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Adhesive class I restorations in sound molar teeth incorporating combined resin-composite and glass ionomer materials: CAD-FE modeling and analysis

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ABSTRACT

Objectives. To investigate the influence of different resin composite and glass ionomer cement material combinations in a "bi-layer" versus a "single-layer" adhesive technique for class I cavity restorations in molars using numerical finite element analysis (FEA).

Materials and Methods. Three virtual restored lower molar models with class I cavities 4 mm deep were created from a sound molar CAD model. A combination of an adhesive and flowable composite with bulk fill composite (model A), of a glass ionomer cement with bulk fill composite (model B) and of an adhesive with bulk fill composite (model C), were considered. Starting from CAD models, 3D-finite element (FE) models were created and analyzed. Solid food was modeled on the occlusal surface and slide-type contact elements were used between tooth surface and food. Polymerization shrinkage was simulated for the composite materials. Physiological masticatory loads were applied to these systems combined with shrinkage. Static linear analyses were carried out. The maximum normal stress criterion was adopted as a measure of potential damage.

Results. All models exhibited high stresses principally located along the tooth tissues–restoration interfaces. All models showed a similar stress trend along enamel–restoration interface, where stresses up to 22 MPa and 19 MPa was recorded in the enamel and restoration, respectively. A and C models showed a similar stress trend along the dentin-restoration interface with a lower stress level in model A, where stresses up to 11.5 MPa and 7.5 MPa were recorded in the dentin and restoration, respectively, whereas stresses of 17 MPa and 9 MPa were detected for model C. In contrast to A and C models, the model B showed a reduced stress level in dentin, in the lower restoration layer and no stress on the cavity floor.

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Significance. FE analysis supported the positive effect of a "bi-layer" restorative technique in a 4 mm deep class I cavities in lower molars versus "single-layer" bulk fill composite technique.

1. Introduction

Resin-based composites have become a revolutionary innovation in direct restorative materials for several decades. These materials were developed mainly to restore the esthetics and function of the human dentition and are now extensively used for class I and II restorations [1–3].

When the final cavity is extensive in width, different material selection indications exist—including direct versus indirect restorative combinations. Guidance is necessary to help dental professionals make the right decisions between available options [4].

Resin-based composites exhibit volumetric polymerization shrinkage from 1% up to 4.8% depending on numerous chemical and physical factors, especially the presence of dimethacrylate matrix monomers and the volume percent of inorganic filler [5]. Shrinkage stress is physically linked with this phenomenon and it occurs depending both on resin-composite characteristics, such as Young's modulus of the material, together with the host geometry (boundary conditions) and the stiffness of residual tissue [6].

When class I cavities are adhesively restored, shrinkage stresses act internally and marginally to produce a failure risk by creating conditions for a gap [7]. So, the primary origin of stress in a restored tooth usually comes by dimensional changes of the composite at the interface of tooth and restorative material or by occlusal loads [8]. These phenomena have been investigated both by laboratory experiments [9–12] and by finite element analysis [13–23].

Clinical success and longevity of dental posterior restorations are governed by many factors. These include material selection, patient oral health compliance and the operator's skill [24].

Marginal cavity adaptation of restorations in bonded dentin cavities reflects complex interactions between adhesive bonding on the one hand, and polymerization shrinkage strain, stress and elastic modulus, on the other [18]. The level of shrinkage stress and debonding in particular are probably more dependent upon the shape and hence constrains of the cavity [25]. These also depend upon the quality of polymerization, (DC, degree of conversion) as determined by effective irradiation by light-curing devices. The shrinkage of the bottom layer in adhesive class I posterior restorations, where an high C-factor configuration exists, is directed toward the center and may result in cervical microleakage (gap) when the stress surpasses the resin–dentin bond strength [23]. In the past, dentists usually did not restore a 4 mm deep cavity in a single bulk increment. The incremental technique and reduced thickness of the first layer of composite were used to regulate the shrinkage direction and to prevent microleakage [25,26].

