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Laboratory Research

Impact of Quantity of Resin, C-factor, and Geometry on Resin Composite Polymerization Shrinkage Stress in Class V Restorations

ALS Borges • AB Borges • TA Xavier
MC Bottino • JA Platt

Clinical Relevance

Adhesive dentistry allows for the simple removal of decayed tissue to guide preparation design. Knowledge about differences in stress concentration within cavities can help in understanding the impact of shape and cavosurface angle of the cavity, optimizing the distribution of stress during the cure of the restorative material and improving the expected lifetime of the restoration.

*Alexandre LS Borges, DDS, MS, PhD, Department of Dental Materials and Prosthodontics, Universidade Estadual Paulista - UNESP - São José dos Campos Dental School, São José dos Campos, SP, Brazil

Alessandra Bühler Borges, DDS, MS, PhD, Department of Restorative Dentistry, Universidade Estadual Paulista - UNESP - São José dos Campos Dental School, São José dos Campos, SP, Brazil

Thaty Aparecida Xavier, PhD, Department of Dental Materials, School of Dentistry, São Paulo University - USP, Sao Paulo, SP, Brazil

Marco C Bottino, DDS, MS, PhD, Department of Restorative Dentistry, Indiana University, Indianapolis, IN, USA

Jeffrey A Platt, DDS, MS, Department of Restorative Dentistry, Indiana University, Indianapolis, IN, USA

*Corresponding author: Av. Eng. Francisco José Longo, 777 Jd. São Dimas Sao Jose dos Campos, SP 12245-000 Brazil; e-mail: aleborges@fosjc.unesp.br

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SUMMARY

Objective: This study evaluated the effect of quantity of resin composite, C-factor, and geometry in Class V restorations on shrinkage stress after bulk fill insertion of resin using two-dimensional finite element analysis.

Methods: An image of a buccolingual longitudinal plane in the middle of an upper first premolar and supporting tissues was used for modeling 10 groups: cylindrical cavity, erosion, and abfraction lesions with the same C-factor (1.57), a second cylindrical cavity and abfraction lesion with the same quantity of resin (QR) as the erosion lesion, and then all repeated with a bevel on the occlusal cavosurface angle. The 10 groups were imported into Ansys 13.0 for two-dimensional finite element analysis. The mesh was built with 30,000 triangle and square elements of 0.1 mm in length for

all the models. All materials were considered isotropic, homogeneous, elastic, and linear, and the resin composite shrinkage was simulated by thermal analogy. The maximum principal (MPS) and von Mises stresses (VMS) were analyzed for comparing the behavior of the groups.

Results: Different values of angles for the cavosurface margin in enamel and dentin were obtained for all groups and the higher the angle, the lower the stress concentration. When the groups with the same C-factor and QR were compared, the erosion shape cavity showed the highest MPS and VMS values, and abfraction shape, the lowest. A cavosurface bevel decreased the stress values on the occlusal margin. The geometry factor overcame the effects of C-factor and QR in some situations.

Conclusion: Within the limitations of the current methodology, it is possible to conclude that the combination of all variables studied influences the stress, but the geometry is the most important factor to be considered by the operator.

INTRODUCTION

Besides the fracture of remaining tooth structure, some effects of microleakage, such as stained and degraded margins and secondary caries, are common causes of failure of resin composite restorations in clinical practice. If the material is rigid, the shrinkage of the composite can induce stress on adhesive interfaces that mechanically challenge the hybrid layer and potentially overcome the bond strength at the interface.[1,2] Gaps in the interface can allow marginal leakage, followed by discoloration and bacterial contamination. The association of secondary caries and marginal staining with failures of the adhesive interface would be rational, in spite of the absence of validating clinical studies.[3-5]

Shrinkage of dental resin composites occurs due to the addition of monomer molecules into a polymer network,[6] reducing the space among the original molecules. This chemical reaction generates contraction stresses in the resin composite with deformation of the surrounding tooth structure.[7] Besides the polymerization reaction, other factors can influence the shrinkage stresses and gap formation at the tooth-restoration interface.[1]

Since microleakage can lead to clinical restoration failures, a good marginal adaptation might increase the service life of a resin composite. The quality of the marginal adaptation can be influenced by the bonding system and by factors related to the stress developed during the polymerization of the material. Stress is influenced by factors such as the mechanical properties and amount of shrinkage of the resin composite, the cavity size and geometry, and the restorative placement and curing technique.[8]

