Combining structural-thermal coupled field FE analysis and the Taguchi method to evaluate the relative contributions of multi-factors in a premolar adhesive MOD restoration

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Abstract

This study investigates the biomechanical interactions among restorative material, cavity dimensions, adhesive layer adaptation, and load conditions on the biomechanical response of an adhesive Class II MOD restoration during oral temperature changes. A validated finite-element (FE) model was used to perform the structural-thermal coupled field analyses and the Taguchi method was employed to identify the significance of each design factor in controlling the stress. The results indicated that thermal expansion in restorative material amplified the thermal effect and dominated the tooth stress value (69%) at high temperatures. The percentage contributions of the load conditions, cavity depth, and cement modulus increased the effect on tooth stress values 46, 32, and 14%, respectively, when the tooth temperature was returned to 37°C. Load conditions were also the main factor influencing the resin cement stress values, irrespective of temperature changes. Increased stress values occurred with composite resin, lateral force, a deeper cavity, and a higher luting cement modulus. This study identified that a deeper cavity might increase the risk of a restored tooth fracture, as well as a ceramic inlay with a lower thermal expansion, attaining a proper occlusal adjustment to reduce the lateral occlusal force and low modulus luting material application to obtain a better force-transmission mechanism are recommended.

Keywords: finite element analysis; thermal; Taguchi method; MOD restoration; biomechanics

1. Introduction

Losses of tooth structure require a restoration to approach the tooth's original strength. Indirect composite and ceramic restorations could present advantages of better anatomic contour and proximal contact, improved polishing, a higher degree of conversion, better aesthetics, and are employed instead of conventional metal inlays.[1] However, the high potential for failure of a MOD restoration drive these indirect restorative materials to meet a number of restorative considerations, such as cavity preparation design, adhesive layer adaptation, oral environment (thermal stress), and physiologic condition, in order to withstand the rigors of mechanical complications. Therefore, restoration evolution may need to include optimizing the many interacting restorative factors that relate to the stress-strain behavior of restored teeth. Accordingly, the aim of this study used FE analysis to investigate the mechanical interactions of the Class II MOD adhesive restored system in multi-factorial parameters (restorative materials selection, cavity preparation design, adhesive layer adaptation, and load condition) with different levels under transient structure-thermal coupled-field analysis. The Taguchi method was used to identify the importance of each parameter on a different oral temperature environment and suggests an optimized biomechanical response for adhesive Class II MOD restoration.

2. Materials and Methods

Factorial design

Using a full factorial approach, a total number of total number 128 analyses (2^7) were required. In this study, Taguchi method was used to reduce the number of analyses. Only eight simulations (L_8) were required. (Table 1).

Table 1- Investigated parameters and Taguchi method levels

Investigated factor	Levels	
	Level 1	Level 2
Restorative material	CAD/CAM ceramic	Composite
Cavity depth	1/2 Buccal cusp-gingiva	3/4 Buccal cusp-gingiva
Cavity isthmus width	1/2 Intercuspal width	2/3 Intercuspal width
Cavity interaxial thickness	1/2 Mesio-distal	1/3 Mesio-distal
Resin cement thickness (μm)	50	100
Resin cement modulus (MPa)	6000	10,000
Load condition	Axial (200N)	Lateral (200N)

FE model generation and validation

A maxillary upper second premolar plaster model was employed as a specimen to be the external shape definition. Using laser scanning obtained surface points of the specimen, and then collected and assembled in a 3D wire-frame structure using a 3D CAD system (Pro/Engineer 2001; Parametric Technology Co., Waltham, MA, USA). The 3D curves were exported in ANSYS, version 11.0 (Swanson Analysis Inc., Houston, PA, USA) to create the volume. The enamel, dentin, and pulpal region volumes were defined according to the literature data. The volumes of the periodontal ligament (PDL; 0.25mm) and alveolar bone (cortical and cancellous) were also created. Two MOD preparation designs were generated using a parametric cutting plane in the sound maxillary premolar (Table 1). All solid models were derived from a single mesh pattern. A parallel fundamental tension-compression experiment will be performed and the strains measured to validate the intact premolar simulation results.

Structure–thermal coupled simulation

Temperature variation with time was applied on the coronal surface nodes as the initial condition to perform the transient FE thermal (heat-transfer) analysis in ANSYS. The structural–thermal coupled analysis was performed to determine the corresponding thermal stress at each time. The axial load (case 1) applied on the tooth at two points on the cusps with the resulting force crossing the central position was 200 N and the lateral load (case 2) acting on the lingual cusp with a 45° inclination to the long axis of the tooth. The exterior nodes at the mesial, distal, and bottom surfaces of the alveolar bone were fixed in all directions as the boundary conditions. The maximum principal stresses in the remaining tooth and resin cement were recorded at time 1 (51°C), 8 (44°C), and 35 s (37°C) for each model in accordance with their material characteristics. The main effects of each level of the seven investigated factors on the mechanical responses at time 1, 8, and 35 s were computed. The data from the simulated results were analyzed using a general linear ANOVA test model using the MINITAB commercial statistical package, Version 12.23 (MINITAB Inc., USA).

3. Results and discussion

The restorative material (69%), load condition (15%), cavity pulpal wall depth (7%), and resin cement modulus (7%) determined the magnitude of the stress values at high temperature (51°C) at time 1 s. The percentage contributions of the load conditions and cavity depth increased gradually with a decrease in tooth temperature. In contrast, the relative importance of restorative material became unimportant when the tooth temperature returned to 37°C. At this temperature, the load condition (46%) and cavity depth (32%) were the most important factors affecting the remaining stress values. The main effect of the luting cement thickness, cavity isthmus width, and cavity interaxial thickness had no significant effect for the tooth stress values. For the resin cement stress values, the results indicated that the cavity pulpal wall depth and the load condition increased the relative significance from 24% to 30% and 41% to 48% with decreasing tooth temperatures, respectively. In contrast, the percentage contributions of the resin cement modulus decreased from 27% to 18% with a decrease in tooth temperature from 51 to 37°C. The maximum stress distributions for the remaining tooth and resin cement for load case 1 (axial), both concentrated at the top of the buccal walls. The corresponding locations for the remaining tooth and resin cement for load case 2 (lateral) were both at the top of the lingual walls.

4. Conclusions

Using Ceramic inlay, lower modulus luting material, attaining proper occlusal adjustments to reduce the lateral occlusal force, and reducing cavity depth are recommended.

5. Reference

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6. Acknowledgements

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