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Original Article

Influence of Inlays/Onlays and Their Material on Stress Distribution in Mandibular Molars: Finite Element Analysis

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Abstract

Background: This study aimed to evaluate the influence of inlays/onlays and their material on stress distribution in mandibular molars with large cavities, using finite element analysis (FEA).

Methods: 3D models of the first mandibular molar were created. Then, a mesio-occluso-distal cavity was created, and cusps were reduced (1.5 mm for buccal cusps and 1 mm for lingual cusps). The restorations were: inlay, onlay that covered buccal cusps (B models), and onlay that covered all cusps (LB models). Inlays and onlays were represented by two materials: nanofill composite resin and polymer-infiltrated ceramic network (PICN). Vertical load of 600 N was applied and von Mises stresses were calculated.

Results: Inlay models showed higher stress concentration in tooth structures than onlay models. Composite resin inlays and onlays transmitted most of the stress to adjacent structures. On the other hand, PICN inlays/onlays absorbed most of stress and transmitted less stress to dental structures than composite resin restorations. Moreover, stress concentrations in PICN onlay models (B-buccal cusps and LB-all cusps) were similar, while composite resin LB onlay showed higher stress concentration in dental structures than composite resin B onlay.

Conclusions: Onlays showed better stress distribution than inlays. PICN might be a suitable choice as a restorative material of inlay/onlay for large cavities in molars, while the composite resin is unfavorable material for such restorations in terms of stress redistribution in dental structures.

Keywords: Ceramics, Composite resins, Inlays, Onlays, Finite element analysis

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Introduction

Posterior teeth show hard tissue loss due to caries, trauma, abrasion, and other factors (1,2). Restorative materials must be biocompatible and able to withstand different conditions in the oral environment (1). The inlay is an intracoronal restoration that does not cover any cusp, whereas the onlay is a partial-coverage restoration that covers at least one cusp (3). Inlays and onlays provide conservative restorations for posterior teeth since preparation for inlay/onlay involves removing about 27%-39% of intact tissues, respectively, while preparation for a full crown requires removing 67.5%-75.6% of intact tissues (4). Furthermore, the mean survival rate of inlays is 90.89%, while it is 93.50% for onlays (5).

Inlays and onlays can be made of several materials such as composite resin and ceramic (6). Composite resin restorations could be fabricated directly in the mouth or indirectly. Direct restorations have some drawbacks such as poor contact points and polymerization shrinkage, while

indirect way provides better mechanical and anatomical properties (2). Indirect composite resin systems contain a high amount of glass fillers. Indirect composite resins provide high mechanical and aesthetic properties, good marginal integrity, and low polymerization shrinkage (7). Composite resin can be classified into megafill, macrofill, midifill, minifill, microfill, hybrid, and nanofill composite resins according to the size and amount of filler particles. Nanofill composite resin contains silica or silica and zirconia as filler particles with a size of 20 nm (7). Having nanofillers in its composition, nanocomposite resin shows high mechanical resistance, high optic properties, low water absorption, and good surface quality. Therefore, it could be used for both anterior and posterior restorations (7). Filtek™ Supreme (3M ESPE, USA) is an example of nanofill composite resin which could be used for direct restorations as well as indirect restorations including inlays and onlays (8).

Ceramic restorations have improved aesthetic



appearance and physical properties; however, they have much higher elastic moduli than dentin (9,10). Trying to produce materials whose elastic moduli are closer to the elastic modulus of dentin and materials that can be milled and fabricated easily, especially by computer aided design/computer aided manufacturing (CAD/CAM) technique, resin-matrix ceramic materials have been introduced (11). Various types and amounts of resin matrices and ceramic fillers are used in resin-matrix ceramics (12). Polymer-infiltrated ceramic network (PICN), which is described as hybrid ceramic, consists of a sintered feldspathic ceramic network (86% by weight) and a polymer network (14% by weight) (11). The ceramic network is pretreated with a coupling agent. Then, it is infiltrated with monomers which polymerize later and organize within the ceramic network. Consequently, the two networks combine together within the material (13).

The results of previous studies about inlays and onlays are still conflicting. Some authors concluded that cusp coverage was necessary to protect dental structures and improve the pattern of stress distribution (10,14), while others found that fracture resistance of inlays (2646.7N) was higher than fracture resistance of onlays (1673.6N) (15). Furthermore, composite resin restorations were found to be associated with good patterns of stress distribution in dental structures (2,6). However, other studies concluded that PICN restorations were better than feldspathic ceramic and composite resin in terms of stress distribution and fracture strength (16,17). The present study was conducted to evaluate the influence of inlays and onlays and their materials on stress distribution in mandibular molars when a vertical load was applied, using finite element analysis (FEA).

