〔**Original**〕 Matsumoto Shigaku 37 : 1～8, 2011

key words : Three-Dimensional Finite-Element — stress — Metal-Ceramic Crown

Influence of coping design on stress distribution of posterior metal-ceramic crowns by three-dimensional finite element analysis

RAORAO WANG[1], XIANQI LI[2], YUANZHI XU[1], QIXIANG YANG[1], DAN WANG[1],
BIN LUI[3], DONGSHENG ZHANG[3], JING YANG[4] and HIROO MIYAZAWA[4]

[1]*Center of Health-Care in Stomatology, Shanghai Tenth People's Hospital, the Medical School of Tongji University, Shanghai, China*
[2]*Department of Hard Tissue Research, Institute for Oral Science, Matsumoto Dental University*
[3]*Department of Mechanics, Shanghai University, Shanghai, China*
[4]*Department of Oral Health Promotion, Institute for Oral Science, Matsumoto Dental University*

Summary

Objectives To find the ideal form of coping for metal molar ceramic crowns, we evaluated their stress distributions under various loading conditions using three-dimensional finite element analysis.

Materials and methods A three-dimensional finite element model representing a lower first molar was constructed. The model was varied to include one of three types of coping, the standard, butterfly, and flat types. A load of 600N, simulating the maximum bite force, was applied vertically to the crowns at the central occlusal surface and mesio-occlusal marginal areas. Loads of 225N, simulating masticatory force, were applied at a 45° angle to the tooth axis.

Results In three of the simulation load tests, the maximum stresses were concentrated around the loading points on the porcelain and coping. The minimum tensile stress value was placed on the butterfly coping crown in the test simulating maximum bite force, when the load was applied to the mesio-occlusal marginal areas.

Conclusion The butterfly coping design optimizes the stress distribution within copings and porcelain and enhances the structural strength of porcelain in metal ceramic crowns.

Introduction

Metal-ceramic crowns are widely used for posterior teeth because of their high strength, good esthetics, and low price. However, while dental ceramic resists compressive loading it tends to succumb to tensile stress. So attempts are being made to enhance the fracture resistance strength of the porcelain layers of metal-ceramic crowns in order to reduce their failure rate[1~3].

In our previous study, lower first molar metal ceramic crowns with flat metal copings were sub-

(recieved November 11, 2010 ; accepted February 10, 2011)

jected to vertical loading[4]. It was found that butterfly copings (the mesial and distal proximal surfaces of these metal copings protrude upward) optimized the stress distribution and enhanced the tensile strength of the porcelain layer.

In this study, the stress distributions of metal ceramic crowns with different metal coping designs were examined under various loading conditions using three–dimensional finite element analysis (3 D FEA). Our objective was to enhance the strength of the porcelain layer by changing the metal coping design and to provide a theoretical basis for the design of an ideal metal frame.

Materials and Methods

1. Metal coping design

Three kinds of metal copings were examined, the standard type, butterfly type, and flat type, as shown in Fig.1.

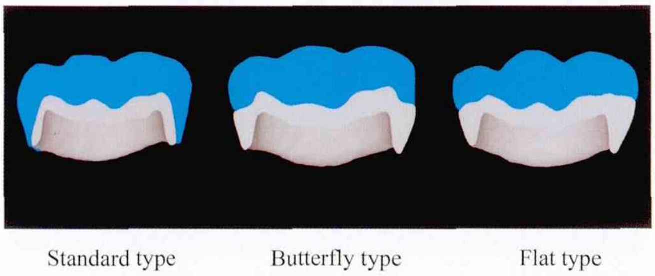


Fig.1 : 3D finite element modeling of metal coping designs (ivory white). Standard type : The metal coping was designed according to typical clinical procedures. Butterfly type : The mesial and distal proximal surfaces of the metal coping protruded upward. The upper surface was 1.0mm lower than the occlusal surface. Flat type : The mesial and distal proximal surfaces of the metal coping protruded upward. The upper surface was at the same height as the top of the metal frame.

