

INFLUENCE OF THE CAVITY SHAPE IN RESTORATIVE DENTISTRY ON THE STRESS-STRAIN DISTRIBUTION IN DENTINE AND ENAMEL CAUSED BY POLYMERIZATION

UTICAJ OBLIKA KAVITETA U RESTORATIVNOJ STOMATOLOGIJI NA RASPODELU NAPON-DEFORMACIJA U DENTINU I GLEĐI IZAZVANOJ POLIMERIZACIJOM

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Keywords

- cavity shape
- FEM
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- stress-strain distribution
- DIC

Abstract

In restorative dentistry it is common practice to replace amalgams with resin based dental composites, with minimal or no additional cavity preparation. Polymerization shrinkage of dental composites causes stress, whose influence is transferred to tooth tissue which may result in the occurrence of micro-cracks and post-operative pain. The aim of this study is to determine the effects of different cavity shapes on stress and strain distribution which occurred due to composite shrinkage. Toward this aim, experimental (Digital Image Correlation method – DIC) and numerical (finite element method – FEM) techniques are used. The numerical model is verified by comparing its results with those obtained by experimental methods. Upon verification, the 3D model of the cavity is modified to develop two new models with the same tooth geometry, but different cavity shapes, in order to determine the effect of their shapes on stress distribution. It is determined that the thickness of dentine around the cavity plays a significant role in stress and strain distribution.

INTRODUCTION

Increased use of polymer composites as dental fillings lead to a great number of cases where existing amalgam fillings are replaced by dental composites, /1/. In dentistry, it is common practice to replace amalgams with composites, with minimal or no additional cavity preparation. Since cavity shape preparation depends on the material used for filling, sharp cavity angles in accordance with Black's principle can influence the modified stress and strain distribution, compared to adhesive cavity type. In

Ključne reči

- oblik kaviteta
- metoda konačnih elemenata (FEM)
- polimerizacijski napon
- raspodela napon-deformacija
- korelacija digitalnih slika (DIC)

Izvod

U restorativnoj stomatologiji je učestala praksa zamene amalgama stomatološkim kompozitima na bazi smole, uz minimalnu dodatnu pripremu kaviteta ili bez nje. Polimerizacijsko skupljanje stomatoloških kompozita prouzrokuje napon, čiji se uticaj prenosi na zubno tkivo, što može dovesti do pojave mikroprslina i postoperativnih bolova. Cilj ovog rada je da se odredi uticaj različitih oblika kaviteta na raspodelu napona i deformacija, izazvanih skupljanjem kompozita. U tu svrhu su korišćene eksperimentalna metoda korelacije digitalnih slika (DIC) i numerička metoda konačnih elemenata (FEM). Numerički model je verifikovan poređenjem rezultata proračuna sa rezultatima dobijenim eksperimentalnom metodom. Nakon verifikacije, postojeći 3D model kaviteta je modifikovan u cilju dobijanja dva nova modela sa istom geometrijom zuba i različitim oblicima kaviteta, kako bi se odredio uticaj ovih oblika na raspodelu napona. Utvrđeno je da debljina dentina oko kaviteta igra značajnu ulogu u raspodeli napona i deformacija.

dental practice, adhesive cavity refers to cavity preparation using round borers, for the purpose of obtaining rounded corners between lateral walls and the bottom of the cavity. The main reason for this approach is the micro-mechanical and chemical bond between aesthetic material and tooth tissue, which excludes the need for rectangular preparation according to Black, necessary for metal fillings in order to achieve macro-mechanical retention, /2/. Available scientific literature contains barely any data on experimental analysis of cavity shape change influence on stresses caused by composite shrinkage. In this paper, the behaviour

of tooth tissue-adhesive-composite systems subjected to load is analysed in a multidisciplinary manner, using experimental and finite element methods.