Today, bulk-fill dental composites may partially overcome some of these limits [23]. But, to fully explore the clinical benefits of bulk-fill composites, it appears that more clinical studies are required on bulk-filled deep and large restorations [27]. So, a careful layering technique may still be appropriate and necessary [15,28] or a multilayer with different materials [30]. In these cases, materials with lower rigidity and minimal shrinkage are indicated.

So, the aim of the present analysis was to study various combinations of adhesive resin composites and non-shrink glass ionomers, via "bi-layer" restorative techniques, compared to a bulk-fill composite technique, on the mechanical behaviour of 4 mm class I restorations in a lower molar, by means of linear elastic 3D finite element analysis (3D-FEA).

2. Materials and methods

Biomechanical responses in dental applications have been extensively investigated by means of modern CAD–FEM (Computer Aided Design and Finite Element Method) techniques [14–23,30,31]. By using these techniques, a 3D CAD model of a sound tooth (Fig. 1) was created.

Starting from this 3D CAD model, three models with class I cavities in lower molars (Fig. 1) were obtained and analyzed to investigate the influence on the stress distribution of resin-composite and glass ionomer cement (GIC) material combinations in a "bi-layer" technique to replace enamel and dentin.

These models were designated as A, B and C and detailed in the Table 1. Their geometrical features are shown in Fig. 1.

2.1. *Generation of solid models*

A sound tooth lower molar model was obtained via reverse engineering techniques. The shapes of dentin and enamel were digitized with a micro-CT scanner system (Bruker microCT, Kontich, Belgium). Image data sets were processed via InVesalius 3.1.1 software (www.cti.gov.br/en) and 3-D tessellated surfaces were created. Starting from 3-D tessellated surfaces, cross-section curves were generated and the parametric 3D CAD model was created using loft surfaces in Rhinoceros® 6 (Robert McNeel & Associates, USA). Boolean operations ensured the congruence of interfacial boundaries of dentin and enamel. The tooth model was cut 2.5 mm below the cervical area to obtain the final model.

The bucco-lingual and mesio-distal widths were 10.60 mm and 12.36 mm, respectively, and the thickness of enamel was about 1.5 mm. Class I pulp and lateral walls had rounded modelled angles.

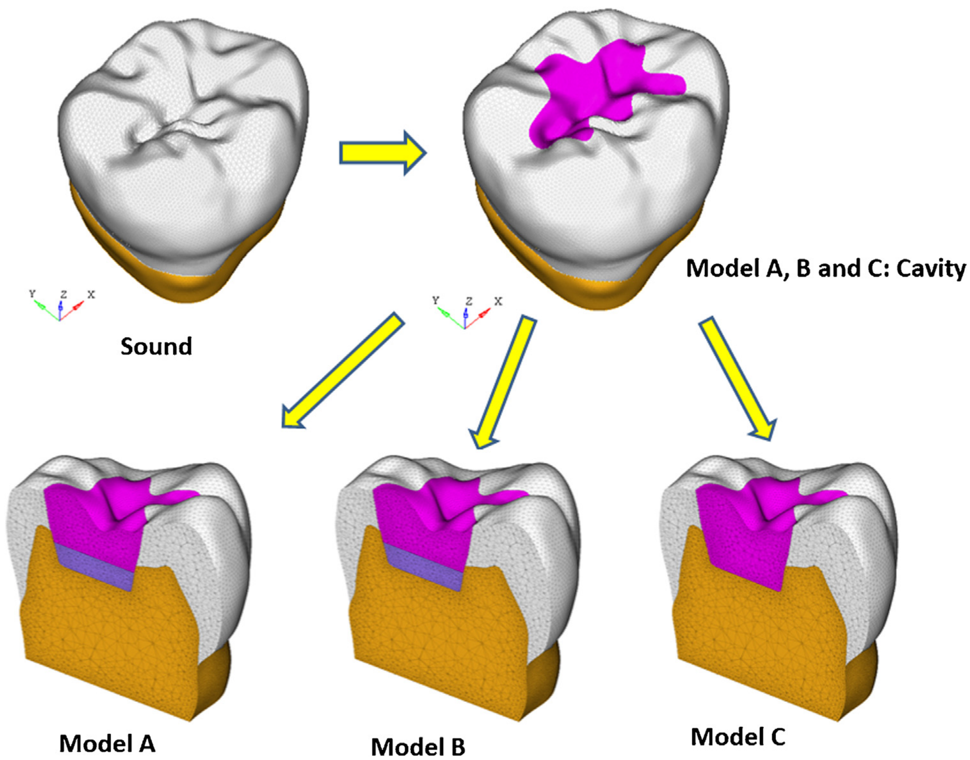

Fig. 1 – The geometrical features of analyzed models.

