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Investigation of the effect of the application of different full ceramic materials on stress distribution to minimally invasive posterior fixed bridge restorations by finite element analysis

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Abstract

Aim: The aim of this study was to examine the effect of different types of all-ceramic materials used in various designs of partial posterior indirect restorations on stress distribution through finite element analysis.

Methodology: Intact mandibular first premolar and first molar teeth were selected. After being soaked in saline solution for a week, 3D radiographic images were taken using cone-beam computed tomography (CBCT). Following root canal treatment, preparations were made for inlay restorations on both teeth. CBCT images were taken again after the preparations. Data from CBCT scans were used to create 3D models in the Mimics program. Restoration designs were prepared in Standard Tessellation Language (STL) format using the EXOCAD program. The models were transferred to SolidWorks for collision processes with cement designs and then exported in Standard for the Exchange of Product Model Data (STP) format. These files were imported into the ABAQUS program for finite element analysis, with properties assigned for each restoration type. Vertical forces of 600 N were applied to the occlusal surfaces, and stress values were recorded in Von Mises Stress (VMS) values.

Results: The results of the study showed that the VMS value on inlay bridge restorations was lower in mesio-occluso-distal inlay (MODI) compared to mesio-occlusal-disto-occlusal inlay (MO-DOI). Zirconia-reinforced lithium silicate (ZLS) exhibited the lowest VMS value for enamel loads, while nano-hybrid composite ceramics with resin matrix (RMNH) showed the lowest stress distribution in the restoration material. In posterior adhesive indirect bridge restorations, material rigidity reduced tooth load distribution. Thus, MODI preparations are preferable due to reduced stress on teeth. ZLS is advantageous as the restoration material for minimizing enamel stress.

Conclusion: In cortical and trabecular bone, similar values were found across all three restorations. The highest stress concentration, excluding the area around the restoration, was observed in lithium disilicate.

Keywords: Inlay bridge, indirect restorations, stress distribution, finite element analysis, Von Mises stress

Introduction

Operative dentistry, for many years, has been influenced by the principles established by Dr. G. V. Black, which were based on the knowledge and dental materials available at that time. Black's approach, centered on the concept of "extension for prevention," has evolved over time due to advancements in materials and techniques, giving way to the modern approach of "prevention of extension." (1).

Minimally invasive dentistry is a therapeutic approach focused on preserving natural tooth structure. This method endeavors to resolve dental issues with minimal intervention to the dental tissues. Recently, it has gained substantial popularity among clinicians. Treating edentulous spaces with a minimally invasive approach enhances motivation to use this treatment modality in both clinicians and patients (2).

Various treatment methods are available today for single tooth deficiencies for different reasons. The choice of treatment method is influenced by factors such as the patient's economic status and the location and size of the missing area. Although implant treatments have become widespread for addressing single tooth deficiencies, this option may sometimes be less preferred by patients due to high costs, the requirement for surgical intervention, unsuitability for patients with systemic issues, and a relatively long treatment duration compared to other methods (3). It also directs patients toward metal-ceramic, all-ceramic, and zirconia bridge prostheses, as well as minimally invasive dental bridge treatments (4).

In structurally compromised teeth with significant substance loss, the use of indirect restorations has increased due to the enhanced mechanical durability of adhesive resin cements and other restorative materials and the ability to produce them in a much shorter time with the widespread use of CAD-CAM applications. Preserving tooth structure is crucial for ensuring the longevity of both the teeth and the restorations placed on them (5, 6). The bonding of these restorations to teeth with resin cement enhances their mechanical resistance against fracture and occlusal forces. Additionally, their resistance to oral fluids and maintenance of dimensional stability are reasons they are preferred by clinicians (7, 8).