The method for three-dimensional optical strain and displacement analysis is based on digital image correlation (DIC). The system records the measured object before, during and after the load has been applied. Measuring does not depend on the type and dimensions of the object being measured. DIC is widely applied in experimental mechanics, [3-11], and is frequently used for verifying results obtained by FEM, [10].

FEM is a modern numerical method based on developing and discretizing a numerical model based on a physical one. FEM is used for the design and calculation of structures and elements, by solving continuum mechanics problems using computers [12-15]. It can be viewed as a process of dividing a numerical model into a finite number of smaller elements with simpler geometry, physical properties and finite dimensions. Elements are mutually connected by nodes. Shape and size of elements is determined depending on the complexity of the model and the required accuracy. Based on given mechanical properties, boundary conditions and loads, FEM calculates the displacement field in every node. The stress and strain within the model are then determined based on these displacements.

Values of composite shrinkage typically depend on the type of filler and resin, and their ratio, [16, 17]. Composite shrinkage occurs as a consequence of monomers bonding into polymer chains, during which initial inter-molecular distances between monomers decrease. Risk of failure of composite-adhesive-tooth bond occurs due to the appearance of shrinkage stresses, i.e. due to the composite acting with tensile forces on cavity walls. It is assumed that, because of stiffness and shape of the tooth due to shrinkage, an increase in stress on boundary surfaces between the tooth and filling will occur. Boundary tooth surfaces in cavities are subjected to high stress concentrations, especially in locations of considerable changes in geometry since, due to its mechanical properties, the tooth tends to maintain its initial shape.

The aim of this paper is to compare the effects different cavity shapes on stress and strain distribution in cavities with 1 mm radius at corners (adhesive cavity shape), rectangular shaped cavities according to Black and cavities with undercut lateral sides (pear-shaped cavity).

MATERIALS AND METHODS

An intact human third molar, extracted for orthodontic purposes, is used for the digitalization of a tooth model. Root of the tooth is submerged in an acrylic base up to the enamel-cement border in order to ensure easier positioning and placing, along with easier manipulation during the experiment. The occlusal and mesial tooth surfaces are cut flat upon which the modified class II cavity is prepared. Such approach enables composite shrinkage from the occlusal direction, as well as experimental measuring of the displacement from the axial direction. The cavity is made using a CNC cutting machine, using a rounded cutter with a diameter of 2 mm (Fig. 1). Dimensions and shape of cavities are shown in Fig. 2. After cavities have been made, a 37% orthophosphoric acid is applied for a duration of 15 s to the tooth and the adhesive system Excite F is then applied which is dispersed using a mild stream of air and is polymerized for 10 s.

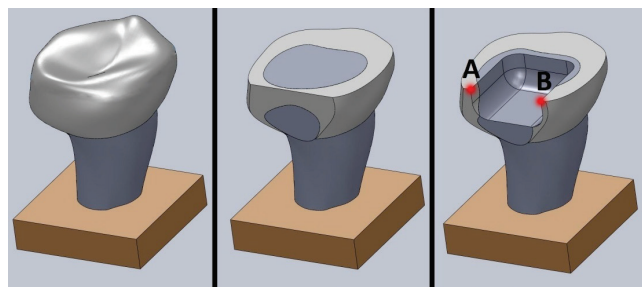


Figure 1. Left: root implanted in acrylic resin; centre: cut top and lateral surface; right: prepared cavity.

Slika 1. Levo: koren smešten u akrilnoj smoli; sredina: odsečena gornja i bočna površina; desno: pripremljen kavitet

