Conservative Dentistry Journal Vol. 14 No. 2 July-December 2024; 47-51

Literature Review

Evaluation of stress distribution in coronal base and restorative materials: A narrative review of finite element analysis studies

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ABSTRACT

Background: *Analyzing the stresses created by functional and parafunctional forces on teeth, bones, soft tissues, and intraoral dental materials is crucial for enhancing the success and development of restorations.* ***Purpose:*** *The purpose of this review is to evaluate studies that examine stress distribution in coronal base and restorative materials using the method of finite element analysis.* ***Review:*** *The three-dimensional finite element analysis method is extensively utilized to study biomechanical behavior and assess stress distribution within dental materials. Numerous studies from 2010 to 2024 have investigated the stress caused by polymerization shrinkage and the distribution of stress in various base and restorative materials.* ***Conclusion:*** *This review emphasizes findings related to stress distribution in coronal base and restorative materials, stressing the importance of considering the elastic modulus and thickness of base materials, and highlighting the need for additional research in this field.*

Keywords: *Finite Element Analysis, Pediatric Dentistry, Stress Distribution, Coronal Base and Restorative Materials.*

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INTRODUCTION

Dentistry is a rapidly evolving field of healthcare that involves working with various materials. These materials are exposed to numerous forces and stresses from different angles created by oral tissues.[1,2] Determining the behavior under force and stress analysis of living tissues or organs is often complex, costly, and in some cases, impossible.[3] However, analyzing the stresses created by functional and parafunctional forces on teeth, bones, soft tissues, and intraoral dental materials is crucial for enhancing the success and development of restorations.[4] Therefore, stress analysis may be required in models that simulate living tissues. Various stress analysis methods are used to identify the regions where intraoral forces concentrate, to strengthen these areas, and to determine the ideal design.[5]

Finite Element Analysis (FEA) is an engineering technique applied to evaluate stress and strain in various materials, including biological tissues. This method relies on modeling the structures to be analyzed as realistically as possible and expressing them mathematically. With the advancement of computer technology, FEA has become more widely used in research. This computer-assisted analysis offers more detailed and realistic results compared to other methods. The FEA technique involves dividing the structure into a finite number of elements and mathematically analyzing its behavior under applied forces. In the model, the shape changes, stress distribution, and intensity resulting from forces applied at certain magnitudes, directions, and areas are identified in this way.[6,7] To perform an analysis using the Finite Element Analysis (FEA) method, certain data are entered into the computer; these include the geometric model (area), material behavior (elastic modulus, Poisson's ratio, and density), loading forces, and finally boundary conditions. Once the model is fully defined and meshed, stress analysis is performed, and stress distributions are obtained.[8]

Moreover, FEA is a broadly used research tool in dentistry which offers significant advantages compared to laboratory tests. These advantages include the ease of adjusting variables, the ability to perform simulations without the need for biological samples, and providing high standardization. Although FEA is effective in visualizing maximum stress and displacement points, its disadvantages include difficulties in simulating complex geometries and the impact of time-dependent changing conditions on materials. Despite these limitations, FEA can reduce the need for laboratory tests, but it is not expected to completely replace them. While it offers the advantage of providing quick solutions, it has certain limitations, such as not fully simulating the tooth and supporting structures' biological dynamics.[9] With the rapid advancements in restorative techniques and dental materials, FEA has become a commonly utilized and accepted method in numerous biomechanical studies to evaluate the effect and distribution of stress on dental materials.[10]

DOI: https://doi.org/10.20473/cdj.v14i2.2024.47-51

This review aims to summarize finite element analysis (FEA) studies evaluating stress distribution in coronal base and restorative materials and assess their impact on clinical performance. The study highlights FEA's capacity to perform stress analyses with high accuracy and flexibility under complex geometry and material properties, emphasizing its superiority over other techniques. Furthermore, the advantages of FEA and its implications for clinical applications are discussed.

METHODS

The three-dimensional finite element analysis method is extensively utilized to study biomechanical behavior and assess stress distribution within dental materials. Numerous studies from 2010 to 2024 have investigated the stress caused by polymerization shrinkage and the distribution of stress in various base and restorative materials. Information obtained from these studies are discussed in this review.