With the advancement of optical properties, such as light translucency and transparency, the aesthetic appearance and biocompatibility of all-ceramics, which resemble natural teeth, have become more prominent than metal-supported systems (9). However, the fragile structure of all-ceramics has limited their use in the posterior region and in multi-unit restorations due to problems such as chipping and cracking (10). Researchers have conducted various studies to improve lithium disilicate glass ceramics (LS), preferring their superior aesthetic properties despite their fragility. However, zirconia, despite its superior mechanical properties, is aesthetically weak because it is an opaque material (11). The superior properties of LS and zirconia materials have been combined to obtain zirconia-reinforced lithium silicate (ZLS). ZLS has enhanced durability due to the presence of zirconia in its composition, while its aesthetic properties are improved through the incorporation of lithium silicate particles (12, 13).

Polymer infiltrated ceramic network (PICN) is a composite resin-based ceramic. Unlike traditional composites containing inorganic particles, this material has a 3D geometrically intertwined network structure, which contains two different network structures (14). These materials are more durable against fractures and cracks at marginal edges than ceramics. Additionally, they do not require heat application after shaping, as is the case with ceramics (15).

Nano-hybrid composite ceramics with resin matrix (RMNH) are ceramic materials containing fillers dispersed within a resin matrix. They offer advantages such as not requiring sintering or firing processes, high wear resistance, high flexibility, good mechanical properties, and high radiopacity (16).

The mechanical resistance of restorations against chewing forces is crucial for their production and their safe use in patients. If the average maximum occlusal forces are below the load-bearing capacity of the restorations, no issues are expected in their clinical use (17). Mechanical parameters not only induce stresses in the restoration material but also result in stresses within the dental tissues. Finite element analysis (FEA) aims to model and investigate the biomechanical behavior of elements with complex structures. It is a mathematical method that enables the prediction of situations, such as stress and strain distribution, that will be encountered when using the restoration without physically producing it (18, 19).

The mechanical strength of posterior fixed partial dentures varies according to the restorative materials used (20). Additionally, topics requiring investigation in dentistry include the forces transmitted to teeth and periodontal tissues.

The aim of this study is to examine the stress distribution of different types of partial posterior bridge designs using various all-ceramic materials through finite element analysis. The null hypothesis of the study is that different designs of partial posterior bridges using different all-ceramic materials will not affect the stress distribution.

Materials and Methods

Intact, caries-free mandibular first premolar and first molar teeth were selected for the study. The teeth were soaked in saline solution for one week. After performing root canal treatment on the teeth, mesio-oclusal inlay (MOI) preparations were made on the molar tooth, followed by disto-occlusal inlay (DOI) preparations on the premolar tooth. Following the preparations, cone-beam computed tomography (CBCT) scans were taken to obtain 3D radiographic images of the teeth, which were then converted to mesio-occluso-distal inlay (MODI) cavities and rescanned with CBCT. The data obtained from both CBCT scans were extracted in Digital Imaging and Communications in Medicine (DICOM) format and transferred to Mimics software to create 3D models of the teeth. EXOCAD software was used to prepare restoration designs that were compatible with the preparations in Standard Tessellation Language (STL) format. The obtained data, along with cement designs with a thickness of 30 µm, were transferred to the SolidWorks program for alignment processes and then exported in Standard for the Exchange of Product Model Data (STP) format. The models in the SolidWorks program are shown in Figure 1 and Figure 2.