Standard type : the metal coping was of consistent thickness. The lingual shoulder stopped at the mesial and distal lingual axial angle, according to the typical clinical procedure.

Butterfly type : the mesial and distal proximal surfaces of the metal coping protruded upward towards the surface, which was 1.0mm lower than the occlusal surface.

Flat type : the mesia and distal proximal surfaces of the metal coping protruded upward towards the occlusal surface.

The occlusal surface of the metal coping was curved to fit well with the abutment tooth.

2. Three–dimensional (3D) finite element modeling of lower first molar metal ceramic crowns

A standard lower first molar (D50–500A, Nissin Dental Products, Japan) was replicated to produce an abutment tooth, a metal coping, and a porcelain layer. The restored tooth was scanned from a mesiodistal view using a GE Micro–CT scanner (SCANCO μCT80, SCANCO Medical AG Company, Swiss) with a voxel resolution of 36μm[5]. The sequential sliced images were imported into 3D image conversion software (Simpleware Ltd. UK) to build a 3D model. The output file was imported into the 3D FEA software ANSYS Workbench 11.0 (Ansys, Inc., America) to facilitate finite element analysis. The interface between the porcelain and coping layers was glued. The standard type coping consisted of 399747 elements and 575886 nodes, the butterfly type consisted of 480557 elements and 694608 nodes, and the flat type consisted of 400831 elements and 580852 nodes (Fig.2).

3. Material parameters

The 3D element model was assumed to consist of a uniform, continuous, and isotropic linear elas-

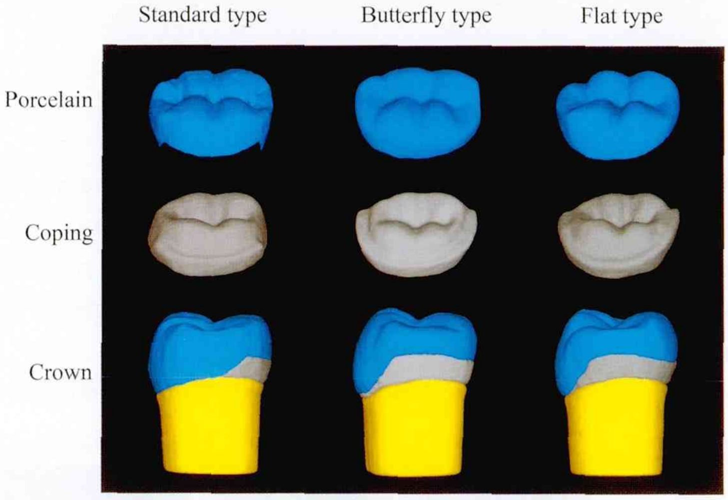
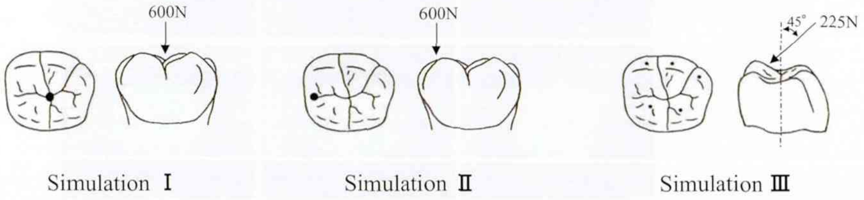


Fig.2 : The layers composing the FEA model.



Simulation Ⅰ Simulation Ⅱ Simulation Ⅲ

Fig.3 : Schematics of the three loading conditions. Simulation Ⅰ: A concentrated occlusal load of 600N was applied vertically along the tooth axis to the central fossa region. Simulation Ⅱ: A concentrated occlusal load of 600N was applied vertically along the tooth axis to the mesio-occlusal marginal area. Simulation Ⅲ: A concentrated occlusal load was applied to 5 points, the buccal surfaces of the mesiobuccal cusp, the distobuccal cusp, the distal cusp, and the two lingual cusps. A total load of 225N was applied at an angle of 45 degrees to the tooth axis (45N at each loading point).