Materials and Methods

Modelling and Preparation

This study was performed using 3D FEA. A left first mandibular molar was scanned by cone-beam computed tomographic imaging (CBCT). Then, the scans were imported to Materialise Mimics software version 21.0 (Leuven, Belgium) to isolate tooth structures. Materialise 3-Matic software (Leuven, Belgium) was also used and 3D models were exported as STL files. Using a reverse engineering program (Geomagic Studio 2012, Geomagic Inc, USA), the models were refined and saved as IGES files. Afterwards, they were converted into solid bodies by PowerShape Ultimate 2017 (Autodesk Inc, USA) which was also used to perform Boolean operations. Then, SolidWorks 2018 (Dassault Systèmes SolidWorks Corporation, USA) was used to create 3D models of spongy bone, cortical bone, and tooth structures. A mesio-occluso-distal (MOD) cavity was created for an inlay preparation. The occlusal cavity was larger than two-thirds of the intercuspal distance in width and 2.0 mm in depth. The inlay preparation was modified by reducing the cusps to represent preparations for buccal-cusp-coverage onlay (B onlay model) and all-cusp-coverage onlay (LB onlay

model). Buccal cusps were reduced by 1.5 mm and lingual cusps were reduced by 1.0 mm.

The studied restorations included inlay, B onlay (covered buccal cusps), and LB onlay (covered all cusps) (Figure 1). Finally, all objects were imported into ANSYS Workbench version 20.0 R2 (Ansys Inc; Canonsburg, Pennsylvania, USA) as parasolid (x.t) files to perform FEA. Two restorative materials were represented for each restoration: (C) composite resin and (P) PICN. A mesh of linear tetrahedral quadratic elements connected in nodes was generated for each model. The total number of elements and nodes in the models is summarized in Table 1.

Material Properties and Meshing

All materials were assumed to be isotropic, homogeneous, and linear elastic. The mechanical properties of all materials used in this study are taken from the literature. A summary of the mechanical properties is shown in Table 2.

Boundary Conditions

The models were fixed at the inferior surface of the cortical bone. A vertical load of 600 N was applied to buccal cusp tips, central fossa, and distal marginal ridge. Then, stresses were analyzed according to von Mises stress in all models.

Results

The data obtained from the FEA were presented in maps with a color scale ranging from the highest values (purple and red colors) to the lowest values (blue color) in all models. Stress distribution patterns in the models are shown in Figures 2 to 5. The von Mises theory was used to determine the stress distribution in enamel, dentin, and restoration. The maximum stress values evaluated in

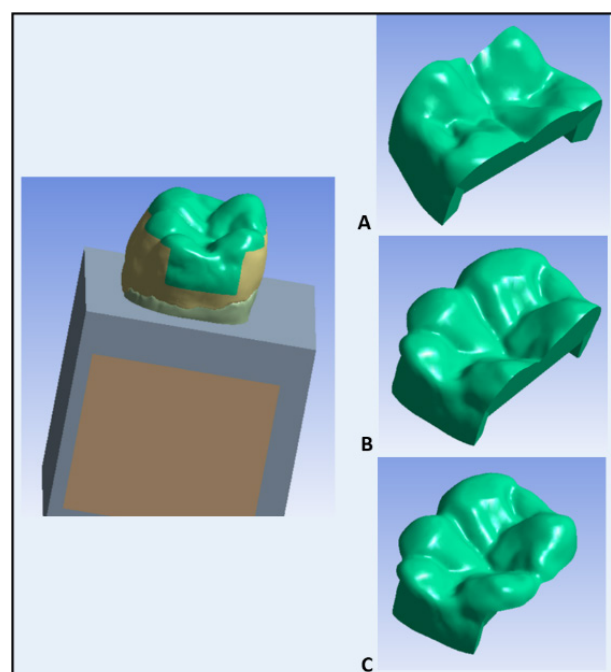


Figure 1. The Studied Model. A: Inlay, B: Onlay covering buccal cusps, and C: Onlay covering all cusps.

megapascals (MPa) are summarized in Table 3.

Stress Distribution in Tooth Structures

Color maps showed that stress was concentrated in the cervical area of the tooth in all models (Figures 2 and 3). It was also concentrated in the buccal cusps and the internal buccal wall of the occlusal cavity in inlay models (Figures 2C and 3C).