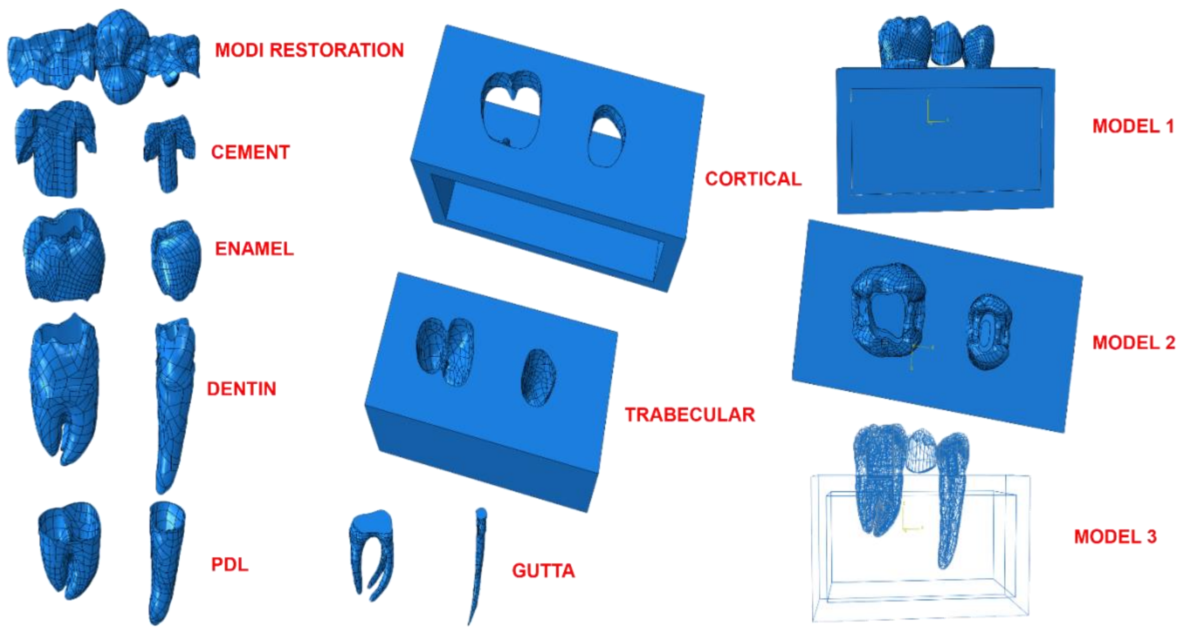

Figure 1. Models of MODI design

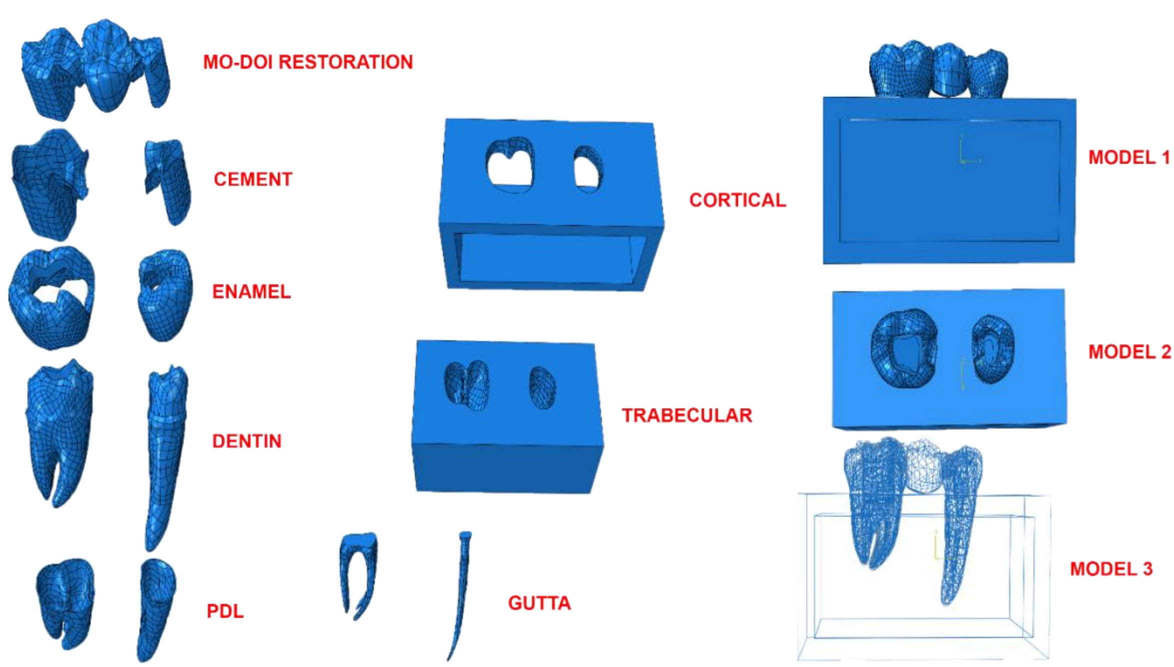

Figure 2. Models of MO-DOI design

The STP files were transferred to the ABAQUS program for finite element analysis. Restorations were designed with ZLS (Vita Suprinity – VS), RMNH (Cerasmart – CS), and PICN (Vita Enamic – VE) materials, with their properties provided in Table 1. A vertical force of 600 N, considered the average chewing force, was applied to the occlusal surfaces of the models, and the teeth were immobilized within the jawbone in all directions. Stress values were recorded in terms of von Mises Stress (vMS) values. The material properties used in the ABAQUS program are shown in Table 1.