● loading point
↓ loading direction

tic material ; i.e., to meet small deformation conditions. The elastic moduli of porcelain, Co-Cr alloys, cement, and dentin substrate were defined as 68.9, 218.0, 22.4, and 18.6 GPa, respectively, and their Poisson's ratios were assumed to be 0.28, 0.33, 0.35, and 0.31, respectively[6].

4. Load simulations

Three different loads were applied to the metal ceramic crown in areas with a diameter of 3mm[7] (Fig. 3).

Simulation Ⅰ: a load of 600N, simulating the maximum bite force, was applied vertically to the central occlusal region.

Simulation Ⅱ: a load of 600N, simulating the maximum bite force, was applied vertically to the mesio-occlusal marginal area.

Simulation Ⅲ: a load of 225N[8,9], simulating masticatory force, was applied to 5 points (45N at each loading point, 45° to the tooth axis), the buccal surfaces of the mesiobuccal cusp, distobuccal cusp, distal cusp, and the two lingual cusps.

5. Stress distribution analysis

The FEA software ANSYS Workbench 11.0 (Ansys, Inc., America) was used to analyze the stress distribution in the porcelain layer and metal coping under various static loads.

Results

1. Tensile stress distribution in the porcelain layer

The maximum tensile stress was concentrated around the loading points on the surface of the crown. In simulation Ⅱ, the tensile stress in the porcelain butterfly coping increased to 46.63 MPa, which was lower than those of the standard type (66.74Mpa) and flat type (58.19Mpa). In simulations Ⅰ and Ⅲ, there was not much difference among the three coping designs (Fig.4).

2. von–Mises stress distribution within the metal coping

Concentrated von–Mises stress was seen at the metal–porcelain interface below the loaded areas.

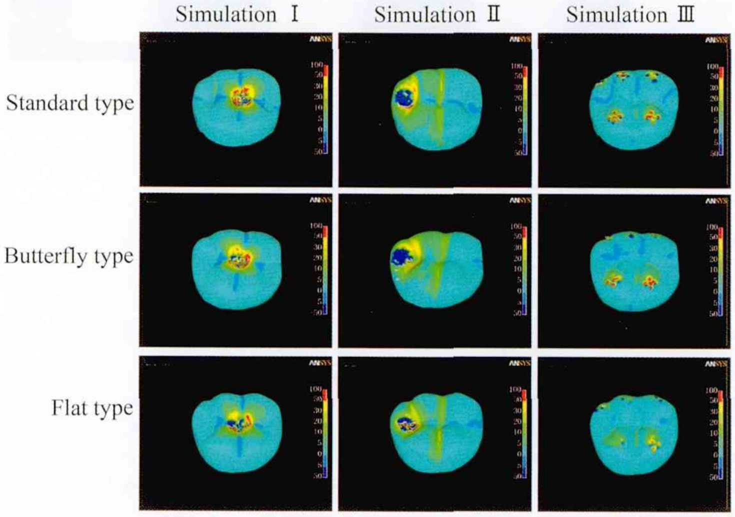


Fig.4 : Stress distribution in the porcelain layer. Areas of concentrated stress in the porcelain layer can be seen around the loading areas in all three loading conditions. In simulation Ⅰ, the maximum tensile stress values in the porcelain layer were high for all three types of coping (60 MPa), which is close to the maximum tensile stress value for porcelain (65–75MPa). In simulation Ⅱ and Ⅲ, the maximum tensile stress placed on the porcelain layer was highest in the standard type.

