THREE-DIMENSIONAL BIOMECHANICAL STUDY OF FUNCTIONAL STRESSES IN COMPOSITE RESTORATIONS OF MASTICATORY TEETH

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ABSTRACT

OBJECTIVE: The aim of the present work was to study and evaluate the intensity of stresses in the adhesive bond in composite restorations of masticatory teeth after light-curing, under temperature changes and masticatory loads.

MATERIALS AND METHODS: Data for the 3D model generation of a maxillary premolar were obtained during a routine CT head scan. Thirty-three cross-sections of tooth 25 were selected and used to create a 3D geometric model enmeshed using the finite element method (FEM) (made up of 106556 elements and 608724 nodes). The pulp cavity and the periodontal ligament were constructed in the same way and integrated into the premolar model. Eight cavity configurations with converging walls were designed, resistant to masticatory forces (enamel/dentin = 1/1). A comparative computer simulation was carried out of the polymerization shrinkage forces of the composite material (CM), temperature changes in the oral cavity and functional masticatory loads. The distribution of the generated stress on the adhesive bond was evaluated in eight different class I and II cavity configurations. The location of crack formation was assessed in the cases of rupture of the adhesive bond.

RESULTS: In all cavity configurations, stress concentration in the adhesive layer is higher at the interface with the dental tissues. Low temperatures (5 °C) generate forces that are greater than the strength of the adhesive bond in all studied cavity configurations. The distribution of the generated stresses under the effect of axial and tangent forces of 300 N is similar to that under the effect of temperature factors. The axial masticatory forces have a pronounced adverse effect on the adhesive bond in all cavity configurations.

CONCLUSIONS: Low temperatures and axial masticatory forces play an important role for the marginal integrity. They exacerbate the adverse effects of polymerization shrinkage in composite restorations of masticatory teeth.

Key words: finite element method, functional loads, composite restorations

INTRODUCTION

The finite element method (FEM) is used as in the biomechanical testing of adhesion bond in composite restorations. It is a high-tech, modern, highly reproducible and non-invasive technique for studying biomechanical behaviour of restored teeth. It could be used to analyze stresses generated after light-curing of composite restorations, and the impact of temperature changes and masticatory loads. The ability to re-create the conditions in the oral cavity during chewing makes FEM a prognostic and evaluation tool. By splitting, zooming and rotating the mathematical model, detailed information can be obtained about the mechanism of transmission and distribution of the loads applied to the hard dental tissues (HDT)-adhesive-composite material (CM) interfaces, which remain “hidden” in a clinical situation. Its advantage is related to the possibility of establishing the influence of a combination of interrelated factors that optimally re-create the clinical situation: the mechanical characteristics of the restorative material, cavity geometry and interface conditions (adhesive bond quality). An undisputed advantage of this method is the three-dimensional (3D) representation of the studied variables. The visualized results obtained by colour mapping and animated simulations of residual stresses and deformations facilitate the perception of cumbersome mathematical data.

AIM

The aim of the present work was to study and evaluate the intensity of stresses in the adhesive bond in composite restorations of masticatory teeth after light-curing, under temperature changes and masticatory loads.
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MATERIALS AND METHODS

Data for a 3D model generation of a maxillary premolar were obtained during a routine CT head scan. Thirty-three selected cross-sections of tooth 25 were used to create a 3D geometric model meshed using FEM (made up of 106566 elements and 608724 nodes). The pulp cavity and the periodontal ligament were constructed in the same manner and integrated into the premolar model.

Eight cavity configurations were designed:

Three class I cavities: one with a restricted design (model A2), and two classically shaped, corresponding to a moderate (model A) and deep (model A1) carious process.

Three class II MO cavities: one with a restricted design (model B2) and two classically shaped, corresponding to a moderate (model B) and deep (model B1) carious process.

Two class II MOD classically shaped cavities corresponding to a moderate (model C) and deep (model C1) carious process.

Classical preparations have converging walls, resistant to masticatory forces (enamel/dentin = 1/1). The external cavity edges were not bevelled and all internal corners were rounded.

The modelled adhesive layer and restoration reproduced the hybrid zone of our clinical study on composite restorations of class I and II carious lesions with one step self-etch adhesive (Adper Prompt L-Pop, 3MESPE) and a three-step system (Adper Scotchbond Multi Purpose, 3MESPE).

The FEM-generated maxillary premolar, pulp cavity, periodontal ligament, adhesive layer and composite restoration were integrated into a single model for each of the eight cavity configurations.

The results obtained in this study are consistent with data by other authors, therefore they allow us to consider the model as realistic and to use it in the studies of polymerization shrinkage stresses and deformations of the composite material in adhesive restorations.