Stress concentration in the composite resin inlay model was higher compared to PICN inlay model (Figures 2C and 3C). Inlay models had more stress concentration in enamel and dentin than B and LB onlay models (Figures 2 and 3).

In onlay models (B and LB), stresses were concentrated in the internal buccal wall of the occlusal cavity as well as the cervical area of the tooth, particularly the distal cervical region. Stress in dental structures in B onlay model was similar to stress in LB onlay model when the material was PICN (Figures 2A and 2B), while stresses in dental structures in composite resin LB onlay model were higher compared to composite resin B onlay model (Figures 3A and 3B). However, composite resin models showed greater stress concentration in enamel than in PICN models irrespective of the design of the restoration (inlay, B onlay, or LB onlay) (Figures 2 and 3).

The values of von Mises stress in dental structures are shown in Table 3. Composite resin LB onlay model showed the highest values of stress in enamel and dentin among all models.

Table 1. Number of Elements and Nodes of the Models

Model	Elements	Nodes
Inlay	37937	72030
B onlay*	61531	131946
LB onlay**	84525	153238

* B onlay: covered buccal cusps; **LB onlay: covered all cusps.

Table 2. The Mechanical Properties of Studied Materials

Material	Young's modulus (GPa)	Poisson's Ratio	Reference
Enamel	84	0.33	(18)
Dentin	18.6	0.30	(18)
Pulp	0.002	0.45	(19)
Cortical bone	13.7	0.30	(18)
Spongy bone	1.37	0.30	(18)
PICN	30	0.23	(20,21)
Composite resin	12.7	0.35	(18)

Table 3. The Values of von Mises Stresses (MPa) in Dental Structures and Restorations in All Models

Model	Enamel	Dentin	Restoration
Inlay/PICN (P)	212.74	45.387	60.501
Inlay/Composite resin (C)	209.54	42.896	59.412
B ¹ -Onlay/P*	354.35	137.72	71.376
B ¹ -Onlay/C**	234.26	42.343	88.801
LB ² -Onlay/P*	374.49	205.44	79.515
LB ² -Onlay/C**	408.88	257.33	90.148

¹ B: onlay that covered buccal cusps; ² LB: onlay that covered all cusps. *P: PICN (polymer infiltrated network ceramic); ** C: composite resin.

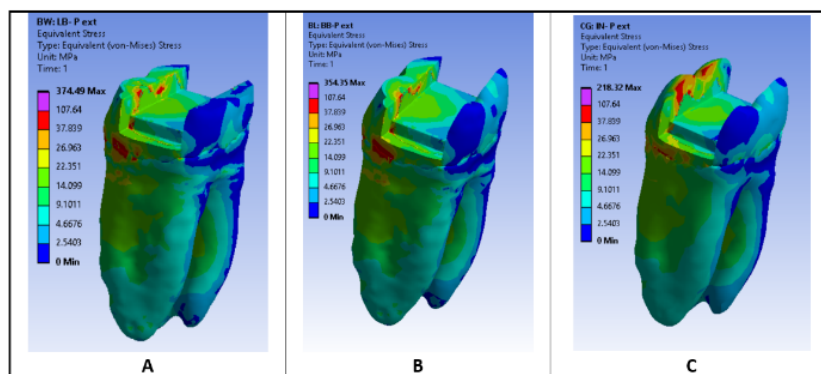


Figure 2. Stress Distribution in Dental Structures in PICN Models: (A) LB onlay model (all cusp coverage), (B) B onlay model (buccal cusp coverage), (C) Inlay model.

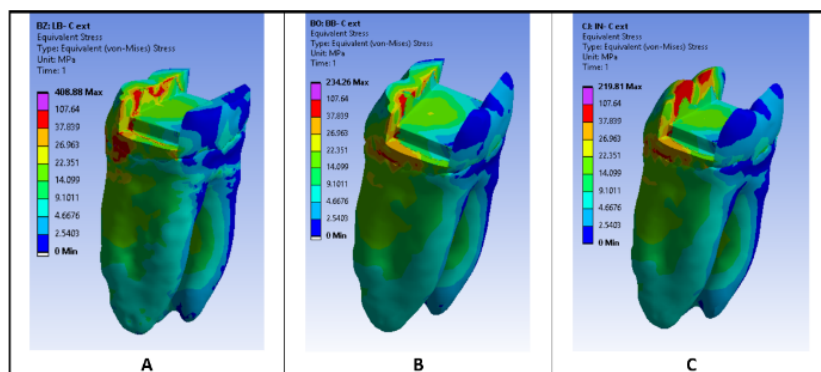


Figure 3. Stress Distribution in Dental Structures in Composite Resin Models: (A) LB onlay model (all cusp coverage), (B) B onlay model (buccal cusp coverage), (C) Inlay model.