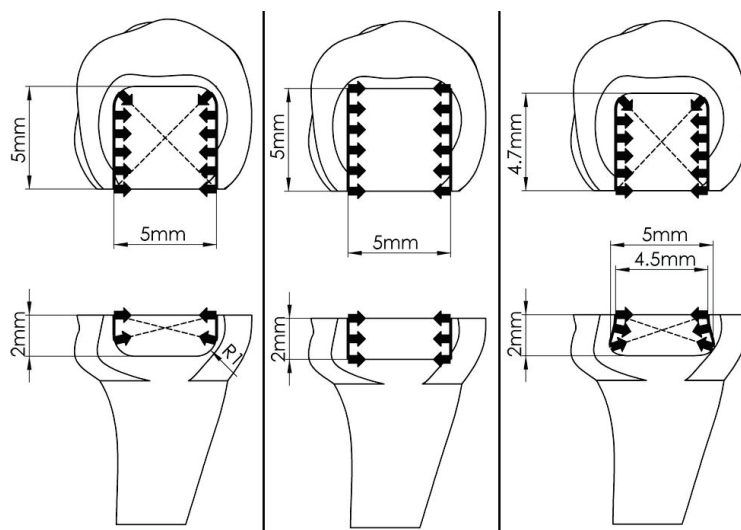


Figure 2. Left: model 1 - round corners; centre: model 2 - sharp corners; right: model 3 - undercut corners.

Slika 2. Levo: model 1 - zaobljene ivice; sredina: model 2 - oštre ivice; desno: model 3 - zasečene ivice

A nano-hybrid composite Tetric EvoCeram (Ivoclar Vivadent, Schaan, Liechtenstein) is applied to the cavity in a single layer using a plastic instrument 'number six'. In addition, a transparent celluloid matrix is used in the area where the approximal wall is missing. Excess material from the occlusal part of the cavity is removed using the same dental instrument.

Experimental measuring is performed using a DIC system which consists of the software package Aramis, a sensor unit, a stand, a PC, lights and a trigger box, /5/. According to manufacturer's instructions, prior to measuring, preparation of the specimen by means of applying a stochastic pattern, as well as system calibration is performed for measuring a volume of 15×11×1.9 mm. Before and after shrinkage, displacement between upper opposite cavity walls (A and B, shown in Fig. 1 - right) is measured.

For the purpose of developing the models, images are placed in 3D space and sketches of cross sections are made. All of the sketches are made according to the images taken from different cross sections, during the cutting of a tooth, after which they have been turned into vector projections used for developing sketches. Only relevant cross sections are taken into account. Figure 3 shows one of the cross sections at the depth of 1.2 mm from the top surface, and the sketch created from it. The inner sketch is used for defining the dentine, and the outer for the enamel.



Figure 3. Cross-section of tooth with dentine and enamel.
Slika 3. Poprečni presek zuba, dentina i gleđi

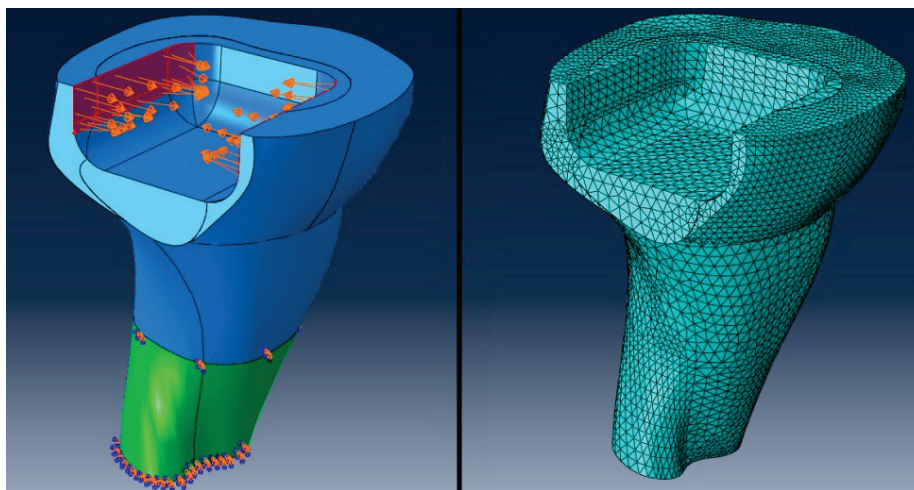


Figure 4. Left: load (red) and boundary condition (green), right: mesh.
Slika 4. Levo: opterećenje (crveno) i granični uslov (zeleno), desno: mreža

By using this method it is possible to define the border between enamel and dentine. The 3D model is developed using SolidWorks software. Sketches are connected using the loft command. By applying this approach, two separate bodies are modelled and material properties for different parts of the tooth are defined. Conversion of the 3D body to a numerical model is performed using Abaqus/CAE software, wherein the parts are made into an assembly.