Table 1 – Restorative material combinations and thicknesses.

Model	Adhesive layer	Restorative lower layer	Restorative upper layer	Single restorative material
A	10 μm thick	Flowable resin composite (1.5 mm thick)	Bulk fill resin composite (about 2.5 mm thick)	-
B	-	Glass-Ionomer cement (GIC) (1.5 mm thick)	Bulk fill resin composite (about 2.5 mm thick)	-
C	10 μm thick	-	-	Bulk fill resin composite (about 4 mm)

The tooth model was placed in a coordinate system, with X- and Y-axes for the bucco-lingual and mesio-distal directions, respectively. The Z-axis was oriented vertically (Fig. 1).

A class I cavity, about 4.0 mm deep, was modelled in Rhinoceros® 6 and the restored models were obtained via Boolean operations between the cavity, enamel and dentin surfaces.

Variability of masticatory function, depending on the contact between tooth surface and food bolus, was allowed for by modelling food on the occlusal surface (Fig. 2).

2.2. *Numerical simulation*

The mechanical behavior of the three multilayer restored models (Table 1) was analyzed via 3D Finite Element (FE) analysis using HyperWorks® 14.0 (Altair Engineering Inc, USA).

HyperWorks® 14.0 software was used to mesh components of the models. All volumes were discretized by 4-node tetrahedral elements CTETRA with a global size ranging from 0.05 mm to 0.15 mm. To minimize the mesh-dependency of results, due to the small radius of curvature and notch effects, mesh refinement techniques were used. The total number of nodes and elements are summarized in the Table 2.

The mechanical properties assigned to each material and the magnitudes of linear shrinkage (%), of materials exhibiting shrinkage, are given in Table 3.

All the FE analyses were focused on load during the closing phase of the chewing cycle. The variability of chewing function was considered dependent on the contact between food and tooth surface. Solid food (apple pulp [30,31,32]) was modelled on the occlusal surface (Fig. 2) and slide-type contact elements were used between tooth surface and food.

It is known that shrinkage stresses in teeth restored with composite materials may be less than those calculated on the basis of an elastic model. During the curing process, stress relaxation accompanies the viscous flow of composites and the Young modulus E and viscosity increase rapidly. To take this into account, the simplified approach proposed by Kowalczyk [15] was used and the final shrinkage S_{max} was reduced according to the rule $S_r = (\sigma_r/\sigma)\ S_{max}$. So an effective linear