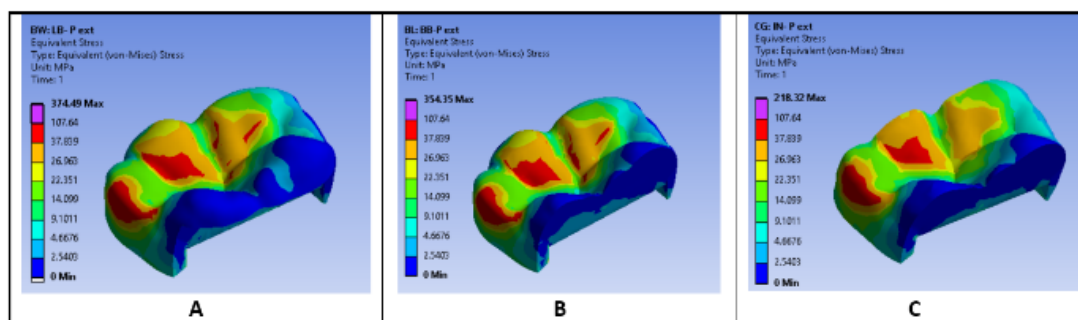


Figure 4. Stress Distribution in PICN Restorations: (A) LB onlay model (all cusp coverage), (B) B onlay model (buccal cusp coverage), (C) Inlay model.

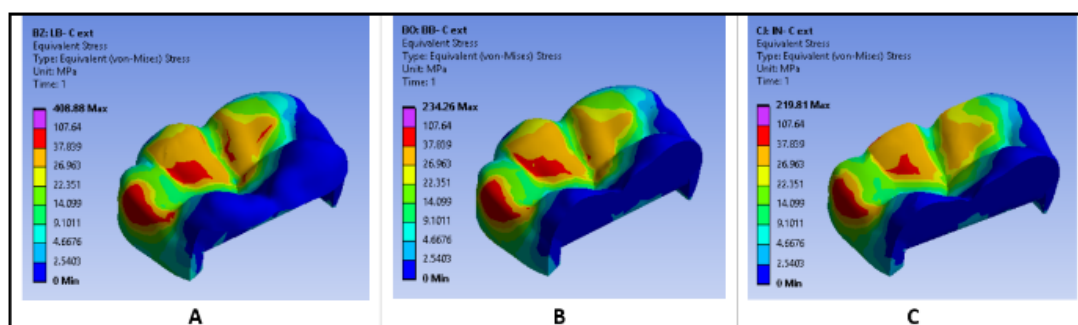


Figure 5. Stress Distribution in Composite Resin Restorations: A. LB onlay model (all cusp coverage), B. B onlay model (buccal cusp coverage), C. Inlay model.

Stress Distribution in Restorations

Stress was concentrated in the internal slope of the middle buccal cusp and the distal marginal ridge in inlays and onlays. Stress lay on larger space in onlays than in inlays (Figures 4 and 5). It was also concentrated in the mesio-buccal cusp of PICN onlays (B and LB) and composite resin LB onlay (Figures 4A, 4B, and 5A). Stresses in restoration in both B and LB PICN onlay models were similar (Figures 4A and 4B), whereas the composite resin LB onlay model showed greater stress in the restoration than B onlay model (Figures 5A and 5B). All PICN models showed higher stress concentration in the restoration than composite resin models (Figures 4 and 5). The values of von Mises stresses in all restorations are shown in Table 3. Composite resin LB onlay showed the greatest value of stress in the restoration.

Discussion

FEA is considered an effective tool to analyze stresses in complex structures and evaluate their behavior under diverse conditions. Using FEA helps to predict the clinical performance of the restorative materials and the dental tissues in tooth-restoration complex (22). The current study aimed to evaluate stress distribution in mandibular molars with large cavities restored by inlays and onlays from different materials. Therefore, MOD cavities were created as mentioned in the literature (23). An average load of 600 N was applied to occlusal contact points (2,18). Then, stress was analyzed using equivalent von Mises stress, which is considered an indicator of the potential failure in the studied structures as it calculates all principal stresses (tensile, shear, and compressive stresses) in the

study field (22).