The C-factor (CF) is defined as the ratio of bonded to unbonded surfaces of the dental cavity, and its value is supposed to be directly related to the stress developed at the interface bonding area.[9,10] Several laboratory studies with tensilometers have shown a positive correlation between shrinkage stress and CF,[11-13] but clinical assessments need to be carefully performed due to the complex geometries involved. Stresses generated by a composite bonded within a cavity depend not only on the CF but also on the compliance of the remaining wall structures and the mass or volume of resin composite involved.[14]

Many techniques and materials have been developed in an attempt to obtain long-term retention for esthetic restorations placed in cervical areas. For moderately large-sized restorations, incremental resin composite placement is recommended to decrease the effects of polymerization shrinkage. However, the incremental technique also has disadvantages, such as the possibility of incorporating voids between composite layers and the increased time required to place and cure each layer. This has encouraged the development of composites that report adequate polymerization with a 4-mm depth, allowing for a bulk fill. A previous study has suggested that fewer increments or a bulk-fill could be successful.[15] The present study approaches this idea conceptually by investigating the impact of different cavity designs on the shrinkage polymerization stress developed by the resin composite.

A finite element analysis (FEA) was applied to factors inherent to shrinkage stress. The purpose of this study was to evaluate the effect of quantity of resin (QR), C-factor, and geometry on shrinkage stress of Class V restorations simulating a bulk-fill insertion technique. The null hypotheses tested were that the QR, C-factor, geometry, and existence of a bevel have no influence on the polymerization shrinkage stress in Class V resin composite restorations.[16-20]

MATERIALS AND METHODS

An image of a buccolingual longitudinal plane of an upper first premolar was replicated in the CAD (Computer Aided Design) Rhinoceros software (ver-

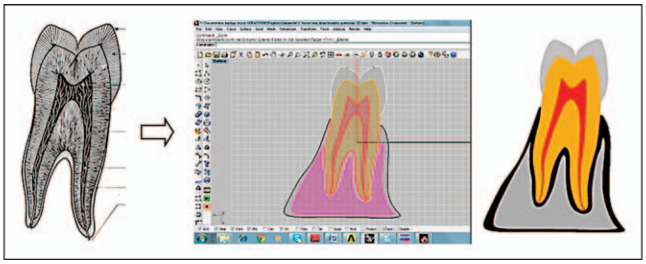

Figure 1. *Two-dimensional geometry of a healthy upper first premolar built in CAD software.*

sion 4.0 SR8, McNeel North America, Seattle, WA, USA) and virtually inserted into an image of the alveolus of the posterior maxillary alveolar process obtained from a human anatomy book [21] (Figure 1). A healthy tooth was used as the standard for all groups.

The first situation, model 1, was a Class V erosion lesion, measuring 3 mm gingivo-occlusally and 2 mm in depth, and simulated the preparation made by a 3-mm diameter spherical bur. The values of C-factor (1.57) and cross-sectional area of restorative material (3.4 mm^2) obtained for this model were used as a reference for further models. The cross-sectional area represents the QR in this two-dimensional analysis. Models 2-5 used abfraction and cylindrical geometries, first holding the C-factor constant to model 1 and then the cross-sectional area. Each of these five models was further modified by inclusion of an occlusal cavosurface marginal bevel at 158° and 1-mm length to analyze the effect of the bevel on the shrinkage stress distribution. Figure 2 shows the 10 groups analyzed in this work.

These CAD models were imported as parasolid format files into ANSYS software (ANSYS 13.0, ANSYS Inc, Houston, TX, USA) for the numerical simulations by FEA. All materials were considered homogenous, linearly elastic, and isotropic. Their mechanical properties are summarized in Table 1.

The mesh was built with triangle and square elements with slow transition and high smoothing as mesh controls. Tests varying the size of elements were carried out until 10% of convergence of the results was reached, which determined that the ideal element size was 0.1 mm. The total number of elements was about 30,000 in all models.

