximum principal stress on the porcelain.

3) Stress distribution within abutment tooth

The equivalent stress of steel abutment tooth happened at the proximal-occlusal line angle of loading area, while the equivalent stress concentration of dentine abutment tooth occurs at the shoulder portion of the loading side (Fig.10). The maximum equivalent stress of Design Ⅰ steel abutment tooth is much higher than that of Design Ⅱ and Design Ⅲ, by contrast, there is almost no difference comparing the maximum equivalent stresses of dentine abutment tooth for different Designs (Fig.11).

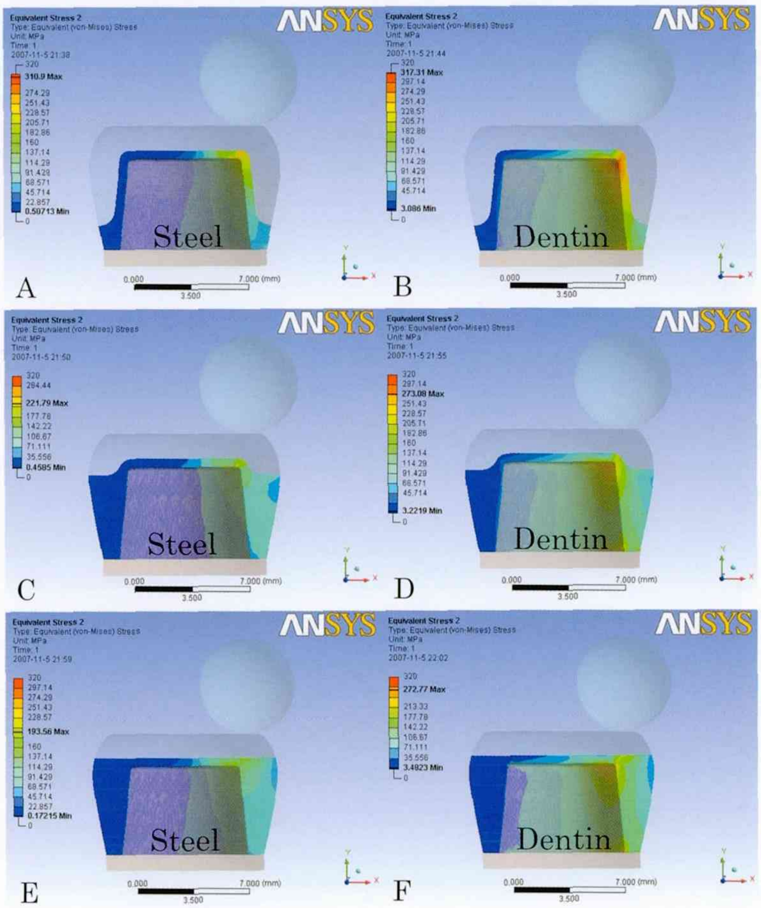


Fig.8 : Distribution of equivalent (von–Mises) stress on metal coping. A and B : Design Ⅰ ; C and D : Design Ⅱ ; E and F : Design Ⅲ. A, C and E : Steel abutment ; B, D and F : Dentin abutment.

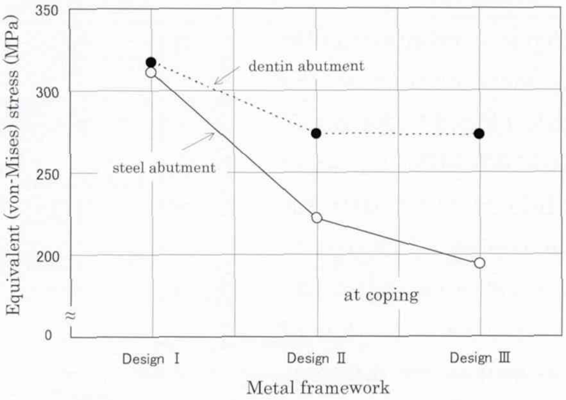


Fig.9 : Relationship between metal framework and equivalent (von–Mises) stress on the coping.