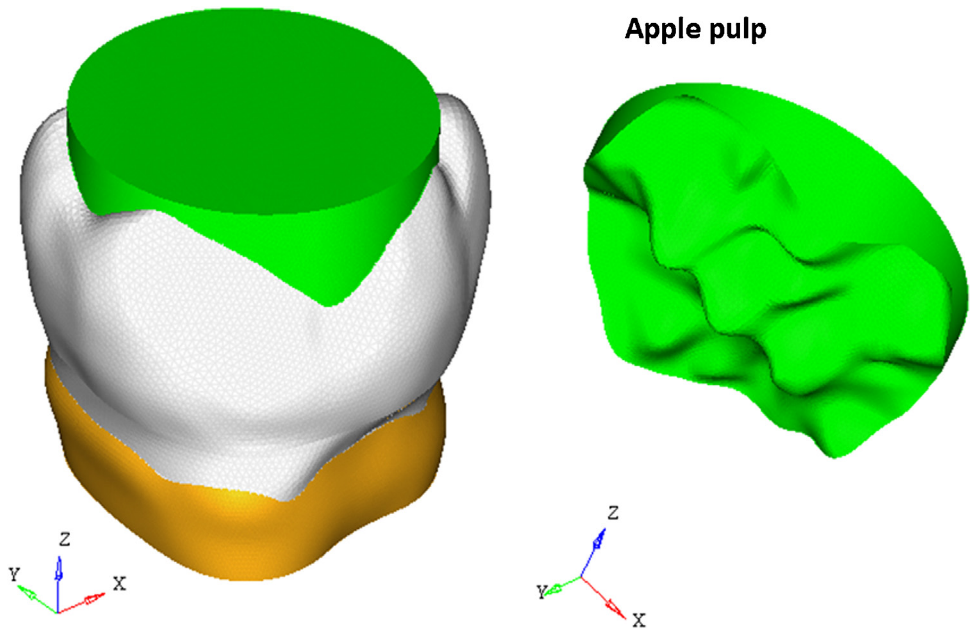

Fig. 2 – Food modelling on the occlusal surfaces.

Table 2 – Analyzed tooth models and technical features.

Model	Total number of nodes	Total number of elements	Total number of contact elements	Total of degrees of freedom
A	177773	835725	26045	591954
B	180666	849617	27564	604263
C	176684	835037	25521	587571

shrinkage $S_r = 0.001$ was adopted in the analyses. Polymerization shrinkage for the adhesive layers and materials was simulated using the thermal expansion approach, by assigning a one-degree drop in temperature.

Physiological masticatory loads [31–33] were simulated as an occlusal static load of 600 N and a transversal load of 20 N. These were applied on the food in the vertical and bucco-lingual directions, respectively. These loads were simultaneously applied in combination with shrinkage effects.

Nodal displacements on the lower surfaces of models were constrained in all directions. Static linear analyses were carried out. The analyses were performed considering a non-failure condition and all materials were assumed to behave elastically.

3. Results

The resultant stress distributions for the aforementioned models, were compared and analyzed.

As these materials exhibit brittle behavior, the maximum principal stress was adopted as a measure of potential damage. So, the first principal stress was used to analyze results. Fig. 3 shows the first principal stress distributions for enamel, dentin and restorative material for each model due to occlusal and transversal loads in combination with shrinkage effects. Cross sections along the bucco-lingual direction of the tooth were considered. Fig. 4 depicts overall contour plots of first principal stress for each analyzed model.

Further quantitative results were observed via an inspection line, defined along the cavity wall. First principal stresses were plotted along the inspection line and compared for the different models (Fig. 5).

As seen in Fig. 3, all models exhibited a high stress concentration near tooth tissues-restoration interfaces. All models showed a similar stress trend along the enamel–restoration interface (Fig. 5), where a stresses up to 22 MPa and 19 MPa were recorded in the enamel and restoration, respectively.

The highest stresses gradient in the restoration was located at the top corner of the enamel-dentin interface (Figs. 3 and 5c).

A and C models, where shrinking restored materials were used, showed a similar stress trend along the dentin-restoration interface with a lower stress level in model A (Fig. 5). In particular, stresses up to 11.5 MPa and 7.5 MPa were recorded in the dentine and restoration, respectively, for model A; whereas 17 MPa and 9 MPa were recorded for model C.

In contrast to A and C models, model B - with a shrinking upper layer and non-shrinking lower layer - showed a trend in stress along the dentin-restoration interface that decreased with depth and tended towards zero at the cavity floor (Figs. 3–5). So, reduced stress levels in dentin and in the lower restoration layer were evident.