The restoration-tooth interfaces in all the models were considered perfectly bonded. The polymerization shrinkage of the resin composite was simulated by thermal analogy: the initial temperature was reduced by 1°C and, by attributing a coefficient of

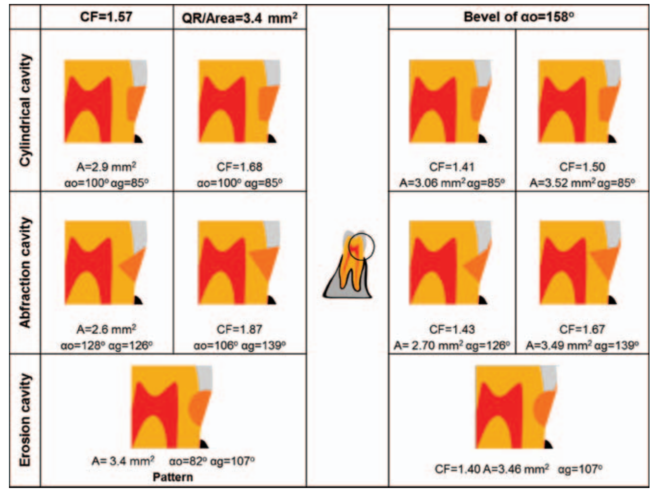

Figure 2. *Geometry of the 10 cavities studied according CF, cross-sectional area of QR, and the angle of cavosurface margin (αo=occlusal and αg=gingival).*

thermal expansion of 0.0021379/°C to the resin, a 0.64% volumetric shrinkage was experienced. The nodes of the top line of the maxillary cortical bone were fully constrained in all directions.

A linear static structural analysis was performed to calculate the stress distribution in the different restoration configurations. The von Mises stress (VMS) was used to observe whether the results were coherent with what should be expected in such biomechanical situations (related to the coherence of the numerical simulations) and to observe the dissipation of the distortional energy throughout the materials. Due to tooth tissue exhibiting a relatively brittle behavior, the maximum principal stress (MPS) was chosen to analyze the stress concentration areas in the occlusal and gingival cavosurface angle regions.

RESULTS

The influence of CF, QR, and bevel on equivalent von Mises and maximum principal stresses is shown in Figures 3 and 4, respectively. The symbol "α" represents the angle between the cavosurface margin and occlusal (αo) and gingival (αg) inner cavity walls. As indicated by the scales, the hotter (more red) colors in the figures represent higher values of stress, in MPa.

The numbers found in the rows labeled VMS-MPa or MPS-MPa represent the stress on the occlusal margin (left cell) and the gingival margin (right cell). In Figure 3, when there are two numbers for VMS in the same cell, the higher value refers to the peak

Table 1: *Mechanical Properties of the Material Used in the Numerical Simulations*

Material	Elastic Modulus, GPa	Poisson's Ratio	Coefficient of Thermal Expansion, mm/°C; Reference Temperature: 25°C	Reference
Enamel	41.00	0.30	—	Ko and others, 1992[16]
Dentin	18.6	0.31	—	Rees and others, 1994[17]
Pulp chamber	0.002	0.45	—	Rubin and others, 1983[18]
Cortical bone	13.7	0.30	—	Ko and others, 1992[16]
Cancellous bone	1.37	0.30	—	Ko and others, 1992[16]
Periodontal ligament	0.069	0.45	—	Holmes and others, 1996[19]
Low shrinkage composite	6.00	0.30	0.0021379 (for 0.64% of pos gel volumetric shrinkage)	Boaro & others, 2010[20]

stress that occurred distant to the restoration edge, and the lower value to the stress developed near the edge.

It can be observed in Figure 3 that the presence of a bevel resulted in a decrease of the VMS on the cavosurface margin on enamel.

The highest VMS in the abfraction geometry was concentrated along the pulpal surface, and its value is shown below the respective image.

For geometries with the same CF (the first column of Figures 3 and 4), the highest values of peak VMS and MPS were erosion (42.90 and 36.14 MPa), cylindrical (32.45 and 26.96 MPa), and abfraction (18.54 and 16.05 MPa). For the factor QR, this followed the sequence of 3.4 mm^2 (erosion), 2.9 mm^2 (cylindrical), and 2.6 mm^2 (abfraction).