A comparative computer simulation was performed of the polymerization shrinkage forces of the composite material, temperature changes in the oral cavity and functional masticatory loads. The distribution of the stresses generated in the adhesive bond in eight different class I and II cavity configurations was investigated. The location of crack formation in the case of adhesive bond rupture was assessed.

RESULTS

INFLUENCE OF TEMPERATURE CHANGES IN THE ORAL CAVITY ON THE ADHESIVE BOND

Figures 1, 2 and 3 present the stress distribution in the adhesive bond as a result of temperature changes in the oral cavity. In all cavity configurations, the stress concentration in the adhesive layer is greater at the interface with the dental tissues. Low temperatures (5 °C) generated greater forces than the adhesive bond strength in all studied cavity configurations. The stresses arising from the effect of higher temperature (55 °C) were smaller and were concentrated on smaller areas.

INFLUENCE OF MASTICATORY FORCES ON THE ADHESIVE BOND DURING FUNCTIONAL LOADING

The effect of axial and tangent forces of 300 N (Figs 4, 5, 6) was studied. The distribution of the generated stresses was similar to the effect of temperature factors. The axial masticatory forces had a pronounced adverse effect on the adhesive bond in all cavity configurations.

DISCUSSION

The effects of stress concentration in the cavity walls depend on the adhesive bond strength. Literature offers various information about its tensile strength in single-component adhesives and in adhesives with a separate etching step. According to Van Meerbeek, B. et al., it is 26 MPa and 55 MPa, respectively. Barmeier W and Cooley R found that bond strength to enamel was from 15.5 (± 3.0) to 23.7 (± 5.6) MPa. In an analysis of 50 tests of dentin bond strength, Al-Salehi S, et al. report an average tensile strength of 9.20 MPa (± 6.25) and shear strength of 12.97 MPa (± 6.29). The 60 MPa stresses established in this study in the described areas exceed the strength of the adhesive bond. In shallow and narrow class I and II MO and MOD cavities, there is a risk of micro-crack formation with clinical effects of permeability and secondary caries. In wide and deep cavity configurations (models A1, B1, C1), stress concentration at the side of dentin is smaller and the adhesive bond is maintained. Stress concentrations are larger in the HDT. In restricted, pear-shaped class I and II cavities (models A2 and B2), the forces resulting from post-polymerization stresses are smaller than the strength of the adhesive bond with HDT and CM. These configurations afford the most suitable...
conditions for a stable bond with the cavity walls and the restoration.

Low temperatures and axial masticatory forces generate stresses that exceed the adhesive bond strength at the enamel-dentin interface in all cavity configurations. These factors are important for the progress of micro-crack formation between the adhesive layer and cavity walls resulting from the concentration of post-polymerization stresses. They can be viewed as aggravating circumstances that augment the adverse effects of polymerization shrinkage of composite restorations of masticatory teeth.

In all configurations, the cavity corners and enamel walls are the locations of the highest stresses. In the eight generated cavities, there is a favourable stress distribution in the adhesive bonding with the composite material.

The cavity configuration determines the number of free non-bonded walls and therefore the number of walls participating in the adhesive bonding. The ratio between the two types of walls of each cavity determines its C-factor (factor of cavity Configuration or factor of Contraction stress).

$$C = \frac{\text{all bonded walls}}{\text{all unbonded walls}}$$

The configuration factor shows the extent to which

![Figure 1](image1.png)

**Figure 1.** Distribution of stresses due to temperature changes in the adhesive layer in models A, A1 and A2

![Figure 2](image2.png)

**Figure 2.** Distribution of stresses due to temperature changes in the adhesive layer in models B, B1 and B2

![Figure 3](image3.png)

**Figure 3.** Distribution of stresses due to temperature changes in the adhesive layer in models C and C1.
the cavity walls will limit the fluidity of CM and its ability to compensate for the polymerization stress. Established by Bowen R in 1967, experimentally demonstrated by Feilzer A, et al. the C-factor is a commonly accepted criterion for predicting post-polymerization stress. In box-like class I cavities, the CM bonds to five walls. Only one composite surface remains free to compensate by its fluidity the stresses occurring during polymerization. The C-factor in this case is \( \frac{5}{1} = 5 \) provided that all cavity walls are of the same area. Class V cavities have lower C-factor between 1.5 and 3, depending on their design. Most class II and III cavities have a C-factor between 1 and 2, while in class IV cavities the C-factor is \( \leq 1 \). The fewer cavity walls are involved in a composite restoration, the less residual stress will occur. If two cavities have the same size but different design, the one that is deeper and with a more irregular geometry will have a higher C-factor. From a clinical point of view, all cavity preparations with few unbonded walls run a potentially higher risk of polymerization shrinkage. The effects of residual stresses in the tooth-restoration system depend on the adhesive bond strength. The stronger the bond, the higher the degree to which the stresses concentrate in the
cavity walls, become deformed, and the greater the likelihood for post-operative sensitivity to occur.\textsuperscript{10-13} In recent years, a number of researchers\textsuperscript{12-15} challenged the role of the C-factor as the sole criterion determining stresses and deformations occurring after polymerization. In support of this view, the authors applied the following data: when compared, small and large class I cavities with nearly similar C-factor showed significant differences in the stresses at the interface layer. The C-factor of large class I cavities is much bigger than that of class II MOD configurations, but the stress levels are almost identical. The latter cavities, which clearly have a more favorable C-factor compared to small MOD cavities, generate significantly higher residual stress.