Discussion

1. *Evaluations on metal frame design and load–to–fracture value*

The idea to obtain most ideal physical performance through combination of brittle and elastic materials has been one focus in material technology for long. Dental porcelains resist compressive loading but succumb to tensile stress. Therefore, the metal substructure must be designed so that any tensile stresses in the porcelain are minimized[3].

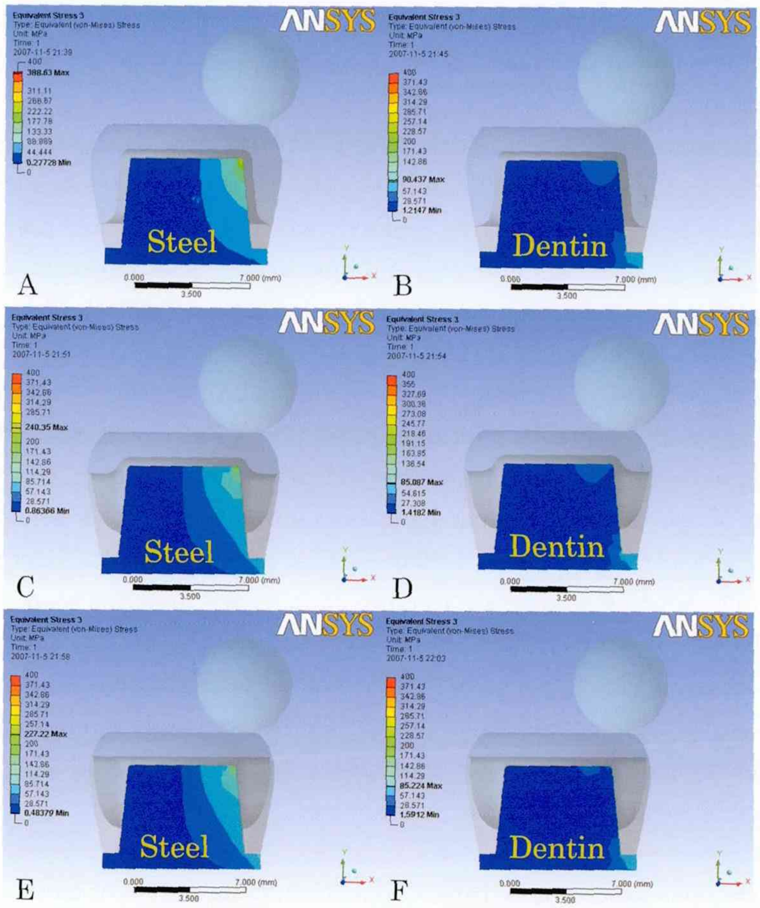


Fig.10 : Distribution of equivalent (von–Mises) stress on the abutments. A and B : Design Ⅰ ; C and D : Design Ⅱ ; E and F : Design Ⅲ. A, C and E : Steel abutment ; B, D and F : Dentin abutment.

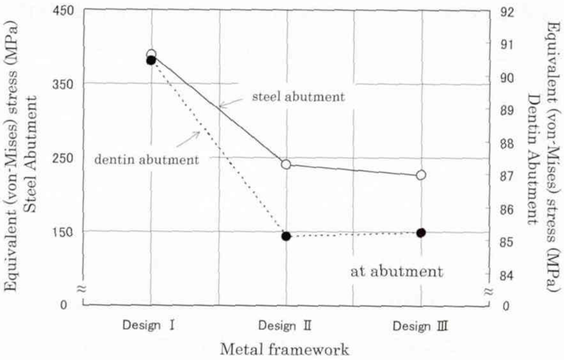


Fig.11 : Relationship between metal framework and equivalent (von–Mises) stress on the abutment.