Table 1. The mechanical properties of dental tissues and materials

Material	Elastic Modulus (GPa)	Poisson Ratio
Enamel (21)	84	0.33
Dentin (21)	18.6	0.31
Gutta (22)	0.69(x10^{-3})	0.45
Periodontal Ligament (23)	0.05(x10^{-3})	0.49
ZLS (VS) (24)	104.9	0.21
PISA (VE) (24)	30	0.23
RMNH (CS) (21)	9.6	0.306

GPa: Gigapascal

Results

From a restoration perspective, the highest stress values were generally observed in MODI restorations. Upon examination of the stresses on the restorations, the highest stress value was observed in the inlay design with a ZLS feature in the MODI design, while the lowest value was observed in RMNH in the MO-DOI design. The stress values on the restoration are shown in Figure 3.

When examining the stress values on the enamel, it was found that the stress values were higher in the premolar region in both designs. The highest stress value on the enamel was observed in MODI RMNH in the premolar region, while the lowest value was observed in MO-DOI ZLS in the molar region. The stress values on the enamel are shown in Figure 4.

When examining the stress values on the periodontal ligament (PDL), it was found that the stress values were higher in the molar region in both designs. The highest stress value on the PDL was observed in MO-DOI ZLS in the molar region, while the lowest stress value was observed in MO-DOI RMNH in the premolar region. The stress values on the PDL are shown in Figure 5.

The von Mises stress values for the components are shown in Table 2.