The present study confirms these results. It was found that, compared to deep and wide class I configurations (model A1), with almost the same C-factor (5.4 and 4.7, respectively), in shallow and narrow cavities (model A) there are large differences in the levels of equivalent stresses in the interface layer. The C-factor (4.7) of large class I cavities (model A1) is much bigger than that of wide and deep class II MOD cavities (model B1, C = 1.5), however, the stress levels are almost identical. Cavity shapes (model C) with an obviously more favorable C-factor (1.5) in comparison with model A1 (4.7) generate stronger residual stresses. In the cavity configuration (model A2) with the highest C-factor (7.6), the most favourable stress distribution was established in the adhesive bond to the cavity walls and CM.

CONCLUSIONS

A weak point in the distribution of stresses after polymerization at the level of the hybrid layer in class I and II cavity shapes is the bond between the adhesive and the cavity walls.

In shallow and narrow class I and II MO and MOD cavities, there is a risk of rupture of the bond with the cavity walls and formation of a micro-crack.

In wide and deep cavity configurations (models A1, B1, C1), the stress concentration at the dentin side is smaller and the adhesive bond is maintained. Stresses are concentrated mostly in the HDT.

In restricted, pear-like class I and II cavities are the most suitable conditions for a strong bond with the cavity wall and the restoration.

Low temperatures and axial masticatory forces play an important role for the marginal integrity. They exacerbate the adverse effects of polymerization shrinkage in composite restorations of masticatory teeth.

REFERENCES

ЗД БИОМЕХАНИЧЕСКОЕ ИССЛЕДОВАНИЕ ФУНКЦИОНАЛЬНЫХ НАПРЯЖЕНИЙ В ОБТУРАЦИЯХ ИЗ КОМПОЗИТНОГО МАТЕРИАЛА НА ЖЕВАТЕЛЬНЫХ ЗУБАХ

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РЕЗЮМЕ

Цель: Настоящее исследование ставит себе цель изучить и определить величину напряжений в адгезивной связке при композитных обтурациях на жевательных зубах после фотополимеризации, температурных изменений и жевательных нагрузок.

Материалы и методы: Данные о создании 3D модели верхнего премоляра получены при рутинном компьютерном томографическом исследовании головы. Из селектированных 33 поперечных срезов на 25 создана геометрическая модель, покрытая сетью посредством метода конечных элементов (из 106 556 элементов и 608 724 узлов). Аналогичным способом созданы пульпарная полость и периодонтальный лигамент и интегрированы в модель премоляра. Конструировано 8 кавитетных конфигураций с конвергирующими стенками, резистентными к жевательным силам (эмаль/дентин = 1/1). Осуществлена сравнительная компьютерная симуляция сил полимеризационного сжатия композитного материала, температурных изменений в полости рта и функциональных жевательных нагрузок. Исследовано распределение генерированных напряжений на адгезивную связку при восьми различных I и II класса кавитетных конфигурациях. Исследовано и место формирования щели в случаях разрыва адгезивной связки.

Результаты: При всех кавитетных конфигурациях концентрация напряжений в адгезивном слое более высокая по поверхности соприкосновения со зубными тканями. Низкие температуры (5 °С) генерируют силы, более большие по сравнению с прочностью адгезивной связки при всех исследованных кавитетных конфигурациях. Распределение генерированных напряжений при воздействии аксиальных и косых сил величиной 300 N аналогично с этим при воздействии температурных факторов. Аксиальные жевательные силы оказывают неблагоприятный эффект на адгезивную связку при всех кавитетных конфигурациях.

Выводы: Низкие температуры и аксиальные жевательные силы имеют важную роль для маргинального интегритета. Они усиливают неблагоприятные эффекты от полимеризационного сжатия при композитных обтурациях на жевательных зубах.