RESULTS

Investigation of Stress Distribution in Coronal Base Materials

In the study by Zhan Liu et al., the outcome of four different base materials on stress distribution in teeth and composite resin restoration under occlusal loading in a Class I cavity was investigated. The model using light-cured glass ionomer cement was shown to have the lowest stress on dentin and enamel, indicating that its use as a single-layer base material is an ideal option. Additionally, in dual-layer base applications, light-cured calcium hydroxide was found to be superior to self-curing calcium hydroxide according to von Mises stress analyses. Furthermore, when evaluated as single-layer base materials, light-cured glass ionomer was found to be a more effective option than self-curing calcium hydroxide.[13]

In a study by Jung et al., the impact of diverse base materials and their thicknesses on the extent and stress distribution in maxillary premolars with MOD cavity composite restorations was evaluated using 3D FEA. The results indicated that in Class II MOD cavities when applying base materials such as glass ionomer cement, low-flowing resin cement, and tricalcium silicate cement reduced marginal stress caused by composite resin polymerization shrinkage. However, it was concluded that variations in the elastic moduli of base materials and polymerization shrinkage did not impact stress distribution in composite resin and the tooth, and that differences in base material thickness (0.5 mm and 1.0 mm) did not have a significant impact on stress distribution.[14] Similarly, an in vitro study reported that changes in base thickness from 0.5 mm to 1.0 mm for both resin-modified glass ionomer cement and low-flowing resin cement did not significantly alter the stress induced by the composite resin polymerization shrinkage of the.[15] On the other hand, in vital pulp therapies, the compressive strength of pulp cap materials is considered an vital physical property. In this context, a study examining the stress distribution on mineral trioxide aggregate (MTA) put over pulp perforations during restoration, and the application of MTA at various thicknesses with different perforation widths, showed that stress decreased as MTA thickness increased. According to the study, it is indicated that MTA should be applied at a thickness of at least 2-3 mm to withstand the pressures applied during restoration.[16]

In the research by Gönder et al., the effects of two different types of cement (glass ionomer cement and resin cement) at different thicknesses and amalgams with different Young's modulus values on stress distribution in restoration, dentin, enamel, and in Class II disto-occlusal (DO) cavities were examined using finite element analysis (FEA). The study results revealed that glass ionomer and resin cements did not create a significant difference in stress accumulation at any thickness. However, both types of cement with a thickness of 150 µm demonstrated reduced stress accumulation on the surface of restoration. Additionally, the combination of 150 µm thick amalgam and cement with a 50 GPa Young's modulus was associated with the lowest stress accumulation. These findings suggest that optimizing cement thickness and using materials with a high elastic modulus in clinical applications can improve stress distribution.[17]

In the study by Anatavara et al., the effects of using flowable composite resin under Class I resin composite restorations on stress by occlusal force and polymerization shrinkage were investigated. The study results showed that adhesive layer and the enamel at the cavo-surface region were among the structures most affected by shrinkage stress, and the use of flowable composite resin reduced this stress.[18] Similarly, Yamamoto et al. suggested materials with a higher elastic modulus are appropriate for use as base materials in posterior restorations.[19]

A recent study used Finite Element Analysis to analyze the stress generated in areas restored with composite resin in post endodontically treated teeth. This study examined the effects of different base materials and restorative techniques on stress formation and revealed that oblique forces generated more stress compared to vertical. Additionally, it was found that the use of coronal overlay and fiber-reinforced restorative materials after endodontic treatment did not significantly affect stress distribution on the tooth.[20]

However, in the 3D finite element analysis (FEA) study by Halaçoğlu and Kıvanç Yamanel examining the effects of different base materials on stress after root canal treatment, short fiber-reinforced composite resins were found to be advantageous in preventing high stress in both the restoration and the tooth due to their elastic modulus being similar to dentin. The study demonstrated that in post endodontic treated teeth, different base materials, particularly glass ionomer cements and fiber-reinforced composites, could be more suitable choices in preventing stress formation due to their elastic moduli being similar to dentin.[21] Some of the studies investigating stress distribution in coronal base materials are summarized in Table 1.