Previous study made by the author[4)] shows that the compressive strength at the central part is much higher than that at the marginal area of PFM crown occlusal surface. We believe the marginal porcelain is the weakest area due to lack of metal support in PFM crown, which may cause the marginal porcelain to break more probable than central porcelain on occlusal surface. We may consider the possibility to reduce porcelain fracture in marginal area by properly increasing metal support on the proximal area of PFM crown. Based on this idea by setting stainless steel standardized die[5)] of mandibular first molar as the benchmark, we have designed and fabricated PFM crowns with three different metal frames, which are traditional (Design Ⅰ), butterfly (Design Ⅱ) and flat (Design Ⅲ) morphology. Then we have compared their fracture strength on proximal porcelain through mechanical load test. In order to control the force direction more effectively without interference from dental cusp as well as pits and fissures of occlusal surface, the occlusal surface of PFM crown was designed as a smooth flat plane.

The testing results showed that the fracture strength of PFM crowns with butterfly and flat frame is obviously superior to that with traditional one. The PFM crown restoration with traditional framework is made by porcelain overlaying method, which forms thicker porcelain layer on the proximal surface, especially at proximal buccal and lingual extension intervals, which may result in weak resistance against the instantaneous tensile stress on surface11–13). More important, as the proximal porcelain–metal interface is about parallel to the load direction perpendicular to the occlusal surface, the shearing stress within the porcelain–metal interface and porcelain will be increased, while the structural strength will be reduced. For PFM crown restoration with butterfly frame, as the proximal porcelain on occlusal surface is supported by coping, the porcelain thickness as long as the shear stresses within the porcelain–metal interface and porcelain are reduced when bearing perpendicular load to the occlusal surface, so that the resistance against the fracture of porcelain is enhanced. Therefore, the porcelain fracture on marginal area has been effectively improved by changing load–bearing in proximal porcelain on occlusal surface through butterfly frame.

Additionally, in this experiment, we have first attempted to use *in vivo* Micro–CT for positioning correction on PFM crown loading point from coronal section, sagittal section and horizontal section (Fig.2), which not only ensured sample load consistency, but has also relatively avoided experimental data error caused by loading position deviation as well.

2. *Model analysis*

Stress analysis methods for crown by three–dimensional simulation of tooth are such as photoelastic test14,15), finite element analysis16–20) etc. Photoelastic test is difficult in model fabrication. Furthermore, it could not fully reflect subsequent change in stress distribution due to morphology change. Therefore, photoelastic test is not applicable for stress distribution comparison based on morphology change of metal frame in this experiment.

Starting from analysis on strain, finite element analysis is a comprehensive analytical method from the aspects such as geometry, physics and mechanics etc. by taking advantage of the relations between stress and strain as well as static conditions. Along with creating the analytical model, once the fundamental model is established, it would be featured with openness and editability to enable comparison among subsequent changes in stress distribution due to morphology change.

The accuracy of three–dimensional finite element analytical results depends on the similarity of established model21). In order to simulate and reveal the mechanical load test and analyze subsequent change of stress distribution in PFM crown due to frame morphology change, we have adopted three–dimensional modeling element partition method to establish the PFM crown of mandibular first molar model consists of abutment tooth, cement, coping and porcelain. Geometric dimensions of individual element model (abutment tooth, cement, porcelain) are all the same except the factors to be observed (frame), this has not only ensured the morphology accuracy of the established model and the consistency to the prototype as well to reflect the crown mechanical structure status visually and accurately, but also ensured the comparability of the models.

In order to ensure the similarity between the simulating load and mechanical load (Fig.4B, C and D), we first assume the simulating abutment to be steel abutment tooth under mechanical load and common natural (dentin) abutment tooth, and assume the load is static, which is constant for surface loading, the load is applied with a sphere, while the loading points of all samples are the same as in the mechanical load test, and the load weight of 2000 N is also the average resistance value for crown by mechanical loading.