Mutual influence between dentine and enamel is defined as a rigid contact for the purpose of transferring stresses and strain directly from one body to the other. Material properties are given in Table 1.

Table 1. Material properties of dentine and enamel, /18/.

Tabela 1. Osobine materijala dentina i gleđi, /18/

	Young's modulus (MPa)	Poisson's ratio
Dentine	18 600	0.31
Enamel	84 100	0.2

In order to verify the numerical model, the simulation is performed using parameters that are identical as in the physical experiment. The model is meshed using Tet elements due to irregular tooth geometry. The number of finite elements is 76264 in total, 44202 for dentine and 32062 for enamel, with 115899 nodes. Element size is defined according to model geometry. Selected size ensured the most optimal replication of the real model. Elements used for discretization of dentine are larger than those used for enamel due to the geometric shape. The boundary condition is defined as fixed in the bottom half of the root, in order to simulate a tooth wedged into acryl. Due to filler shrinkage kinetics, the load is applied only to surfaces that have an opposite surface. It is assumed that in case there are no opposite surfaces present, there will also be no shrinkage stresses, since the free surface of the composite could move without constraints. Rounded cavity surfaces in transition areas are divided into two zones: a zone which has a corresponding opposite side and a zone without one. The load is defined as pressure applied to parts of rounded surfaces, Fig. 4. Load, boundary conditions and mesh for the numerical model are also shown in Fig. 4.

Once the numerical model is verified, three independent models are made: Model 1 with rounded edges, $R = 1$ mm, as in the experiment; Model 2 with right angles, according to Black; and Model 3 with slightly undercut lateral sides, Fig. 2.

Tooth geometry is the same for all three models, along with material properties and boundary conditions. There are minimal differences in element size in the models, due to different cavity shapes. The load used is of the same magnitude, but is applied to different-sized areas depending on cavity shape, i.e. the area of opposite surfaces, Fig. 4. Cavity profiles and zones affected by the load are shown in detail in Fig. 2, for all three models.

Since the load is only applied to areas that have an opposite surface, these areas are: 19.7 mm^2 - Model 1; 16.9 mm^2 - Model 2; and 16.4 mm^2 - Model 3. The number of elements and nodes for each model is shown in Table 2.

Table 2. Numerical parameters / Tabela 2. Numerički parametri

	Model 1	Model 2	Model 3
Element No. (total)	76264	80381	80419
Element No. (dentine)	44202	48255	44931
Elements No. (enamel)	32062	32126	35488
Nodes No.	115899	122482	121974

RESULTS

Measuring determined that the displacement of opposite sides of the cavity due to polymerization stress is $4 \mu\text{m}$, Fig. 5. Load in the numerical model (Fig. 4, left) is applied to opposite surfaces using an iterative method, in form of shrinkage stress, for the purpose of obtaining approximately

equal values for displacement in the experimental (Fig. 5) and numerical models (Fig. 6).