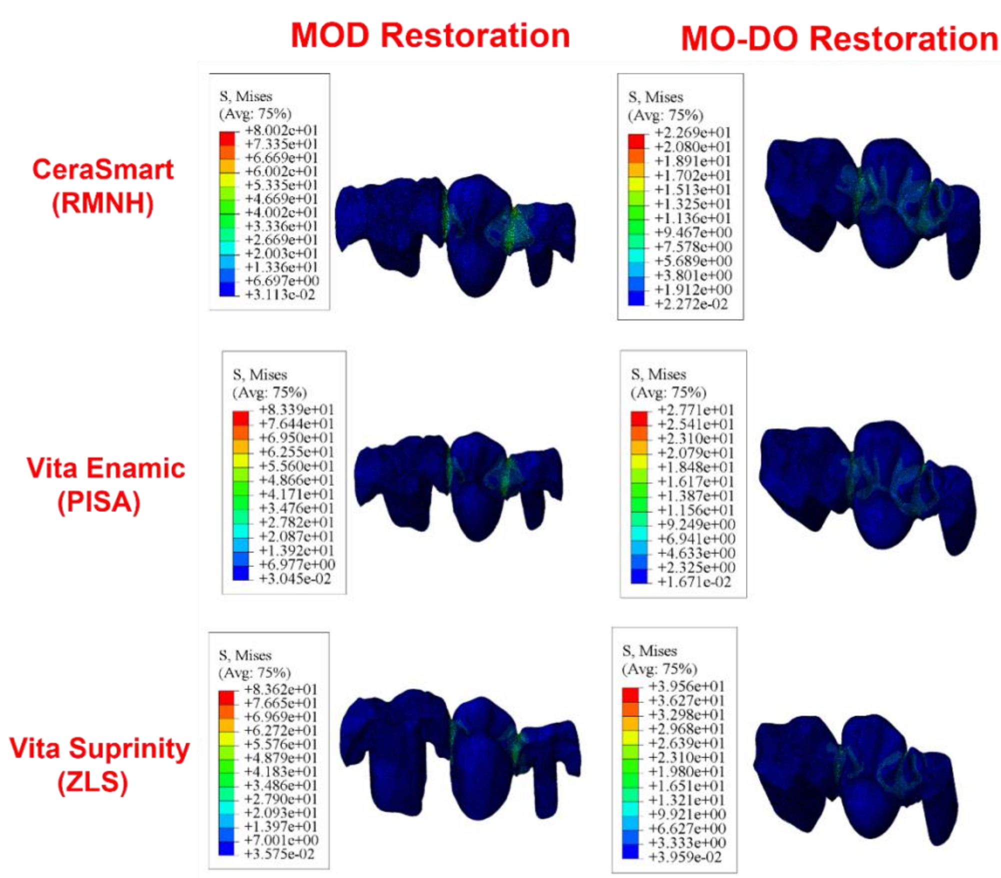

Figure 3. The stress values on the restoration

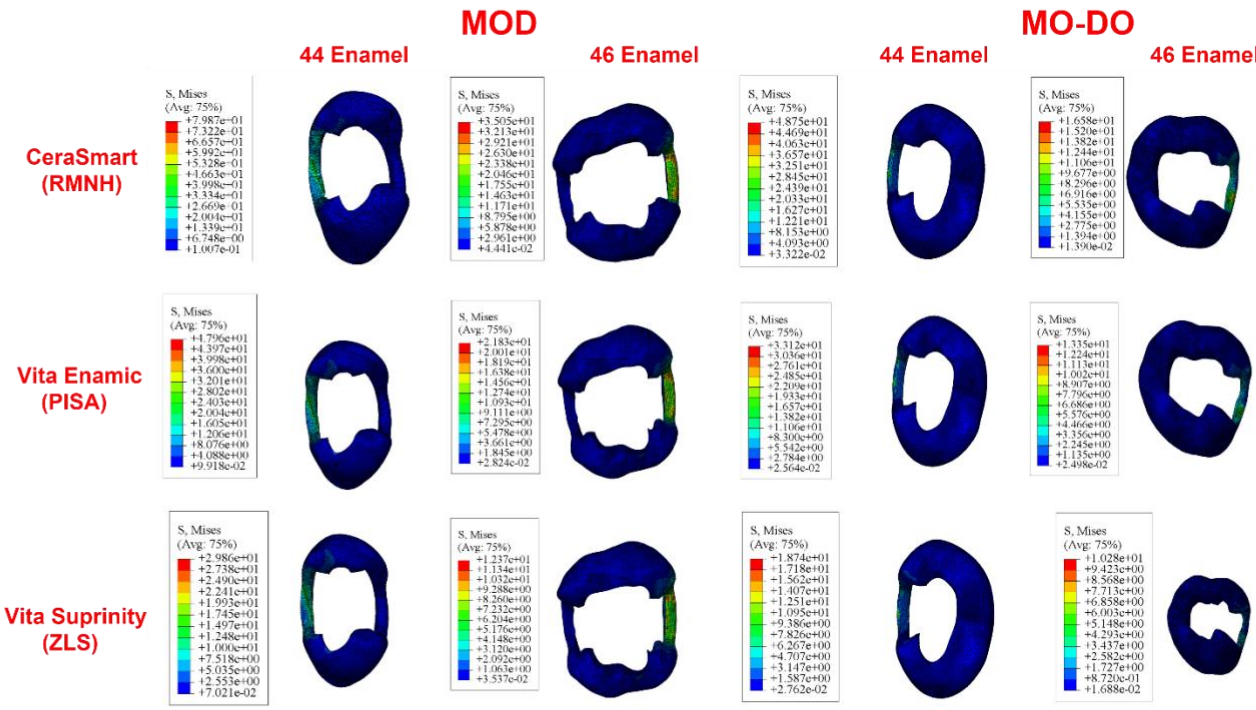

Figure 4. The stress values on the enamel

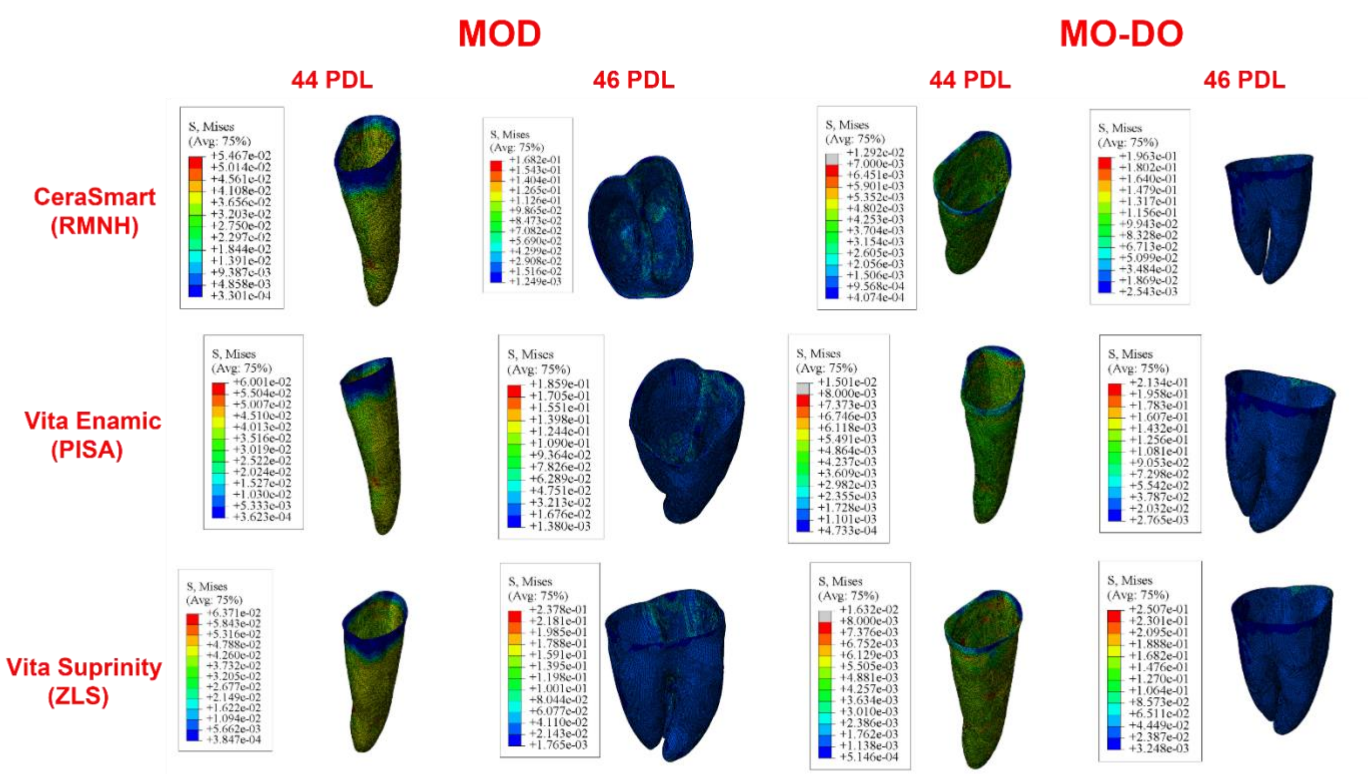

Figure 5. The stress values on the periodontal ligament

Table 2. Von mises stress analysis for component (MPa)

	MODI (RMNH)	MODI (PISA)	MODI (ZLS)	MO-DOI (RMNH)	MO-DOI (PISA)	MO-DOI (ZLS)
Restoration	80.02	83.39	83.62	22.69	27.71	39.56
44 Enamel	79.87	47.96	29.86	48.75	33.12	18.74
46 Enamel	35.05	21.83	12.37	16.58	13.35	10.28
44 PDL	0.05467	0.06001	0.06371	0.01292	0.01501	0.01632
46 PDL	0.1682	0.1859	0.2378	0.1963	0.2134	0,2507

Discussion

According to the results obtained in the study, it has been concluded that the stress values are influenced by the restoration type and material. As the impact of different all-ceramic materials on stress distributions in partial posterior bridge designs with different configurations was found, the null hypothesis has been rejected.

