Comparison of the Stress Distribution in Class I and Class II Amalgam and Bulk-Fill Composite Restorations Using CAD-FEM Modeling

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This study compares the mechanical strengths of bulk-fill composite resin and amalgam material to investigate the stress distribution and capacity to mitigate stress of restored Class I and Class II teeth under chewing loads, using finite element analysis. A 3D model of a human mandibular first molar and four Class I (C1) and Class II (C2) caries, including 95-degree cavity-margin angles, were created. Different material combinations were simulated: model C1-A and C2-A, with an amalgam material; and model C1-C and C2-C, with a bulk-fill composite resin. Solid 3D elements with four grid points were employed for modeling the tooth. A vertical occlusal load of 600 N was applied, and nodal displacements on the bottom cutting surfaces were constrained in all directions. All materials were assumed to be isotropic and elastic, and a static linear analysis was performed. The highest maximum principal stress was observed in C2-C, followed by C1-C, C2-A, and C1-A, respectively. The maximum principal stress load on the lingual cusp was recorded at the junction of the lingual margin (C1-C and C2-C), and stress was recorded on the line of restoration and enamel (C1-A and C2-A). Restoration materials and cavity preparations influence the stress distribution at the restoration-tooth interface and, consequently, the measured bond strength. Int J Periodontics Restorative Dent 2021;41:e1–e9. doi: 10.11607/prd.5024

Dental caries is a complex, chronic, and multifactorial disease, and it remains one of the most common health problems in industrialized and developing countries. A number of different techniques and a variety of materials can be used to restore or fill teeth affected by decay. The materials employed in modern dentistry to restore decayed teeth are principally dental amalgam, resin composite, and ceramic systems. However, the incidence of dental caries remains high despite the use of modern techniques and advanced dental filling materials in the diagnosis, prevention, and treatment of caries. The success of dental caries treatment depends on the lifespan of the filling material, which means that improving the quality of the filling material is an important issue in the field of dentistry. The qualities that an ideal dental material should exhibit include being sufficiently biocompatible to resist the influence of the oral caries medium, providing a strong and permanent connection to the structures of hard tooth tissues, possessing complex physical and mechanical properties corresponding to the properties of restored natural tissues, and promoting the recovery and regeneration of tissues.

Dental amalgam is considered to be an excellent and versatile dental restorative material. It has been...
used in dentistry for over 150 years due to its low cost, ease of application, strength, durability, and bacteriostatic effect. Yet, the popularity of amalgam as a restorative material is decreasing due to concerns about its detrimental health effects, negative environmental impacts, and relatively poor esthetics. Furthermore, aside from its poor appearance, the major limitation of dental amalgam is its inability to bond to the remaining tooth tissues, meaning that an effective seal is not created between the restoration and the tooth. Resin composite is the most common alternative to dental amalgam, although in the case of moderate to large composite restorations, it is associated with higher failure rates, more recurrent deterioration, and increased replacement frequency when compared with dental amalgam. However, the popularity of resin composite is now 3 to 3.5 times higher than that of dental amalgam despite the differences in durability (eg, the higher failure rates of composite restorations). The latest trend in composite technology concerns the development of so-called “bulk-fill” composites, which were created in order to cure up to 4 mm in depth. Bulk-filling techniques have become more widely used following the development of filling materials characterized by improved curing, controlled polymerization contraction stresses, and reduced cuspal deflection. Additionally, the use of bulk-filling techniques simplifies the restorative procedure, therefore saving clinical time spent treating deep and wide caries.

The restorations performed via bulk-filling techniques represent a complex system that consists of different substrates and interfaces, while the long-term performance of such restorations is the result of the behavior of various components and their ability to withstand both stress and deformation. The survival of composite restorations depends on the type of restoration, the number of bonded surfaces, the size of the cavity, and the type of restored tooth.

A finite element analysis (FEA) is a numerical method used to calculate various parameters when complex structures are loaded. In an FEA, the 3D tooth geometry is approximated by many small and simply shaped elements, while the deformation in terms of the stress-strain relation is evaluated for the single elements and then calculated for the whole structure. In addition, the application of an FEA allows for the calculation of the stress and strain within both the tooth structure and the biomaterials, which cannot be measured in vivo. Moreover, the use of numerical models and in vitro simulations is highly valuable with regard to saving time and money in laboratory and clinical research.