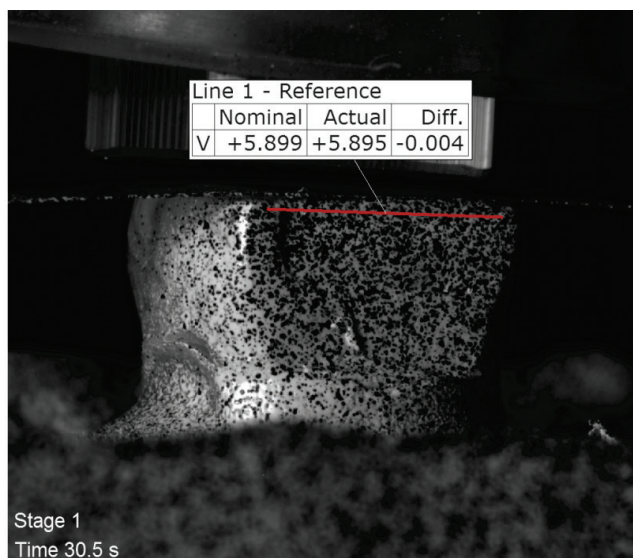


Figure 5. Experimental measurement: displacement of opposite cavity sides after polymerization.

Slika 5. Eksperimentalno merenje: pomeranje suprotnih strana kaviteta posle polimerizacije

It can be seen from Fig. 6 that the displacement of cavity walls in the numerical model along the Z axis (U_3) is the same as in the experimental model (Fig. 5) and is equal to $4 \mu\text{m}$. This displacement represents the sum of displacements of the left cavity wall ($1786 \mu\text{m}$) and the right wall ($2221 \mu\text{m}$).

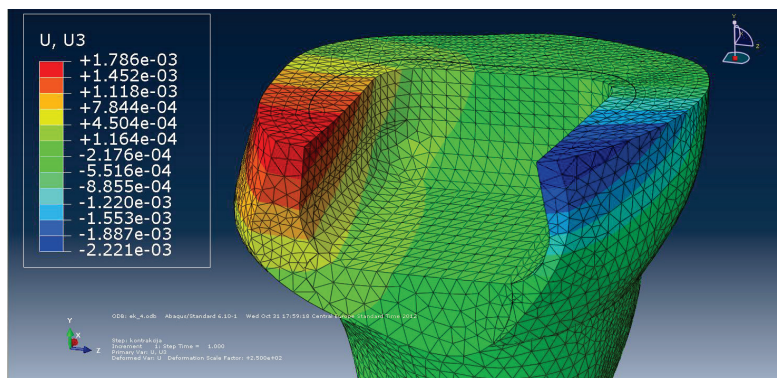


Figure 6. Displacement field due to material shrinkage. / Slika 6. Polje pomeranja usled skupljanja materijala

Numerically calculated polymerization stress that is necessary in order to replicate experimentally obtained displacement between opposite cavity walls, for composite Tetric EvoCeram, equals to 1.8 MPa .

Shown in Fig. 7 is the stress distribution for Model 1 along with reference measuring points (D1, D2, E1, E2) used for further comparison of stresses between models. Stress distribution for Models 2 and 3 is shown in Fig. 8.

Given in Table 3 are the values of stresses in the observed points (Fig. 7) along with their percent increase compared to Model 1. The stress and strain distribution for Model 1 is shown in Fig. 9.