In molar stress analysis, as the impact on internal frame stress distribution by root and pulp can be ignored, they are usually excluded in modeling process[22,23)]. In the modeling process for this experiment, we've ignored tooth root and pulp, and set the cement thickness as 0.06mm[7)], which could ensure the consistency between the three–dimensional simulation and mechanical load.

3. ***Stress distribution for porcelain***

As shown in Figure 6, stress within the loading area on the porcelain (crown) surface mostly appears as compressive stress, while the tensile stress causing porcelain break (maximum principal stress) is distributed in the proximal and occlusal surface transitional part area, which is the same as reported by Kojima[22)] and Yamamoto[23)]. The maximum principal stress distribution of porcelain will be changed subsequently with the change of framework morphology under the same static load. The maximum principal stress for the porcelain of PFM crowns with butterfly and flat frame is distinctly lower than that with traditional frame (as shown in Fig.7). That is, the butterfly and flat frame design has optimized the stress distribution in the porcelain of PFM crown, and has improved the capability against the marginal porcelain damage for PFM crown. The main reason for this improvement is the butterfly and flat frame structure, which provide more metal support area for porcelain on the proximal surface of PFM crown and will sustain partial load, therefore the stress within proximal porcelain is relatively lessened, so that the principal stress on porcelain is reduced, and the structural strength of porcelain and the porcelain–metal interface is improved as well.

Porcelain is a kind of brittle material, though it's compressive strength is as high as 600 MPa, its tensile strength is only as low as 65~75 MPa[10)]. When the force applied is perpendicular to the occlusal surface, the pressure is transmitted to the abutment tooth through the frame, the crown and abutment tooth are compressed (Fig.6) and may expand horizontally (in x or y direction). As the elastic modulus of the abutment tooth and crown is different[8,9)], so their horizontal extension rates are also different, therefore tensile stress occurs in the interface between the crown and the abutment tooth. When the tensile stress is close to or exceeds the resistance strength limit, the stress concentration area will become the original point for porcelain fracture.

Of course, the abutment tooth will also suffer strong compressive strength in the stress concentration area, causing compressive distortion and crown strain shown in Figure 6. As the Young's Modulus of natural tooth is lower than steel tooth[8,9)], the PFM crown strain rate of natural tooth is therefore higher than that of steel tooth.

4. ***Stress distribution within metal coping***

The coping strain is critical to resistance strength of porcelain and porcelain–to–metal combination, the larger strain, the easier porcelain fracture or exfoliation may occur. To control and reduce the strain of metal coping effectively is very important for the porcelain's ability against fracture.

As shown in Figure 9, no matter on natural and steel abutment tooth model, not only the equivalent stress value for traditional frame is higher than that for butterfly and flat frame, but the stress also concentrate in the transitional part of proximal occlusal surface in the load area. This indicates that the resistance–proof capability for butterfly and flat frame is higher than that for traditional frame, which means the butterfly frame can effectively improve the resistance–proof capability for porcelain.

5. ***Stress distribution within abutment tooth***

As shown in Figure 10, the stress distribution within natural abutment tooth is obviously different from that within steel abutment tooth.

The equivalent stresses for natural abutment tooth (dentin) are not of much difference for the three designs, this is because the elastic modulus[8,9] of natural tooth is far lower than that of the metal frame, and most of the load is supported by the metal frame. Therefore we can determine that the morphology change of metal frame does not have much impact on stress distribution for natural abutment tooth.

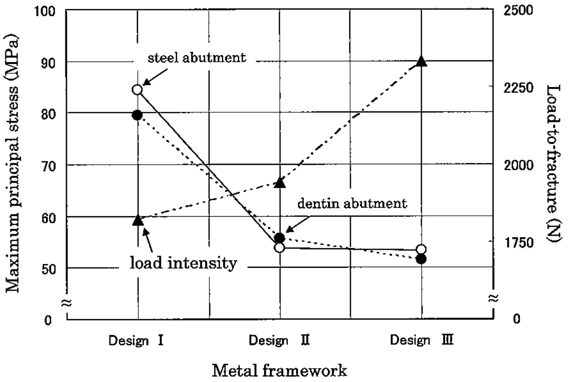


Fig. 12 : Relationship appraisal between three-dimensional finite element analysis and load-to-fracture value.