The present paper aimed to use the finite element method (FEM) to analyze the stress distribution across an intact mandibular molar tooth with a Class I or Class II mesiooccluso-distal (MOD) cavity design, restored using different materials.

Materials and Methods

An intact mandibular first molar tooth was used in this study, as prior studies have shown that the permanent mandibular first molars have the highest incidence of tooth fractures.

Modeling of a Molar Tooth

The first step in the FEA involved modeling. It is important to recognize that the quality of the analysis depends on the accuracy of the model.

An extracted mandibular first molar was scanned by means of computed tomography (CT) using a dental scanner (DW-7140 Series 7, Dental Wings). In this way, a solid virtual model of the tooth was obtained. The model was then exported to Ansys Mechanical R18 software (Fig 1). The Iso-Surface function available in Ansys SpaceClaim was used for the surface tessellation. Then, the 3D volumes were created using SolidWorks Professional software (Dassault Systèmes).

Cavity Preparation Design

A 3D model of the molar and four 3D models of Class I (C1) and Class II (C2) caries with 95-degree cavity-margin angles were created. Different material combinations were then simulated: models C1-A and C2-A, with an amalgam material; and models C1-C and C2-C, with a bulk-fill composite resin. Next, 3D solid
elements (SOLID187, Ansys) with four grid points were employed to model the tooth. Further, bonded-type contact elements were used between the enamel and the dentin.

The Ansys Mechanical R18 software was used to create the finite element models (Figs 2 and 3). The tooth model was placed into the coordinate system in such a way that the x-axis identified the buccolingual direction, the y-axis identified the mesiodistal direction, and the z-axis was oriented upward (Fig 4).

**Material Properties**

The properties of the tooth and the restorative materials were assigned to the models. Different Young’s modulus and Poisson ratio values were used for the restorative materials. The relevant data are presented in Table 1.
Numerical Simulation

Different values of Young’s modulus and Poisson ratio were used for materials. The four finite element models were analyzed successively (Table 2).

An occlusal load of 600 N was applied perpendicular to the occlusal surface, and the nodal displacements on the bottom cutting surfaces were constrained in all directions (Fig 5). All materials were assumed to be isotropic and elastic, and a static linear analysis was performed using Ansys Mechanical R18 software.

Results

The first maximum principal stress was used to assess the effects of the applied conditions (Fig 6). For each numerical experiment, the location, magnitude, and orientation of the maximum principal stress (σ₁) within the tooth model were identified and recorded. The maximum principal stress represents the largest normal stress acting on a plane of no shear stress, and it is determined based on the components of the stress in the buccal lingual plane according to the following equation:

$$\sigma_1 = \sigma_{11} + \sigma_{22} + \left(\frac{(\sigma_{11}-\sigma_{22})^2}{2} + (\sigma_{12})^2\right)^{\frac{1}{2}}$$

The highest maximum principal stress was observed in the C2-C model (129.9 MPa), followed by the C1-C (116.08 MPa), C2-A (72.666 MPa), and C1-A (35.664 MPa) models.

Figure 7a shows the mechanical behavior of the fully sound tooth. In the image, the occlusal load in the sound tooth is homogeneously dis-

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### Table 1 Material Properties

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young’s modulus, MPa</th>
<th>Poisson ratio</th>
<th>Thickness, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dentin</td>
<td>18,000</td>
<td>0.23</td>
<td>–</td>
</tr>
<tr>
<td>Enamel</td>
<td>80,000</td>
<td>0.30</td>
<td>–</td>
</tr>
<tr>
<td>Bulk-fill composite</td>
<td>12,000</td>
<td>0.25</td>
<td>–</td>
</tr>
<tr>
<td>Adhesive bonding</td>
<td>3,000</td>
<td>0.30</td>
<td>10</td>
</tr>
<tr>
<td>Amalgam</td>
<td>50,000</td>
<td>0.29</td>
<td>–</td>
</tr>
</tbody>
</table>