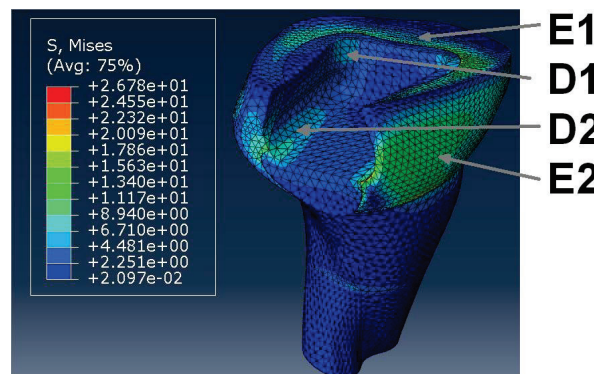


Figure 7. Stress distribution of Model 1. Slika 7. Raspodela napona za Model 1

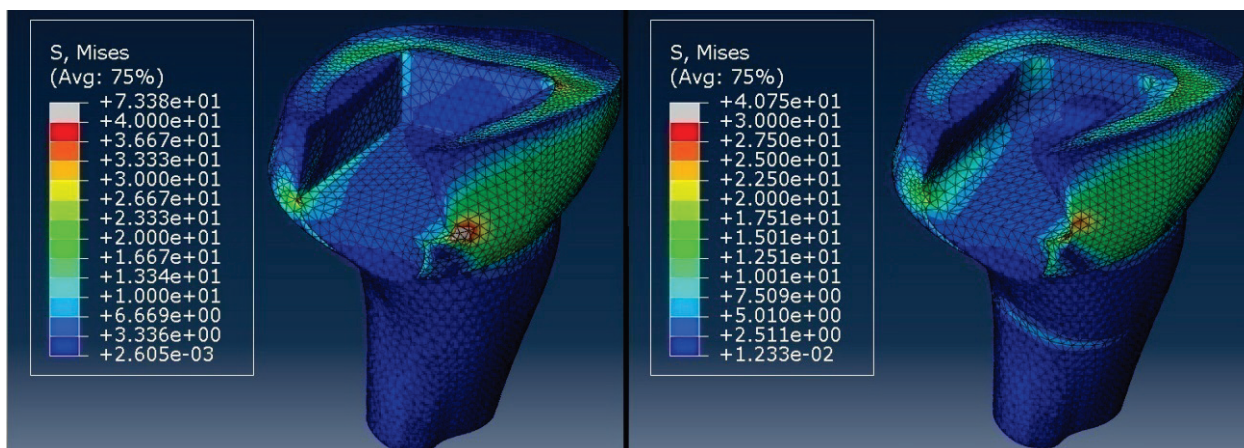


Figure 8. Left: stress distribution of Model 2; right: stress distribution of Model 3.
Slika 8. Levo: raspodela napona za Model 2; desno: raspodela napona za Model 3

Table 3. Stress values and percent increase compared to Model 1.
Tabela 3. Vrednosti napona i procentualni porast u poređenju sa Modelom 1

	Model 1	Model 2		Model 3	
	(MPa)	(MPa)	Increase (%)	(MPa)	Increase (%)
D1 (Dentine)	6	10	66%	8	33%
E1 (Enamel)	6	10	66%	8	33%
E2 (Enamel)	7	13	85%	9	29%
D2 (Dentine)	11	20	81%	14	28%

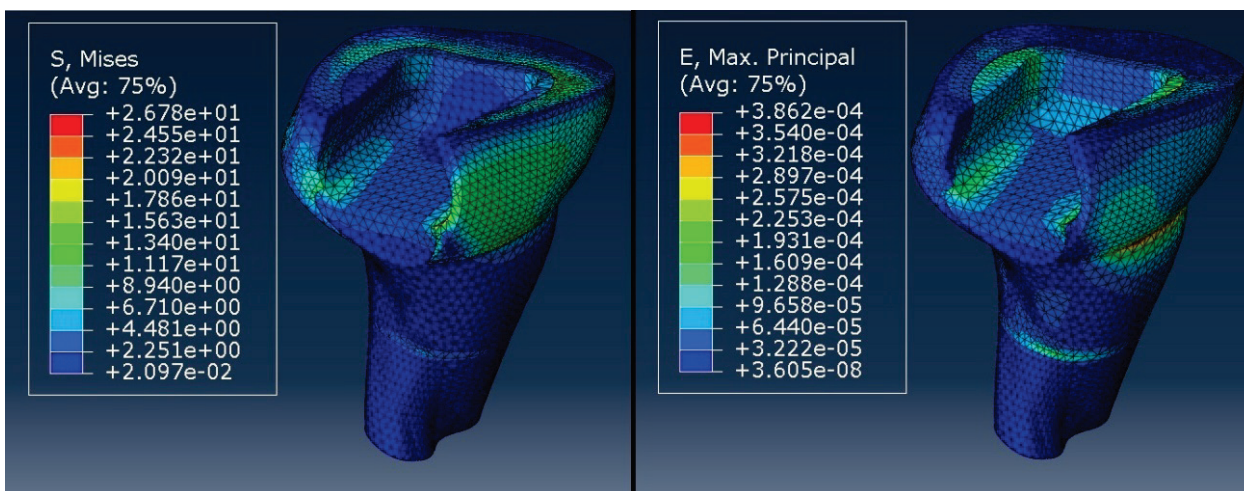


Figure 9. Left: stress distribution in Model 1; right: strain distribution in Model 1.
Slika 9. Levo: raspodela napona za Model 1; desno: raspodela deformacija za Model 1