However, the relative stress concentration within metal frame results in increased compressive stress born by the part of abutment tooth within the concentration area, therefore increases the probability of dentine abutment tooth strain, and the crown strain is also more possible (Fig.6).

Meanwhile, the elastic modulus of steel abutment tooth is close to the metal frame, so that the steel abutment tooth will sustain partial load. Although the stress within metal frame is relatively lessened, the strain rate of abutment tooth is still close to the frame, so the equivalent stress born by the traditional steel abutment tooth is obviously higher than the butterfly and flat design (Fig.11).

In above three-dimensional finite element analysis, no matter for the dentine or steel abutment tooth, the trends of stress distribution change for traditional, butterfly or flat frame of PFM crown are similar, while the tensile stresses decreases in sequence, which is consistent with the results of fracture strength in the mechanical load test (Fig.12).

Conclusions

This study has discussed about the impact on PFM crown's strength and stress distribution by morphology change of metal frame using load-to-fracture value and three-dimensional finite element analysis. The results indicated that, in addition to considering the requirements for good appearance in clinical application, the butterfly and flat frame designs will increase metal support on proximal porcelain, thus effectively change the stress distribution within the coping and porcelain, optimizing stress distribution in PFM crown under perpendicular load, and enhance structural strength of porcelain of PFM crown. This study has not only provided theoretical basis for changes in metal frame design of PFM crown, but also can give a reference basis to design research of coping of all-ceramic crowns such as zirconium oxide etc.

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臼歯陶材焼付鋳造冠におけるメタルフレーム形態の力学的検討

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【目的】本研究では，メタルセラミッククラウンにおける理想的なメタルフレーム形態を模索すべく負荷テストと三次元有限要素法を用いて解析を行い，近遠心側咬合面の強度をもたせる，臨床的に適切なデザインを検討した．

【実験方法】メタルフレーム形態による影響をより明確にするため，メタルフレームのデザインを以下の三種類とした．デザインⅠ：従来通りコーピング外形にあわせた形態（従来型），デザインⅡ：コーピング咬合面に対してメタルフレームの近遠心側は歯頸部方向に1.0 mm 張り出した形態（蝶形型），デザインⅢ：コーピング咬合面に対してメタルフレームはフラットな形態（フラット型）．

負荷テストは，鋳造により作製した三種類のフレーム（各5個）を使って，下顎第一大臼歯陶材焼付鋳造冠を作製し，フレームの隣接面と咬合面の移行部（メタル—陶材界面部）直上に負荷点を設定し，万能試験機にて行った．

解析モデルは，負荷テストに使った下顎第一大臼歯陶材焼付鋳造冠を想定し，支台歯，合着剤，金属コーピングとクラウンからなる三次元有限要素モデルを構築，フレーム隣接面と咬合面の移行部垂直方向に2000 N を負荷した．

【結果と考察】負荷テストの結果は，デザインⅠは1823.0±132.7 N，デザインⅡは1940.4±147.4 N，デザインⅢは2333.9±180.9 N で破壊された．

有限要素法による解析の結果，デザインⅠでは，最大で84.5 MPa の引張応力が発生した．デザインⅡとⅢでは，それぞれ53.8 MPa と53.3 MPa の最大引張応力が発生し，その値はデザインⅠより低い値を示した．即ち，デザインⅠ，Ⅱ，Ⅲとなるにしたがって最大引張り応力は低下し，圧縮応力は増加を示した．

よって，メタルフレームの形態を変化させることにより，クラウン内部の応力分布が変化し，従来の形態に比べ，蝶形とフラット型フレームを用いることより，クラウンがより大きな荷重に耐え得る可能性が示唆された．