Zirconia-reinforced lithium silicate ceramics (ZLS) have emerged as a new class of materials that combine the mechanical strength of zirconia with the aesthetic appearance of glass-ceramic materials (25). These materials are designed to meet the need for restorative materials that provide both optimal aesthetics and sufficient mechanical strength (26). The introduction of ZLS to the market stemmed from the desire to combine the aesthetic properties of lithium disilicate with the durability features of zirconia (27). Studies have demonstrated that zirconia-reinforced lithium silicate ceramics exhibit excellent mechanical and aesthetic properties (28). It has been found that zirconia-reinforced lithium silicate ceramics have smaller particle sizes compared to other ceramics, which could affect their mechanical properties (29). Furthermore, ZLS ceramics have been defined as suitable materials for restorations with minimal invasive vertical preparations, highlighting their versatility in clinical applications (30). Consistent with previous studies, as mentioned, when examined in terms of materials, stress values on ZLS material were generally found to be higher compared to other materials, except in the enamel region.

A study has been conducted to evaluate the fracture resistance of MODI and MO-DOI restorations made from resin matrix nanohybrid ceramic materials, highlighting the advantageous properties of resin matrix ceramics. These properties include an elasticity modulus similar to dentin, shock-absorbing characteristics, high flexibility, and fracture resistance, indicating the potential suitability of resin matrix nanohybrid ceramics for restorative applications (31). Another study concluded that comparing ceramic material options for MODI and MO-DOI restorations, considering the materials' mechanical properties, stress distribution, and clinical performance, is important. Additionally, the fracture resistance of partial indirect restorations made from ceramics, composite resin, resin nanoceramics, or hybrid ceramics using CAD/CAM technology has been evaluated, emphasizing the importance of material selection for fracture resistance. A meta-analysis examined the fracture resistance of various restorative materials, including resin nanoceramics, showed that resin nanoceramic inlays exhibited significantly higher fracture resistance values compared to other materials, suggesting that resin nanoceramic materials may offer superior fracture resistance for MODI and MO-DOI restorations (32). According to the results of this study, when examined in terms of materials, stress values on RMNH material were found to be the lowest, except in the enamel region.

Furthermore, Güngör et al. compared the fracture resistance of CAD/CAM-produced lithium disilicate and resin nanoceramic restorations in endodontically treated teeth. The study revealed differences in fracture resistance between lithium disilicate ceramic and resin nanoceramic restorations, emphasizing the importance of material selection in determining fracture resistance (33). In this study, it was found that the stress distributions exhibited by the two different ceramics evaluated varied in response to applied loads.

In a study, the higher stress values observed in MODI compared to MO-DOI were attributed to the MODI type covering a larger area (34). In this study, the higher stress values found in MODI designs further support these findings. However, the higher stress values in MODI designs do not necessarily imply that this design is less ideal. This is because fatigue analysis was not evaluated in this study, which is considered a limitation and cannot be conclusively considered as the final result.

Additionally, when stress on different materials in restoration types was examined, it was found that the stress on ZLS material was higher. However, since it is believed that ZLS material absorbs stress more effectively, the stress on enamel in such restorations was found to be lower compared to others. This situation may be attributed to the fact that ZLS material is more rigid than others. Therefore, since less stress is transferred to the tooth, this material is thought to be preferable for weak teeth.

Overall, the lowest stress values were observed on the periodontal ligament (PDL) in the study. Particularly, the observation of the lowest values on the PDL for the RMNH material may be attributed to its lower rigidity compared to others. Due to its lower transmission of stress to the periodontal region, it has been concluded that RMNH material may be preferred for teeth that are weak in terms of periodontal health.

Conclusion

The findings from the finite element analysis study lead to the following conclusions:

- The elevated stress values observed on the ZLS material advocate for its selection as a preferred restoration material for weakened teeth.
- The reduced stress transmission to the PDL region with RMNH material suggests its potential preference for teeth weakened in terms of periodontal health.

Disclosures

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