DISCUSSION

The lowest values, 7 MPa, are measured in zone E2 of Model 1. For Model 2, the stress in zone E2 is 13 MPa, due to sharp transitions between sides and bottom of the cavity, as well as the largest area subjected to load. Model 3, suggested as the solution for stress concentration relaxation of existing cavities according to Black, shows a significant lower stress and strain concentration compared to Model 2.

Stress concentration on the outer surface of the tooth, on the vestibular or oral side, occurs due to small thickness of the cavity lateral wall, which in turn is caused by removing the approximate (mesial) surface during tooth preparation. Along the line where the root is wedged in acryl, the stress concentration occurs due to boundary conditions. Values in these locations can be neglected.

It can be noticed that the ratio of dentine to enamel plays a significant role in stress distribution, due to their different mechanical properties. In cases where dentine thickness is very small, i.e. where the cavity is placed very close to, or within the enamel itself, higher stress concentration occurs on the outer side of the remaining part of the tooth crown and this may lead to micro-cracks occurring on the outer surface (E2).

It can also be seen that each of the models is based on identical parameters with the exception of cavity shape. Such approach is used for the purpose to ensure that if there were any errors in form of approximations during model development, they would affect each of the models equally. In this way, comparison between models is limited to the effect of cavity shape on stress and strain distribution. Due

to variable shapes of teeth and cavities, it is impossible to define a uniform model that would cover all possible scenarios. In addition, it is very complicated to develop an exact numerical model due to extremely complex geometry of human teeth. For reasons mentioned above, experimental values obtained by testing a representative molar model are used in order to develop a numerical model for the purpose of simulation.

By comparing the effects of contraction and stresses caused by shrinkage of three cavity shapes for the same tooth, it is determined that Model 1 represents the solution with lowest stress concentration values. In cases where an adhesive cavity shape (Model 1) cannot be made, due to the previous preparation of a rectangular cavity according to Black, this study has shown that Model 3, with slightly undercut lateral sides (pear-shaped cavity), represents an acceptable solution. Due to this, it is common practice in dentistry to modify cavities with existing sharp angles, for the purpose of reducing stress concentration in zones with significant changes in geometry (Fig. 8, zones D2 and D1).

Use of cavity shown in Model 3 has reduced the stress in point E2 by as much as 65% compared to Model 2. Stress reduction is the highest at this location. The undercut zone in the bottom of the cavity represents a rounded surface about which the strain is redistributed, thus reducing stress concentration. In this case, stress concentration in cavity corners is reduced by up to 50% due to rounded corners.

CONCLUSIONS

The ratio between enamel and dentine thickness has had an important role in stress distribution in the cavity. In areas with thin dentine walls, strain is transferred through this zone, causing high stresses in the enamel. In clinical terms, the consequence of this is the increased risk of micro-cracks occurring in the enamel.

In this paper, experimental and numerical methods are used. Verification of the numerical model is performed by comparing the obtained displacement of opposite cavity walls with a 3D non-contact method, whereas total maximum displacement that is obtained, represents a sum of individual displacements for each opposite cavity wall.

Adhesive type of cavity preparation for composite fillers ensures the lowest stress concentration in zones of transition between lateral walls and bottom of the cavity, compared with cavities according to Black and cavities with undercut lateral sides. In case of amalgam replacement, when the cavity is prepared according to Black, it is desirable to round the cavity corners, in order to reduce stress concentration.

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