Color maps showed that stress was concentrated in the loading points which are the occlusal contact points on enamel or onlay. It was also seen in the cervical area of the tooth. This result is consistent with the results of previous studies (2,10,24). Furthermore, stress was concentrated highly in the buccal cusps and the internal buccal wall of the occlusal cavity in inlay models. The finding is consistent with the findings of previous studies (10,18). This pattern of stress concentration might indicate clinical failure of dental structures or chipping of the buccal occlusal margins of inlay (10). Wear of composite resin inlay is higher and faster than the wear of the adjacent enamel. As a result, forces would act mainly on the dental structures which remain in more height than the inlay, and that may lead to tooth fracture (10,25). On the contrary, the wear rate of PICN is low, which is similar to that of lithium disilicate ceramic (20). Consequently, stresses in the buccal wall, which might be in the tooth-inlay interface, may lead to fracture or chipping of PICN inlay rather than fracture of the tooth (10,25).

Onlay models showed less stress concentration in dental tissues than in inlay models. It could be explained by cusp coverage. Forces were applied mainly on B and LB onlay models which absorbed most of the stress, while forces acted mainly on the buccal cusps of enamel with some forces applied on inlay. Therefore, more stresses were concentrated in dental structures in inlay models. These findings are in agreement with many studies which found that cusp coverage is an important factor in protecting the remaining tooth structures (10,14,18).

The pattern of stress distribution in dental structures in

PICN B onlay model was similar to the pattern in PICN LB onlay model, whereas composite resin LB onlay model showed higher stress concentration in dental structures than B onlay model. This result could be attributed to the elastic modulus of the restorative material and its volume (10,26). Due to the low elastic modulus of composite resin, it transmits a lot of stress to tooth structures. Moreover, when more cusps are covered by composite resin onlay, the onlay volume increases and stress transmission to tooth structures increases as well. On the contrary, the elastic modulus of PICN is high and closer to the elastic modulus of dentin compared to composite resin. Furthermore, the more cusps are covered with PICN onlay, the more tooth structure protection could be provided by PICN restoration. This finding is in line with that of a study by Chang et al (27) who found that covering buccal and palatal cusps with ceramic onlays reduced stress concentration in dental structures although their study was carried out on upper premolars.

According to the restorative material and regardless of the restoration design, color maps showed that composite resin models had less stress concentration in the restoration and much more stress concentration in dental structures than PICN models. The results can be explained by the elastic moduli of the studied restorative materials. The higher the elastic modulus of the material, the higher the stress concentrates in the restorations (10). The elastic modulus of PICN is nearly three times as high as the elastic modulus of composite resin. Therefore, composite resin inlays and onlays cause great stress concentration in the surrounding dental tissues, while PICN restorations absorb stresses and minimize stress transmission to tooth structures (10).

Although FEA helps to predict clinical failure, it is hard to create all clinical situations precisely. For instance, all materials were assumed to be linear elastic and homogeneous even though their properties may be different in reality. Moreover, luting cement thickness was not represented since many previous studies accepted it as a part of dental tissues (6,22). It is also difficult to represent a non-uniform thickness of cement layer the same as its real thickness around restoration (2).

Conclusions

Within the limitations of this study, the following conclusions were drawn:

1. Onlays showed a better pattern of stress distribution in dental structures than inlays.
2. PICN inlays/onlays showed good behavior in terms of stress distribution. This behavior may make PICN a good choice as a restorative material for large cavities in molars, particularly when coverage of all cusps is required.
3. Composite resin inlays/onlays did not show a good pattern of stress redistribution in dental structures. Therefore, composite resin might be unsuitable

material for the restoration of large cavities in molars.

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Formal Analysis: Ayham Darwich, Abeer Aljareh.

Investigation: Ayham Darwich, Abeer Aljareh, Omar Aladel.

Methodology: Ayham Darwich, Abeer Aljareh, Omar Aladel.

Resources: Ayham Darwich, Abeer Aljareh, Szabolcs Szávai, Hasan Nazha.

Software: Ayham Darwich, Abeer Aljareh, Szabolcs Szávai, Hasan Nazha.

Supervision: Ayham Darwich, Omar Aladel.

Validation: Szabolcs Szávai, Hasan Nazha.

Visualization: Szabolcs Szávai, Hasan Nazha.

Writing – original draft: Ayham Darwich, Abeer Aljareh.

Writing – review & editing: Abeer Aljareh, Szabolcs Szávai, Hasan Nazha.

Conflict of Interest Disclosures

All authors were fully involved in the study and preparation of the manuscript and declared that they had no conflict of interest.

Ethical Statement

This study was approved by the Ethics Committee of Damascus University (No. 3101 dated 6/8/2018).

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