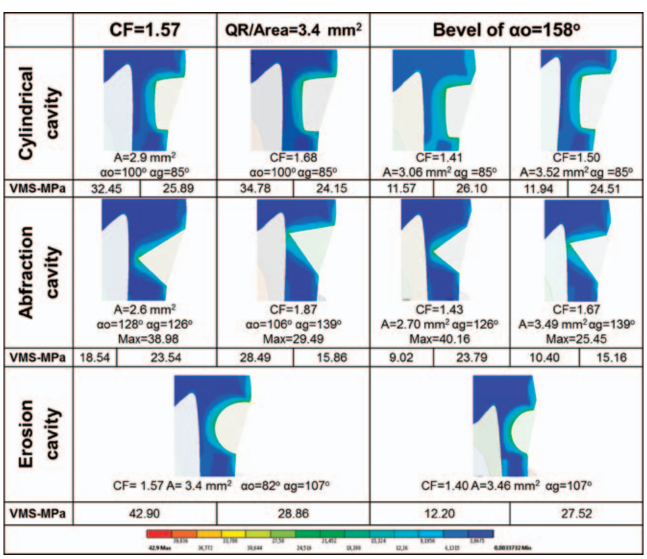

Figure 3. *Details of equivalent von Mises stress of three types of cavities with the same CF, the same cross-sectional area of QR, and with a bevel.*

In the second column of Figures 3 and 4, for groups with the same QR, the order of peak VMS and MPS was erosion (42.90 and 36.14 MPa), cylindrical (34.78 and 28.18 MPa), and abfraction (28.49 and 22.52 MPa). This was similar to that seen with the three geometries having the same CF as shown in the first column. However, in this case, the sequence did not correlate with the CF of 1.87 for abfraction, 1.68 for cylindrical, and 1.57 for erosion. Instead, the cavity with the lower CF showed the higher MPS and VMS values.

In the beveled cavities (the third and fourth columns of Figures 3 and 4), the values of MPS for the cavosurface margin were similar, ranging from 8.48 to 11.83 MPa, as the CF ranged from 1.40 to 1.67, and the area (QR) from 2.7 to 3.46 mm^2, ie, the bevel tended to equalize the values for all the cavities. The bevel decreased the peak stress on the

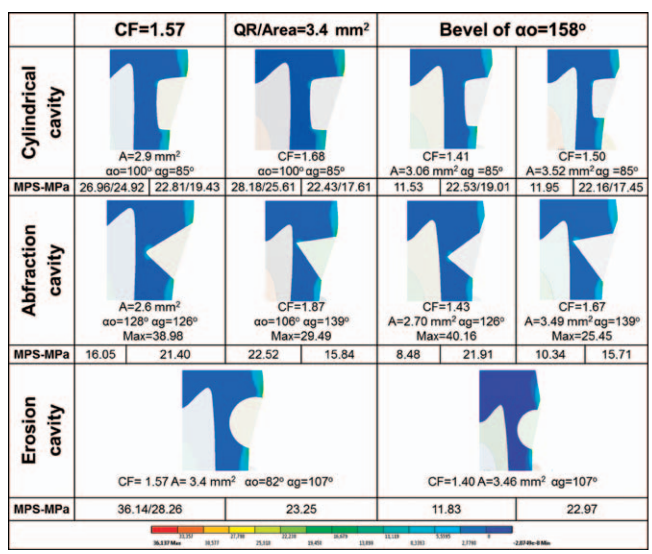

Figure 4. *Details of MPS of three types of cavities with the same CF, the same cross-sectional area of QR, and with a bevel.*

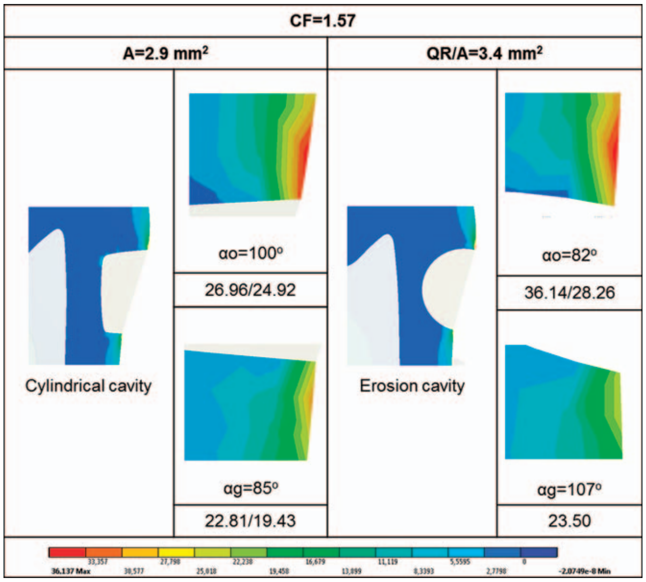

Figure 5. *Difference among the MPS fields in the occlusal and gingival cavosurface angles of the erosion and cylindrical cavities without bevel.*

enamel wall, but had no effect on the gingival wall for all geometries. For erosion and cylindrical unbeveled geometries, the peak stress was close to the cavosurface margin and, when beveled, the overall peak stress decreased. For the abfraction geometry, the peak stress was always more concentrated in the inner angle of the cavity, and the bevel did not have a significant effect. The reduction of the overall peak stress in the entire cavity by placing a bevel was more pronounced in the erosion and cylindrical geometries.