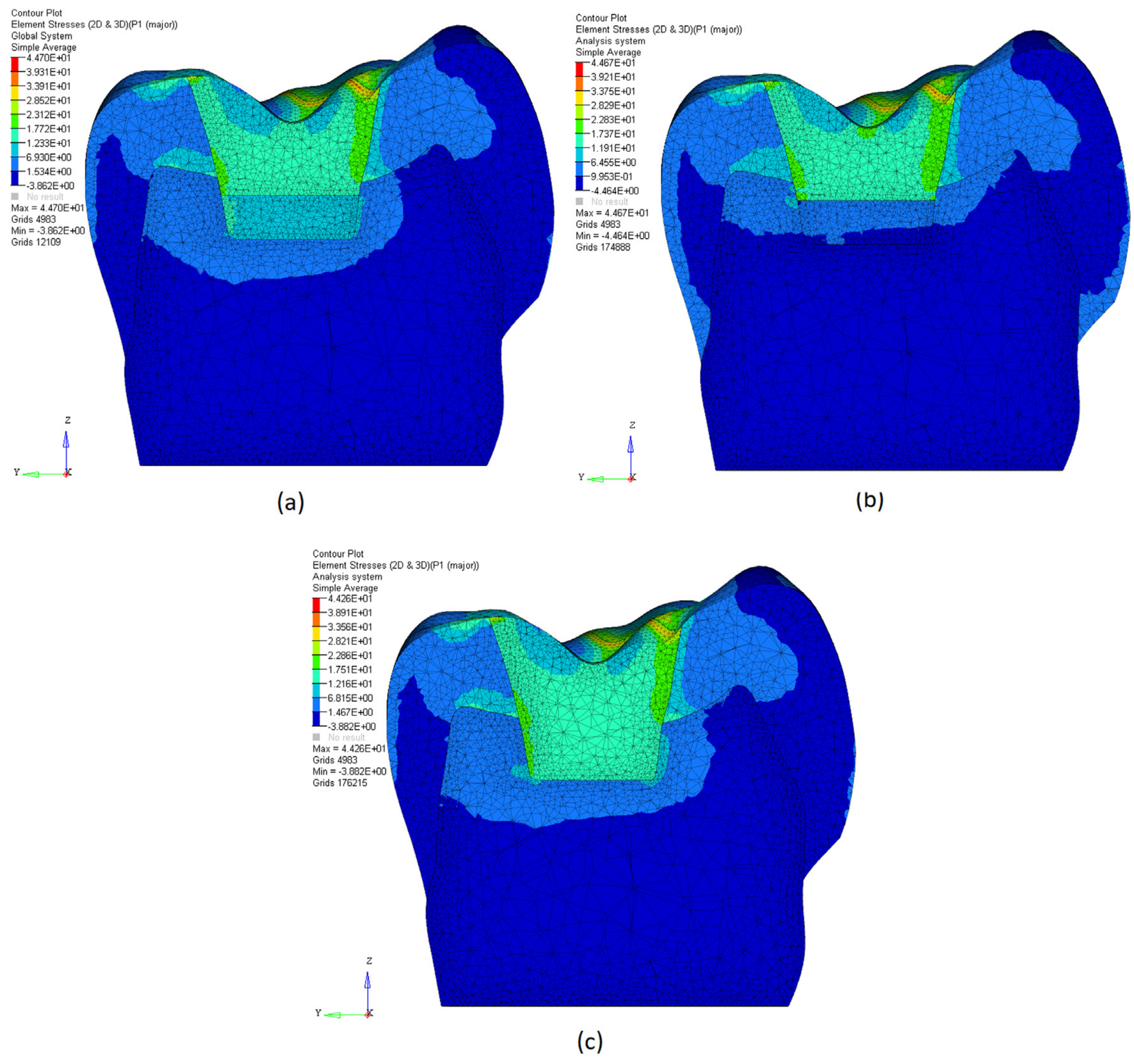

Fig. 3 – First principal stress distributions (MPa) for each analyzed models: (a) Model A; (b) Model B; (c) Model C. The false-color scales vary from model to model, so the exact scale-range for each model should be noted carefully.

Table 3 – Mechanical properties of materials: Young's modulus, Poisson's ratio and linear shrinkage.

Material	Young's modulus (GPa)	Poisson's ratio	Linear shrinkage (%)
Dentin	18.0	0.23	–
Enamel	80.0	0.30	–
Food (apple pulp)	3.41	0.1	–
Adhesive layer	4.0	0.30	1.0
Flowable resin composite	8.0	0.25	1.0
Glass inomer composite (GIC)	8.0	0.25	–
Bulk fill composite	12.00	0.25	1.0

4. Discussion

Anatomical arrangements based on different tissue combinations underlie the complex behavior of teeth under chewing function. Also jaw-muscle activity varies with the mechanical properties of food [32].