### Table 2 FEM Configurations

<table>
<thead>
<tr>
<th>Classification</th>
<th>Restoration class</th>
<th>Filling material</th>
<th>Total elements, n</th>
<th>Total nodes, n</th>
<th>Element quality, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Sound</td>
<td>–</td>
<td>1,229,363</td>
<td>1,702,576</td>
<td>92</td>
</tr>
<tr>
<td>C1-A</td>
<td>Class I</td>
<td>Amalgam</td>
<td>1,151,536</td>
<td>1,649,652</td>
<td>89</td>
</tr>
<tr>
<td>C1-C</td>
<td>Class I</td>
<td>Composite</td>
<td>1,292,999</td>
<td>2,107,771</td>
<td>87</td>
</tr>
<tr>
<td>C2-A</td>
<td>Class II</td>
<td>Amalgam</td>
<td>1,234,335</td>
<td>1,720,702</td>
<td>88</td>
</tr>
<tr>
<td>C2-C</td>
<td>Class II</td>
<td>Composite</td>
<td>1,252,999</td>
<td>1,759,947</td>
<td>86</td>
</tr>
</tbody>
</table>
tributed from the top enamel side down through the dentin. The maximum principal stress was recorded at the junction of the lingual cusp (Figs 7b and 7d, left side). Additionally, the principal stress loading on the lingual cusp was recorded at the junction of the lingual margin (Figs 7c and 7e, left side).

Though Fig 7b (right side) shows that the maximum stress was equally distributed throughout the central cavity, Fig 7d (right side) shows that it was concentrated on the lateral walls. The maximum principal stress was recorded on the line of restoration and enamel in Figs 7c and 7e (right side), and it was recorded on the lateral walls in Fig 7e.

Figures 8 and 9 show two cuts of the models under occlusal force. The mesial (Fig 8) and central (Fig 9) sections of the models are reproduced.

When subjected to the combined effects of the occlusal loading, the highest displacement map and the highest principal stress distribution were recorded in the C2-C model (Fig 7e) in both the mesial box (Fig 8e) and the central cavity (116.08 MPa; Fig 9e).

**Discussion**

Inside the oral cavity, the tooth and the restoration are subjected to two main types of stress: first, mechanical stress generated during functional activities, and second, thermal stress resulting from temperature fluctuations. Therefore, it is important to achieve a thorough understanding of the stress distribution.
Fig 8 Displacement (mm; left) and maximum principal stress distribution (MPa; right) under occlusal loading corresponding to mesial floor boxes, located on the cross-section along the buccolingual direction. (a) Model S (sound tooth model). (b) Model C1-A. (c) Model C1-C. (d) Model C2-A. (e) Model C2-C.

Fig 9 Displacements (mm; left) and maximum principal stress distribution (MPa; right) under occlusal loading at the center of the tooth, located on the cross-section along the buccolingual direction. (a) Model S (sound tooth model). (b) Model C1-A. (c) Model C1-C. (d) Model C2-A. (e) Model C2-C.
in order to enhance the longevity of restorations. The stresses generated during mastication as well as those concerned with polymerization shrinkage are considered to be the main causes of damage to and failure of adhesive dental restorations. The effects of chewing on dental resistance depend on several factors, including age and gender. The masticatory forces constantly change in terms of their direction, intensity, and point of application, depending on the contact between the tooth or restored tooth surface, as well as the food bolus on one side and the hardness and consistency of the food on the other side. A prior study suggested that in the case of a Class II MOD inlay, the 95-degree cavity-margin angles enduring a 600 N load provide a more relevant picture of the principal stress relief. To simulate the load distribution on the occlusal surface during mastication, slide-type contact elements were applied by means of a 3D FEA, although different Young’s modulus values were considered for the bolus, with a stable occlusal loading force (600 N) being maintained in every case. A lower Young’s modulus may allow stress dissipation during the polymerization process, thus reducing the stress in bigger increments at adhesive interfaces, particularly providing stress relief into the cusps. The current study focused on simulated loading and Young’s modulus of the materials involved.

To determine the breaking threshold of a fragile material, it is necessary to determine the main stress in the maximum plane, which serves as an indicator of the fracture, just like the lining material under an external load. Therefore, in the present study, the maximum in-plane principal stress was used to determine the failure thresholds of the adhesives under different loading conditions and different crown materials.