Table 1. Comparison of Stress Distribution Studies on Coronal Base Materials

Authors	Material Type	Cavity Type	Results
Zhan Liu et al.[13]	Light-cured glass ionomer cement, light-cured calcium hydroxide, self-curing calcium hydroxide	Class I	Lowest stress on dentin and enamel with light-cured glass ionomer cement; light-cured calcium hydroxide superior in dual-layer applications
Jung et al.[14]	Glass ionomer cement, low-viscosity resin cement, tricalcium silicate cement	Class II MOD	The use of base materials reduced marginal stress; however, the thickness of the base did not significantly influence stress distribution
Gönder et al.[17]	Resin cement, glass ionomer cement, amalgam with different Young's modulus	Class II disto-occlusal (DO)	Both types of cement at 150 μm resulted in lower stress accumulation; optimizing cement thickness improves stress distribution
Anatavara et al.[18]	Flowable composite resin	Class I	Flowable composite reduced shrinkage stress on enamel and adhesive layer
Halaçoğlu and Yamanel.[21]	Fiber-reinforced composite, glass ionomer cement	Root canal treated teeth	Fiber-reinforced composite and glass ionomer cements suitable for stress reduction in root canal treated teeth

Even though various base materials have been suggested in the literature for use with composite resin restorations, a consensus on the optimal base material and thickness has yet to be established. Thus, more comprehensive studies are required to determine the influence of base materials with different elastic moduli and thicknesses on stress distribution in coronal restorations.

DISCUSSION

Investigation of Stress Distribution in Restorative Materials

Finite Element Analysis (FEA) contributes to understand stress analysis in teeth and restorations and dental biomechanics while enabling the development of biomimetic approaches in restorative dentistry. FEA is widely used to optimize stress distribution in restorative materials and to examine stress distribution in cavity-prepared teeth.[22] In the study by Hasija et al., the stress distribution of different restorative materials in Class V restorations was studied using finite element analysis. A 3D model of the maxillary first premolar tooth was created, and restorations were made using micro-filled composite, glass ionomer cement, resin-modified glass ionomer cement, and flowable composite. The results revealed the best performance was shown by the micro-filled composite, followed by flowable composite, glass ionomer cement, and resin-modified glass ionomer cement, respectively. It is recommended that materials with a high elastic modulus should be used in the restoration of Class V cavities for optimal clinical outcomes.[23]

In the study conducted by Doğan et al., the effects of stress generated by composite resin and glass carbomer materials in inlays in Class I design cavity were investigated. Finite element analysis and three-dimensional modeling were used to evaluate the stresses in hybrid composite and glass carbomer inlays under a 300 N load applied to the occlusal surfaces. The findings revealed that the maximum von Mises stress values in composite resin inlays were lower compared to glass carbomer inlays, although glass carbomer demonstrated greater resistance to applied forces. Within the limitations of this study, it can be advised that glass carbomer may be a more preferable inlay restoration material, as it retains stress within its structure, transmitting less stress to the tooth structure. Glass carbomer inlays were found to be more suitable, especially in cases where the supporting tooth structure is compromised.[24] In the FEA study by Şengül et al., stress distributions were evaluated according to different restorative materials used in primary molar teeth. A total of 12 Class II cavity models and one control model were analyzed. The highest von Mises stress values were shown to concentrate on the enamel and restoration surfaces of the restored tooth. In terms of stress on the enamel, flowable composite resin showed the highest stress, while hybrid composite resin showed the lowest. Regarding stress on the restoration, flowable composite resin had the lowest, and hybrid composite resin had the highest stress. These findings suggest that restorative materials with an appropriate elastic modulus, which can balance stress concentrations, should be chosen to increase the clinical success rate of the tooth's hard tissue and restorative material.[25] In the study by Kantardžić et al., the effects of cusp reduction and isthmus width of the cavity on the stress values of restorative materials in premolars with mesio-occlusal-distal (MOD) cavities were investigated. In three-dimensional models created using computed tomography (CT) scan images, four different restorative materials and three different cavity preparation designs were evaluated. Stress values on enamel were found to vary depending on the cavity preparation design, while stresses in dentin were dependent on the restorative material used. The lowest stress values were observed in models that included cusp coverage and indirect restorations. Specifically, ceramic restorations covering both buccal and palatal cusps showed the most favorable stress distribution in premolars with MOD cavities.[26]

In another study, the stress generated under functional forces in models of maxillary incisors with horizontal and oblique fracture types restored with different fiber-reinforced composite resin restorations (FRC) was evaluated