Stress distributions within posterior teeth are a function of shape, their 3-D stiffness distribution and loading, even though the stiffness (E) of most of the components are known [33].

The mechanical system in posterior teeth resists fracture during mastication and facilitates more uniform stress distributions [33] since high modulus enamel (E = 80 GPa), is combined with more compliant dentin (E = 18 GPa). The mechanical behavior of premolars and molars, adhesively restored using different resin-based composites, has been investigated under occlusal loading either under laboratory conditions [9,12,33,34] or by means of finite element analysis of restored teeth [11,13–22,26].

Restorative materials must create a strong adhesive bridge between the opposing walls of the restored cavity [15,17,18]

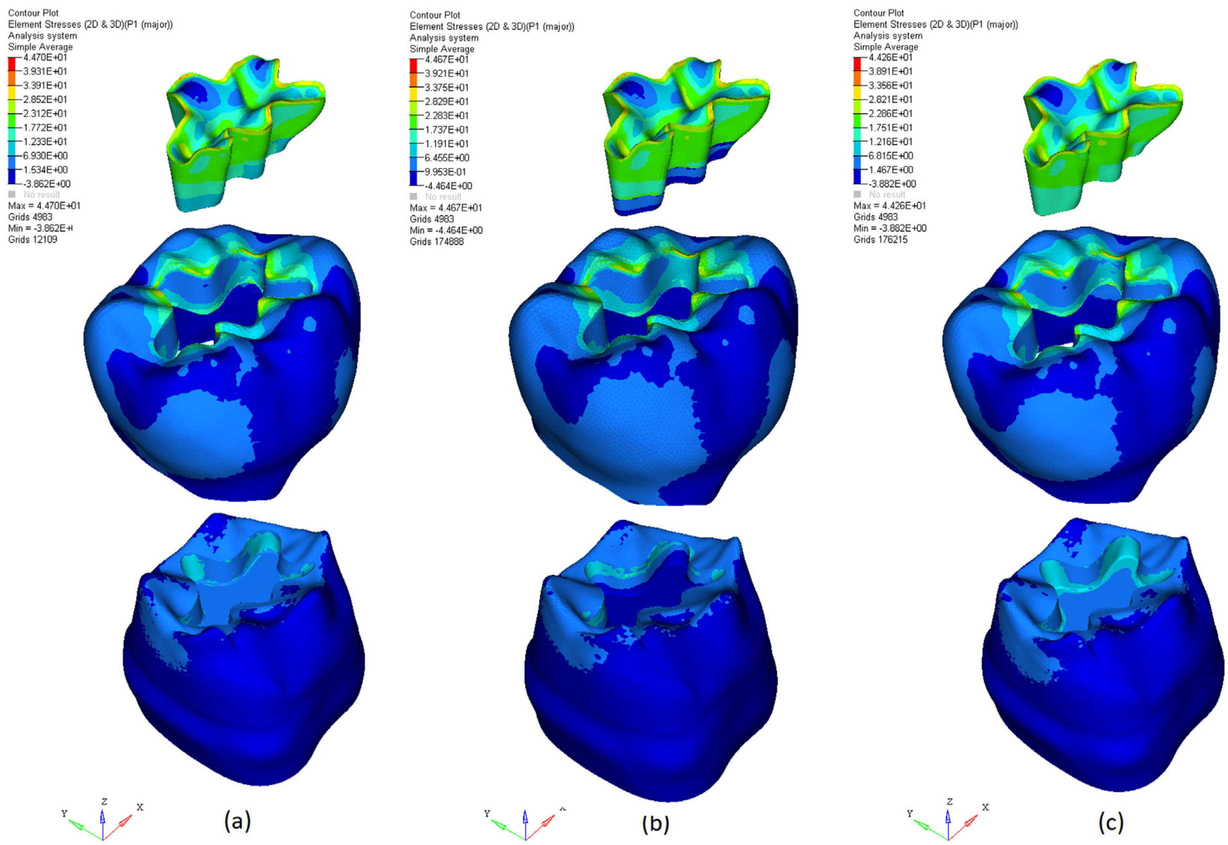

Fig. 4 – Overall contour plots of First principal stress for each analyzed models: (a) Model A; (b) Model B; (c) Model C.

aiming to replicate properties and function of the lost tissues as closely as possible, limiting debonding, marginal leakage and fracture [36,37]. Morphology, function and aesthetics must also be replicated.