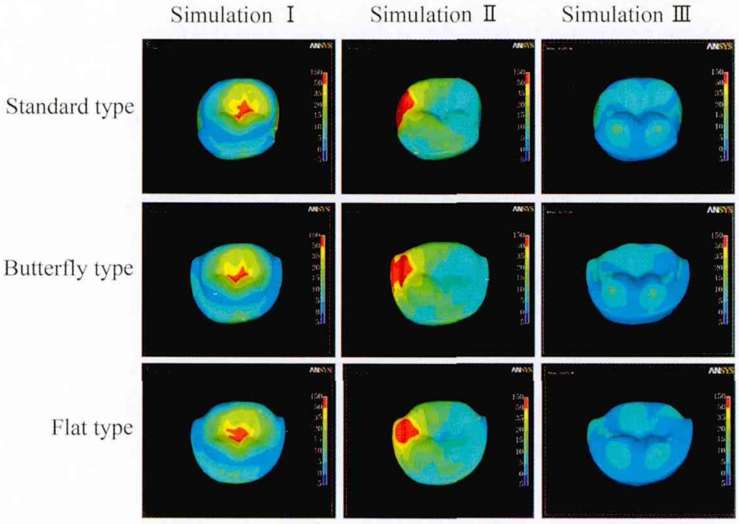


Fig.5 : Stress distribution within metal copings. Concentrated stress within the metal copings can be seen around the loading areas in the three loading conditions. The maximum von–Mises stress values within the different metal copings were all lower than 130MPa, which is far lower than the maximum von–Mises stress value for Co–Cr (500MPa). In the three simulations, the maximum von–Mises stress value within the metal copings was highest for the standard type and lowest for the butterfly type.

In simulations I and Ⅱ, the maximum von-Mises stress values for the butterfly type metal coping were 72.43MPa and 110.12MPa, which were lower than those of the standard type (82.97MPa and 120.84MPa) and the flat type (76.83MPa and 115.65MPa). In simulation Ⅲ, the maximum von-Mises stress values were similar among the three coping designs (Fig. 5).

Discussion

The concept of obtaining more desirable physical properties by combining brittle and elastic materials has been focused on in material technology for a long time. Dental porcelain is able to resist compressive loading but succumbs to tensile stress. Therefore, the metal substructure must be designed so that the tensile stress placed on the porcelain layer is minimized ; hence, the design of the metal coping is vital for enhancing the fracture resistance strength of the porcelain layer.

In our previous study, it was illustrated that when the mesio-distal proximal surfaces of the metal coping protrude, the stress distribution was optimized, and the tensile strength of the porcelain layer in a mandibular first molar model was enhanced4). However, in this model, the occlusal surface was modeled as a simplified flat surface, and the load simulation only involved vertical loading, so the stress distribution in metal ceramic crowns subjected to masticatory force could not be fully simulated. In this study, a more realistic metal ceramic crown was prepared based on a standard first right mandibular molar and scanned with micro CT10). A 3D numerical model was established with the use of modeling software, and finite element analysis was used to evaluate the stress distribution in crowns with various coping designs. Additionally, the maximum occlusal force (load simulations I and Ⅱ) and masticatory force (load simulation Ⅲ) were simulated, so the stress distribution in metal ceramic crowns under different load conditions was well reflected.

The results of this study showed that the maximum tensile stress in the porcelain layer was not concentrated at the metal-ceramic interface, but rather at the area of the surface closest to the loading areas. This was because the loads were applied to a curved circular depressive region composed of cusps, pits, and fissures and extended horizontally across the occlusal surface (in the x or y direction). Once a stress approaches or exceeds the limit of tensile stress for porcelain, the structure of the loaded area may be weakened, and hence, porcelain fractures could occur, as is commonly seen in clinical practice.

In simulation Ⅱ (as shown in Fig.6), the maximum tensile stress in the porcelain of the crown containing the standard type coping was highest (66.74MPa), which is close to the maximum tensile stress value for porcelain (65-75Mpa)11). However, it was lowest (46.63Mpa) in the crowns containing the butterfly type, followed by those containing the flat type coping (58.19Mpa), which were 30.1% and 12.8% lower than the values of the standard type. In simulations I and Ⅲ, while there was not much difference among the three coping types, the maximum tensile stress of the standard type was still a bit higher. We found that the butterfly and flat type metal copings supported the porcelain in the occlusal marginal areas. In these copings, the metal ceramic horizontal interface region was expanded, enlarging the area bearing and distributing the stress. As a consequence, the stress concentration in porcelain was reduced, the strengths of the porcelain layer and the metal-ceramic interface were enhanced, and the fracture resistance strengths of the mesio-occlusal and distal-occlusal marginal areas were also improved.