In the four models of abfraction, those presenting a higher CF (Figures 3 and 4) showed the lowest peak stress.

The bevel changed the cavosurface angles; Figure 5 shows its influence on the peak stress distribution in the cavities where there were reductions in the overall peak stress. Obtuse angles in the cylindrical geometry ($\alpha o = 100°$) showed lower values of peak stress (26.96 MPa) than the acute angle (36.14 MPa) in the erosion geometry ($\alpha o = 82°$).

DISCUSSION

The present study used FEA to investigate the impact of cavity designs on the polymerization stress distribution of direct resin composite restorations in Class V preparations. The results showed a significant influence of the geometry, volume, and C-factor on the shrinkage stress after curing a simulated microhybrid bulk-filled composite.

The two-dimensional models correspond to a simplification of three-dimensional structures. They are not a fully representative simulation of a complex three-dimensional structure, such as the real tooth, because they simulate a condition where a structure has a constant shape along its thickness. The extrapolation of what occurs within these simplified geometries cannot be made directly to the corresponding actual types of cavities, which have shape variation along the mesiodistal thickness. The results represent, partially, what occurs in the buccolingual midline of the tooth crown. However, this simplification demonstrates the importance of considering variables such as the amount of resin that shrinks, CF, and cavity geometry on stresses generated during the curing process. Care is needed in interpreting the two-dimensional simulations: the CF was calculated using the two-dimensional lengths of bonded interface and free surface, while the QR was calculated as an area rather than volume.

There is great difficulty in representing, computationally, the material properties, boundary conditions and loading faithful to the conditions found in clinical situations,[22] and these simplifications mean that the computational simulation will not be absolutely faithful to a real-life model that represents the structures, materials, and dental tissues *in vivo*.[23]

With regard to composite resins, shrinkage stress is a problem that has been investigated by many, since it is considered a significant contributor to the clinical failure of direct adhesive restorations. Many discussions have taken place about the variables that most influence this stress. According to previous studies, filler volume fraction,[24] polymerization shrinkage,[25] camphorquinone concentration,[26] amine concentration,[27] specimen geometry,[28] and curing method[29] are among many factors considered significant in the development of polymerization shrinkage stresses.

With FEA, it is possible to isolate the variables of interest (eg, CF, geometry, volume, area, angle) and to study their individual or combined effects in cases where it is not possible or it is too difficult to perform in an *in vitro* experiment. We simulated two types of lesions with three different geometries: clinical, noncarious lesions (abfraction and erosion), and a standard preparation for microleakage laboratory tests (cylindrical) along with three other variables: C-factor, area (representing composite quantity, QR), and bevel. The color gradient allows for qualitative/quantitative comparison among the groups. In the first three groups, we standardized the C-factor and, because of the geometry, the area (QR) was different. That was the greatest factor impacting wall cavity stress, so using the erosion group, the area (QR) was standardized to observe the effect of geometry on stress concentration.

Many evaluations about which material or restoration technique is most suitable for Class V restorations are made by microleakage tests, with circumferential or cylindrical cavities. However, clinically, the walls in this region do not always have the geometric shape of the cavities used in microleakage laboratory tests. The chosen variables were analyzed to determine whether it is appropriate to extrapolate the results of laboratory Class V adhesive tests made with cylindrical cavities to cases of erosion or abfraction and to make the operator aware of design variables one can control to reduce the stress concentration.

Figures 3 and 4 show the same behavior for the two standardized situations: C-factor and area (QR) and the impact of geometry can be observed. The erosion geometry was made as a hemisphere because, according to the hypothesis idealized, the higher the angle of restorative material at the enamel margin, the higher the stress concentration. Thus, the worst-case scenario would be close to the 90° created by a spherical bur.