Table 2. Comparison of Stress Distribution Studies on Restorative Materials

Authors	Material Type	Cavity Type	Results
Hasija et al.[23]	Micro-filled composite, resin-modified glass ionomer cement, flowable composite, glass ionomer cement,	Class V	Micro-filled composite performed best, followed by flowable composite; high elastic modulus materials recommended
Doğan et al.[24]	Glass carbomer, composite resin	Class I	Glass carbomer exhibited higher resistance to forces; composite resin showed lower von Mises stress
Şengül et al.[25]	Flowable composite resin, hybrid composite resin	Class II	Flowable composite showed highest stress on enamel, hybrid composite lowest stress on enamel
Kantardžić et al.[26]	Ceramic restorations, indirect restorations	Mesio-occlusal-distal (MOD)	Ceramic restorations that covered both the palatal and buccal cusps demonstrated the most favorable stress distribution
Zheng et al.[28]	Ceramic, polymer-infiltrated ceramic (PICN), composite resin produced from CAD-CAM blocks	Endodontically treated teeth	Composite resin endocrowns provided more homogeneous stress distribution and higher fracture resistance
Helal and Wang.[30]	Ceramic endocrowns, fiber-reinforced composite (FRC) post and core	Mandibular molars	Ceramic endocrowns caused lower von Mises stress on dentin compared to FRC post and core

using FEA. In this context, maxillary incisor models with root canal treatment and oblique or horizontal fracture lines were restored using various FRC materials, and these models were simulated in three dimensions. The results indicated that the use of FRC significantly reduced stress in both the cervical area of the root dentin and the restorative material. Among all models, the highest stress values were observed in those restored with only composite resin, whereas the lowest stress values were noted in models utilizing long glass fiber posts. Additionally, models with horizontal fracture lines generated more stress compared to those with oblique fracture lines. These findings indicate that incorporating FRC in teeth with crown fractures could be an effective strategy for minimizing stress in both the cervical area of the dentin root and the restorative material.[27]

The study by Zheng et al., utilizing FEA and in vitro methods, aimed to assess stress distribution and fracture resistance in endodontic treated teeth restored with endocrowns fabricated from polymer-infiltrated ceramic (PICN), ceramic, and composite resin produced from CAD-CAM blocks. The findings indicated that endocrowns made from composite resin exhibited greater fracture resistance and uniform stress distribution. However, further studies from long-term clinical observation are required to validate the accuracy and clinical relevance of these results.[28] Another study found that endocrowns reduce stress concentration on the internal walls of the root canal compared to traditional post-core and crown restorations. These findings indicate that molars restored with endocrowns are less susceptible to root fractures compared to those restored with post-core restorations.[29]

In the study by Helal and Wang, equivalent and contact stresses in lower molars under normal chewing loads were compared using three-dimensional finite element analysis between ceramic crowns and ceramic endocrowns supported by fiber-reinforced composite (FRC) post and core. The study results revealed that ceramic endocrown restorations caused lower von Mises (mvM) stress levels on dentin than traditional ceramic crowns supported by FRC post and core. Additionally, molar teeth restored with ceramic endocrowns were found to be less susceptible to damage compared to those supported by FRC post and core. Properly cemented ceramic endocrowns were determined to have a low risk of fracture or de-cementation during normal chewing loads. These findings suggest that ceramic endocrowns should be recommended as viable, minimal invasive, and aesthetic restorations for endodontically treated molars.[30] Some of the studies evaluating stress distribution in restorative dental materials are summarized in Table 2.

Challenges and Limitations in FEA Studies

The assumption that the models used in FEA are isotropic, homogeneous, and linearly elastic may not fully reflect reality; for example, the tubular structure of dentin may be overlooked.[31] Expert support may often be required to conduct FEA analyses. The commercial software used can be expensive depending on its scope.[32] In vitro studies conducted with computer assistance may not fully replicate clinical situations.[33]

Finite Element Analysis (FEA) has become a crucial means in addressing biomechanical challenges in dentistry. It provides valuable insights into the complex properties of restorative materials and dental structures, contributing to the efficiency and cost-effectiveness of experimental studies. However, the validation of FEA results through laboratory studies is essential to ensure their reliability. This review has discussed how stress analyses conducted using FEA are applied to various restorative materials and dental models, along with their clinical implications. In conclusion, the effectiveness of FEA will be further enhanced when supported by additional experimental studies and the development of more realistic models.

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DOI: https://doi.org/10.20473/cdj.v14i2.2024.47-51