As metal is an elastic material, controlling the von-Mises stress, which represents its yield strength, is effective at enhancing the structural strength of the metal-ceramic interface and in-

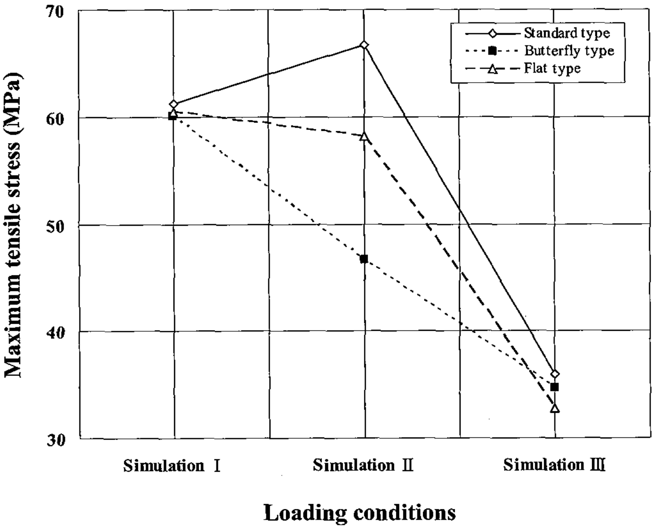


Fig.6 : The maximum tensile stress values for the porcelain layer. The maximum tensile stress values in the porcelain layer for the butterfly and flat type copings were lower than that of the standard type under all three loading conditions.

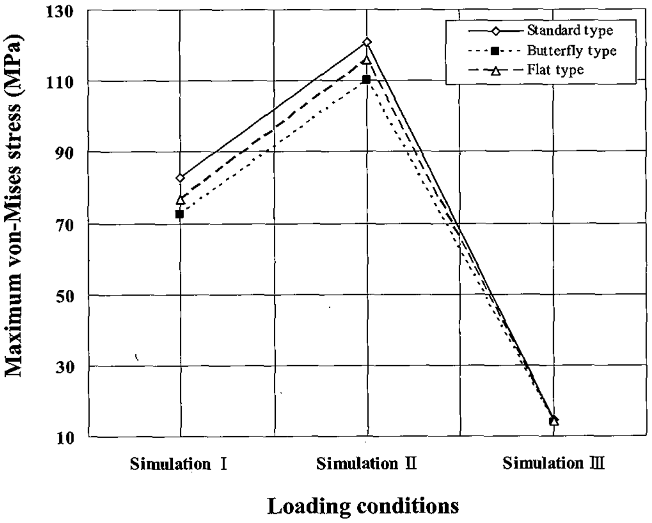


Fig.7 : The maximum von–Mises stress values for metal copings. The maximum von–Mises stress values for the butterfly and flat type metal copings were lower than that of the standard type under all three loading conditions.

creasing the fracture resistance strength of porcelain[12]. It was shown in this study that the von–Mises stress place on the metal copings was concentrated at metal–ceramic interface. As shown in Fig.7, the von–Mises stress was highest in the standard type coping, but lowest in the butterfly type coping under the same loading conditions. It was found that the use of butterfly metal copings results in less von–Mises stress being placed on the metal copings and optimizes the structural strength of the metal–ceramic interface.

Conclusion

In this study, the stress distributions in metal ceramic crowns with different metal coping designs were examined under various loading conditions using three–dimensional finite element analysis (3 D FEA). Different contact areas and forms were found among the different metal coping designs, and the stress distribution in the porcelain layer was also affected by the coping design. Despite the limitations of this study, it was found that butterfly copings reduce the stress distribution in the porcelain layer and optimize the structural strengths of the mesial and distal occlusal marginal areas. It was concluded that the butterfly coping design is an excellent and practical option for metal coping manufacture.

Acknowledgements

This project was supported by the National Natural Science Foundation of China (Grant No.10772111), the Shanghai Natural Science Foundation of China (Grant No.10 ZR 1423400) and Shanghai Municipal Health Bureau (Grant No. 08176).