A solid 3D tooth model was created using CT-based data. This modern approach allows for the creation of a highly detailed 3D finite element model of a tooth, and it plays an important role in investigating different clinical situations in the field of dentistry. The FEA simulations indicated various important features that needed to be observed if high restoration performance was to be obtained in the posterior area. The chosen method is useful for obtaining information about the mechanical behavior of a sound and restored tooth, and it is able to demonstrate the stress distribution within the tooth-restoration complex, which would otherwise be impossible to determine. It also saves both time and cost in experimental studies and clinical trials, and it allows for an infinite number of variables to be studied. Thus, solid 3D modeling and FEA are commonly used technologies in contemporary dentistry, as they are essential tools for nondestructive investigations.

Many in vitro investigations of Class II posterior restorations have highlighted different aspects related to stress distribution with regard to the marginal and internal adaptation of adhesive Class II MOD restorations. The generation of stress and the location of peak stress can drastically change as a result of altered geometry and interfaced materials. Consistent with the present study, Arola et al reported that the lingual cusps of mandibular molars exhibited the highest frequency of fracture. Further, Wayne et al reported that there was a high stress concentration along the amalgam, enamel interface, and lingual transverse ridge of mandibular molars.

In the present study, different cavity designs and different types of materials were compared. It was found that C2 produced more stress than C1, while the composite showed more stress than the amalgam. Coelho Santos and Bezerra found that cavity preparation significantly weakened the remaining tooth structure. Moreover, Eakle et al found that if the restoration is conservative, less fracture occurs in the teeth. The present study also found that cavity preparations significantly weaken the remaining tooth structure. It is likely that the increased stress formation seen in C2 can be explained by this situation.

Ausiello et al evaluated the effects of different restorative materials and cavity designs on the stress distributions across the tooth structures by means of 3D FEA. Resin-composite bulk-filling material, indirect CAD/CAM resin composite inlay, and indirect lithium disilicate machinable inlay were used in their study. The bulk-fill resin composite with 1% polymerization shrinkage was found to negatively affect the marginal and internal stress adaptation in large Class II MOD adhesive restorations.
found no significant difference in the magnitude of the maximum stress between molars with amalgam and light-curing composite restorations. Braga et al. sought to evaluate the effects of flowable bulk-fill and conventional composite resin on the stress distribution within MOD cavity preparations. They reported that the flowable bulk-fill achieved higher microtensile bond strength values than the conventional composite resin.

According to the results of the present study, greater stress formation was observed in the bulk-fill composite material than in the amalgam.

Restoration bond strength is affected by the bond strength of the adhesive system, Young’s modulus values, the remaining tooth structure, and the tooth-restoration interface. Braga et al. reported that the bond strength values for flat-prepared cavities were higher than the MOD cavities, regardless of the type of material that was used. This result may be explained by the configuration factor (C-factor).

The lower the C-factor, the lower the stress level generated. In this study, the principal maximum stress in C2 models occurred more than in C1 models, and this may be related to the C-factor.

In addition, the stress areas were found to be intense in the cusps and along the lingual transverse ridge. In the C2 cavity design, the stress formation was greater, and it increased as the tooth structure weakened. However, a lower Young’s modulus may allow stress dissipation. Therefore, bulk-fill composites, which have a similar Young’s modulus to dental tissues, can be preferred in the posterior region where the occlusal force is high.

**Conclusions**

This study evaluated and compared the stress distribution within mandibular molars with amalgam and bulk-fill composite restorations, as well as with C1 and C2 cavity designs, using an FEA.

Despite the limitations of this study, the following conclusions can be drawn: (1) Restorative materials and cavity preparations influence the stress distribution at the restoration/tooth interface and, consequently, the measured bond strength; (2) in the Class I cavity design, the stresses within the molar with an amalgam restoration were lower than those with a bulk-fill composite restoration, and the maximum stress occurred along the lingual cusp; (3) in the Class II cavity design, the stresses within the molar with an amalgam restoration were lower than those with a bulk-fill composite restoration, and the maximum stress occurred along the lingual cusp and central cavity; and (4) the bulk-fill resin composite negatively affected the stress adaptation in the Class I and Class II MOD restorations.

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**References**

4. Moiseeva NS, Kunin AA. Clinical and laboratory evaluation of microstructural changes in the physical, mechanical and chemical properties of dental filling materials under the influence of an electromagnetic field. EPMA J 2018;9:47–58.