In the present investigation, the biomechanical response of restored tooth models with class I cavities, have been simulated. The maximum normal stress criterion has been considered as a measure of failure probability. More adverse outcomes were found with models A and C.

In these models high stresses were predicted and thus a high risk of marginal damage, as seen in Fig. 3 and 4. For these models, a combination of shrinking resin-based materials such as adhesive (E = 4 GPa), flowable composite (E = 8 GPa) and bulk composite (E = 12 GPa), was used.

Resin composite thickness and its Young's modulus strongly influence stress redistribution at adhesive interfaces particularly in deformation of the cusps [7,13].

Hojjatie and Anusavice [38] provided an analysis using von Mises stress simulation. This showed stresses were dependent on the higher elastic modulus of the restorative material and on the cavity shape. Resin composite onlays showed the best overall performance in minimizing internal stresses. These findings have been partly confirmed in a recent investigation [18], where it was suggested that in Class II MOD inlays, 95° cavity-margin-angles under a 600 N load gave greater relief of principal stresses.

On the other hand it seems that the polymerization shrinkage of the adhesive layer has a lesser influence than flowable or bulk composite for producing stresses because of its normal thickness of 0.01 mm [15].

Potential adverse effects were shown as a consequence of 1% linear polymerization shrinkage of a bulk fill composite on its marginal adaptation to cavity walls [18]. Furthermore, the new generation of conventional and bulk-fill composites may not reduce shrinkage stress in endodontically-treated molars compared to bulk-flow composites [27]. In this context, where composite replaces both enamel and dentin, shrinkage stress has evidently greater consequences than occlusal loading alone. This confirms the findings of: (i) previous class I modeling [8], where residual stress after composite polymerization shrinkage were considered, and (ii) class II MOD adhesive restoration models [17].

To minimize the stresses arising from composite polymerization during restoration of teeth, Kowalczyk [15] proposed a new approach in composite layering of class I composite restoration to overcome this problem arising from bulk placement. This objective was obtained by covering the cavity surfaces with an elongated composite thin layer, vertically and horizontally placed. This layer was termed the “pre-layer” and it was followed, in a second step, by further composite horizontal layering. The finite elements analysis of this modified class I technique showed a 75% reduction in the shrinkage stresses. The “pre-layer” assured a strong connection of the remaining layers with the tooth tissue due to suitable shrinkage vectors. After setting of the “pre-layer” the cavity size was smaller and the C-factor for the pre-layer was close to one