References

1) Li X, Wang Z, Zhang W, Shao W, Zhou Z and Gong S (1998) Long–term observation of 1232 porcelain fused to metal prostheses. J Pract Stomatol **14** : 199–201.

2) Zhu H and Chen C (2006) The analysis of the failure of 198 porcelain fused to metal crown. Chin J Prosthodont **7** : 269–70.

3) Rosenstiel SF, Land MF and Fujimoto J (2001) Contemporary Fixed Prosthodontics. 3rd Ed., 488–512, Mosby Inc.,USA.

4) Wang R, Wang X, Xu Y and Hua Z (2000) Investigation of Fracture Strength of the Centre and the Margin of the Porcelain on the Occlusional Surfaces of Metal–ceramic Crowns. Stomatology **20** : 76–7.

5) Magne P (2007) Efficient 3D finite element analysis of dental restorative procedures using micro–CT data. Dent Mater **23** : 539–48.

6) Wang R, Li X, Yang J, Xu Q, Xu, Q, Yang Q, Hu Q and Miyazawa H (2007) Influences of metal frame design on the mechanical strength of posterior porcelain fused to metal crown. Matsumoto Shigaku **33** : 299–312.

7) Zhang D, Lu C, Zhang X, Mao S and Arola D (2008) Contact fracture of full–ceramic crowns subjected to occlusal loads. J Biomech **41** : 2995–3001.

8) Lundgren D and Laurell L (1986) Occlusal force pattern during chewing and biting in dentitions restored with fixed bridges of cross–arch extension. I. Bilateral end abutments. J Oral Rehabil **13** : 57–71.

9) Gibbs CH, Mahan PE, Lundeen HC, Brehnan K, Walsh EK and Holbrook WB (1981) Occlusal forces during chewing and swallowing as measured by sound transmission. J Prosthet Dent **46** : 443–9.

10) Terakado M, Hashimoto K, Arai Y, Honda M, Sekiwa T and Sato H (2000) Diagnostic imaging with newly developed ortho cubic super–high resolution computed tomography (ortho–CT). Oral Surg Oral Med Oral Pathol Oral Radio Endod **89** : 509–18.

11) Nagasawa S, Yoshida T, Mizoguchi H, Ito M and Oshida Y (2001) Porcelain–metal bonding : part Ⅰ. Effects of repeated baking process. Biomed Mater Eng **11** : 185–95.

12) Miranda P, Pajares A, Guiberteau F, Cumbrera FL and Lawn BR (2001) Contact fracture of brittle bilayer coatings on soft substrates. J Mater Res **16** : 115–26.

抄録：三次元有限要素法を用いた臼歯陶材焼付鋳造冠におけるメタルコーピング形態の力学的検討

汪　饒饒[1]，李　憲起[2]，徐　遠志[1]，楊　启祥[1]，王　丹[1]，
劉　斌[3]，張　東升[3]，楊　静[4]，宮沢裕夫[4]
[1]（同済大・付属上海第十人民医院・口腔医療保健センター）
[2]（松本歯大・総歯研・疾患制御）
[3]（上海大・工学部）
[4]（松本歯大・総歯研・健康増進）

【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コーピング形態を模索すべく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付与し，臨床的に適切なデザインを検討した．

【方法】解析モデルは下顎第一大臼歯陶材焼付鋳造冠とし，その解析には三次元有限要素法を用いた．メタルコーピングのデザインは標準型，蝶形型とフラット型の三種類とした．負荷条件は食物摂取時を想定し，円形の領域荷重とし，クラウンの中心窩と近遠心側部垂直方向に600N，咬頭部は歯軸に対し45度の角度に225Nの負荷を与えた．

【結果】クラウンとコーピングの負荷領域に最大応力が生じた．クラウンの近遠心部垂直負荷の場合には，蝶形型では最小引張応力が生じた．

【結論】従来の形態に比べ，蝶形型コーピングを用いることより，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．