There were two different behaviors observed in this study: first, the higher the angle formed at the cavosurface margin, the lower the VMS (Figure 3) and MPS (Figure 4), except in the cylindrical cavity, where the geometry changed the isocurve distribution[1] and, second, the greatest stress was not located on the edge (Figure 5).

Figure 5 shows that the cavosurface angle influences the value of the tensile stress, the smaller the angle of tooth structure, the greater the stress concentration. For this reason, it is possible to observe in Figures 3 and 4 that the field pattern for VMS and MPS in cylindrical and erosion cavities are more similar to each other (with the closest cavosurface angle values) and different from the abfraction lesions.

Shrinkage polymerization stress has been related to many factors, such as type of composite, light source, energy density, elastic modulus, degree of conversion, C-factor, geometry, and anatomic region of the cavity.[30] The transmission of the stress from one structure to another depends not only on their mechanical properties, but also on the relationship between them, ie, the boundary conditions. The CF has the potential to impact the plastic deformation and, thus, the relaxation of the material occurring during polymerization.[8,11] Figures 3 and 4 show geometry and area overcoming the CF effects: when the CF was constant, the erosion geometry and higher QR resulted in higher stress concentration; but, when QR was kept constant, the higher CF in the abfraction cavity showed lower MPS concentration. These results are consistent with Rodrigues and others,[14] who rejected the hypothesis that interfacial shrinkage stresses between adjoining walls in cavities increases with CF, and with other authors[31-35] who have said that using CF as a single predictor for shrinkage stress has not been universally accepted.

When the margin is placed completely within enamel of bonded restorations, performance is thought to be more predictable, but frequently, Class V lesions extend onto the root surface and poor gingival margin adhesion can increase microleakage. In this study, Figures 3 and 4 show that the angle of the margin combined with the E modulus of the dental tissue influenced polymerization stress distribution. This suggests that beveling the gingival margin that ends in cementum should decrease MPS and VMS and, so, may decrease the microleakage in this region. This is in opposition to the data published by Owens and others,[36] who observed that nonretentive restorations, without a gingival bevel, exhibited significantly less microleakage along the gingival wall and less overall microleakage than did the beveled restorations. But, with *in vitro* testing, other factors, such as light exposure[37] or dentin humidity, that may affect results can be easily modified by the operator.

The effect of geometry on the gingival microleakage has not been tested, while nonsignificant differences were found when comparing the influence of different composites having different mechanical properties. These authors observed a modest decrease in microleakage associated with shrinkage stress for the same cavity shape.[38,39]

In the different clinical situations studied, abfraction and erosion cavities are associated with specific interactions with the tissues involved. This study supports moving the stress concentration away from the margin by increasing the angle of the cavosurface bevel because the stress at the enamel margin can decrease the lifetime of a restoration.

In Figure 3, the second column shows the effect of CF on the three different cavities. The lower the CF, the higher the calculated stress. This was consistent with the observation of El-Sahn and others,[40] who showed that increasing the CF did not negatively affect the bond strength of low-shrinkage composites.

Comparing lesions of beveled abfraction geometry, even with an increase in QR and the resulting increase in CF, the peak stress decreased. This can be explained by a considerable difference in the geometry of this type of cavity: the pulpal wall became thinner (due to higher amounts of resin) and, therefore, more flexible. This may have contributed to the stress decrease during the resin polymerization. This also means that, in the abfraction lesion, the change in geometry overcame the expected effects of increasing CF and amount of resin. This finding about geometry is in accordance with Braga and others.[9] They concluded that shrinkage stress and microleakage in cylindrical restorations are influenced by both their diameter and depth, although cavity depth was found to have a stronger influence than diameter.

Considering the general values of stress (and not just the values achieved at the cavosurface angles), the case that seems more favorable for bond integrity is the abfraction beveled cavity with an area equal to 2.79 mm^2 because it presented, in a general manner, lower stress values.

According to the results obtained, the null hypothesis was rejected because the QR, the design of the cavity, and the bevel influenced the polymerization shrinkage stress. The findings indicate that the cavity geometry is the most important factor to be considered along with the presence or absence of a bevel. Appropriate application of this information can help to decrease the stress generated during resin composite polymerization. In addition, these findings mean that the stress varies among different types of cavities and that results measuring marginal integrity from laboratory tests should only be compared when walls of similar geometry are used.

CONCLUSIONS

Within the limitations of this methodology, it is possible to conclude that C-factor, quantity of restorative material, cavity geometry, and the angle formed at the cavosurface margin, as well as their combined interaction, influence stress distribution in different ways. The occlusal enamel cavosurface margin angle was the most relevant factor in predicting the stress in a Class V cavity.