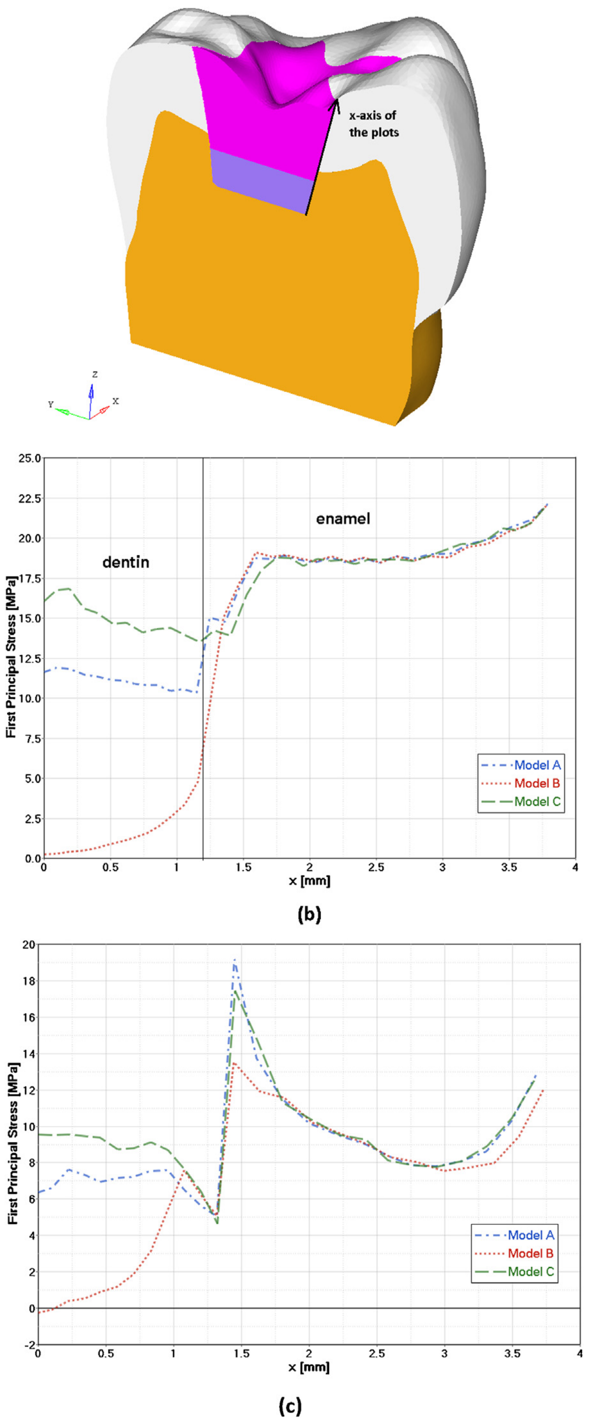

Fig. 5 – First principal stresses (MPa) plotted along an inspection line for each restored model: (a) x-axis of the plot; (b) trend in tooth tissue; (c) trend in material restoration.

($C \approx 1$), which gave quite a good result [15,26]. However, the role of the C-factor, in class I composite restoration has been differently analyzed [5,15,23]. Rodrigues et al. [38] evaluated a stylized model rectangular class I cavity of constant volume and wall thickness via the hypothesis that the interfacial shrinkage-stress at adjoining cavity walls increases steadily as the C-Factor increases. The authors noted that increasing C-Factor did not increase stress-peaks in their FE model of rectangular Class I cavity walls. In our investigation, a 4 mm deep class I cavity had a high C-factor configuration in model C and a decreasing C-factor in "bi-layered" models A and B. It is evident that many factors are involved in the full explanation of polymerization shrinkage stresses in class I designs. Fabianelli et al. [29] confirmed the need of composite layering to reduce the polymerization stresses of commercial composites in large class II cavities. These findings partially support our 3D-finite element analysis by experimental studies of shrinkage stresses in dentin and at the enamel margins.

In the present investigation, Model B, with a non-shrinking GIC lower filling layer produced a better stress-absorbing effect (Fig. 4b) compared to the other two models. This accords with a previous experimental study [35,37] where a liner material was suggested to reduce leakage after fatigue measurements. Sampaio et al. [39], studying class I adhesive restorations, confirmed the positive role of GIC and RMGIC as liners, but in this case thermocycling was used as a mode of stress testing. In Model B, the combination of a 1.5 mm GIC layer and a bulk fill composite significantly reduced the stress intensity in dentin, compared with Models A and C (Figs. 3–5). The high C-configuration stress distribution of models A, B and C were differently reduced, confirming previous results. Han et al. [40] experimentally found that in class I high C-factor cavities, the incremental technique gave improved bonding to the cavity floor than the bulk-fill technique. This suggests limiting bulk filling in class I adhesive restorations and reducing deep class I C-factor configurations via a" bi-layered" technique as we simulated in our A and B models.

5. Conclusions

This FEA linear analysis, assuming isotropic elastic material materials behavior, suggests that:

1 In 4 mm deep class I cavities, the use of a bulk fill composite ($E = 12$ GPa) with 1 % linear shrinkage created unfavorable stress distributions in deep dentin and at the enamel surface;
2 In the same cavities, combining resin-composite and a glass ionomer liner may reduce some of the residual stresses during shrinkage and loading.

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