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Conflict of Interest

The Authors of this manuscript certify that they have no proprietary, financial or other personal interest of any nature or kind in any product, service and/or company that is presented in this article.

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REFERENCES

1. dos Santos GO, da Silva AH, Guimaraes JG, Barcellos Ade A, Sampaio EM, & da Silva EM (2007) Analysis of gap formation at tooth-composite resin interface: Effect of C-factor and light-curing protocol *Journal of Applied Oral Science* **15(4)** 270-274.
2. Moreira da Silva E, dos Santos GO, Guimaraes JG, Barcellos Ade A, & Sampaio EM (2007) The influence of C-factor, flexural modulus and viscous flow on gap formation in resin composite restorations *Operative Dentistry* **32(4)** 356-362.
3. Braga RR, Yamamoto T, Tyler K, Boaro LC, Ferracane JL, & Swain MV (2012) A comparative study between crack analysis and a mechanical test for assessing the polymerization stress of restorative composites *Dental Materials* **28(6)** 632-641.
4. Dennison JB, & Sarrett DC (2012) Prediction and diagnosis of clinical outcomes affecting restoration margins *Journal of Oral Rehabilitation* **39(4)** 301-318.
5. Sarrett DC (2007) Prediction of clinical outcomes of a restoration based on *in vivo* marginal quality evaluation *Journal of Adhesive Dentistry* **9(Supplement 1)** 117-120.
6. Peutzfeldt A (1997) Resin composites in dentistry: The monomer systems *European Journal of Oral Sciences* **105(2)** 97-116.
7. Ferracane JL, & Mitchem JC (2003) Relationship between composite contraction stress and leakage in Class V cavities *American Journal of Dentistry* **16(4)** 239-243.
8. Feilzer AJ, De Gee AJ, & Davidson CL (1987) Setting stress in composite resin in relation to configuration of the restoration *Journal of Dental Research* **66(11)** 1636-1639.
9. Braga RR, Boaro LC, Kuroe T, Azevedo CL, & Singer JM (2006) Influence of cavity dimensions and their derivatives (volume and 'C' factor) on shrinkage stress development and microleakage of composite restorations *Dental Materials* **22(9)** 818-823.
10. Takahashi H, Finger WJ, Wegner K, Utterodt A, Komatsu M, Wostmann B, & Balkenhol M (2010) Factors influencing marginal cavity adaptation of nanofiller containing resin composite restorations *Dental Materials* **26(12)** 1166-1175.
11. Feilzer AJ, De Gee AJ, & Davidson CL (1989) Increased wall-to-wall curing contraction in thin bonded resin layers *Journal of Dental Research* **68(1)** 48-50.

12. Feilzer AJ, De Gee AJ, & Davidson CL (1990) Quantitative determination of stress reduction by flow in composite restorations *Dental Materials* **6(3)** 167-171.

13. Ardu S, Feilzer AJ, Devigus A, & Krejci I (2008) Quantitative clinical evaluation of esthetic properties of incisors *Dental Materials* **24(3)** 333-340.

14. Rodrigues FP, Silikas N, Watts DC, & Ballester RY (2012) Finite element analysis of bonded model Class I 'restorations' after shrinkage *Dental Materials* **28(2)** 123-132.

15. Abbas G, Fleming GJ, Harrington E, Shortall AC, & Burke FJ (2003) Cuspal movement and microleakage in premolar teeth restored with a packable composite cured in bulk or in increments *Journal of Dentistry* **31(6)** 437-444.

16. Ko CC, Chu CS, Chung KH, & Lee MC (1992) Effects of posts on dentin stress distribution in pulpless teeth *Journal of Prosthetic Dentistry* **68(3)** 421-427.

17. Rees JS, Jacobsen PH, & Hickman J (1994) The elastic modulus of dentine determined by static and dynamic methods *Clinical Materials* **17(1)** 11-15.

18. Rubin C, Krishnamurthy N, Capilouto E, & Yi H (1983) Stress analysis of the human tooth using a three-dimensional finite element model *Journal of Dental Research* **62(2)** 82-86.

19. Holmes DC, Diaz-Arnold AM, & Leary JM (1996) Influence of post dimension on stress distribution in dentin *Journal of Prosthetic Dentistry* **75(2)** 140-147.

20. Boaro LC, Goncalves F, Guimaraes TC, Ferracane JL, Versluis A, & Braga RR (2010) Polymerization stress, shrinkage and elastic modulus of current low-shrinkage restorative composites *Dental Materials* **26(12)** 1144-1150.

21. Tallec P (1975) *Morphologie Dentaire* Paris.

22. Coelho CS, Biffi JC, Silva GR, Abrahao A, Campos RE, & Soares CJ (2009) Finite element analysis of weakened roots restored with composite resin and posts *Dental Materials Journal* **28(6)** 671-678.

23. Boaro LC, Goncalves F, & Braga RR (2010) Influence of the bonding substrate in dental composite polymerization stress testing *Acta Biomaterialia* **6(2)** 547-551.

24. Vaidyanathan J, & Vaidyanathan TK (2001) Flexural creep deformation and recovery in dental composites *Journal of Dentistry* **29(8)** 545-551.

25. Feilzer AJ, & Dauvillier BS (2003) Effect of TEGDMA/BisGMA ratio on stress development and viscoelastic properties of experimental two-paste composites *Journal of Dental Research* **82(10)** 824-828.

26. Kalliyana Krishnan V, & Yamuna V (1998) Effect of initiator concentration, exposure time and particle size of the filler upon the mechanical properties of a light-curing radiopaque dental composite *Journal of Oral Rehabilitation* **25(10)** 747-751.

27. Brauer GM, Dulik DM, Antonucci JM, Termini DJ, & Argentar H (1979) New amine accelerators for composite restorative resins *Journal of Dental Research* **58(10)** 1994-2000.

28. Watts DC, & Marouf AS (2000) Optimal specimen geometry in bonded-disk shrinkage-strain measurements on light-cured biomaterials *Dental Materials* **16(6)** 447-451.

29. Yap AU, Wong NY, & Siow KS (2003) Composite cure and shrinkage associated with high intensity curing light *Operative Dentistry* **28(4)** 357-364.

30. Van Ende A, Mine A, De Munck J, Poitevin A, & Van Meerbeek B (2012) Bonding of low-shrinking composites in high C-factor cavities *Journal of Dentistry* **40(4)** 295-303.

31. Ausiello P, Apicella A, Davidson CL, & Rengo S (2001) 3D-finite element analyses of cusp movements in a human upper premolar, restored with adhesive resin-based composites *Journal of Biomechanics* **34(10)** 1269-1277.

32. Watts DC, Marouf AS, & Al-Hindi AM (2003) Photo-polymerization shrinkage-stress kinetics in resin-composites: Methods development *Dental Materials* **19(1)** 1-11.

33. Watts DC, Issa M, Ibrahim A, Wakiaga J, Al-Samadani K, Al-Azraqi M, & Silikas N (2008) Edge strength of resin-composite margins *Dental Materials* **24(1)** 129-133.

34. Watts DC, & Satterthwaite JD (2008) Axial shrinkage-stress depends upon both C-factor and composite mass *Dental Materials* **24(1)** 1-8.

35. Versluis A, Douglas WH, Cross M, & Sakaguchi RL (1996) Does an incremental filling technique reduce polymerization shrinkage stresses? *Journal of Dental Research* **75(3)** 871-878.

36. Owens BM, Halter TK, & Brown DM (1998) Microleakage of tooth-colored restorations with a beveled gingival margin *Quintessence International* **29(6)** 356-361.

37. Sakaguchi RL, Wiltbank BD, & Murchison CF (2004) Contraction force rate of polymer composites is linearly correlated with irradiance *Dental Materials* **20(4)** 402-407.

38. Palin WM, Fleming GJ, Burke FJ, Marquis PM, & Randall RC (2005) The influence of short and medium-term water immersion on the hydrolytic stability of novel low-shrink dental composites *Dental Materials* **21(9)** 852-863.

39. Palin WM, Fleming GJ, Nathwani H, Burke FJ, & Randall RC (2005) In vitro cuspal deflection and microleakage of maxillary premolars restored with novel low-shrink dental composites *Dental Materials* **21(4)** 324-335.

40. El-Sahn NA, El-Kassas DW, El-Damanhoury HM, Fahmy OM, Gomaa H, & Platt JA (2011) Effect of C-factor on microtensile bond strengths of low-shrinkage composites *Operative Dentistry* **36(3)** 281-292.