

Original Article

Evaluation and Comparison of Stress Distribution in Restored Cervical Lesions of Mandibular Premolars: Three-dimensional Finite Element Analysis

Swathi Pai¹, Nithesh Naik², Vathsala Patil³, Jaskirat Kaur⁴, Swetank Awast², Nithin Nayak²

¹Department of Conservative Dentistry and Endodontics, Manipal College of Dental Sciences, Manipal, Manipal Academy of Higher Education, Manipal, Karnataka, India, ²Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India, ³Department of Oral Medicine and Radiology, Manipal College of Dental Sciences, Manipal, Manipal Academy of Higher Education, Manipal, Karnataka, India, ⁴Manipal College of Dental Sciences, Manipal Academy of Higher Education, Manipal, Karnataka, India

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INTRODUCTION

Cervical cavities (class V) are areas with high stress distribution due to the tooth configuration in the arch.^[1,2] The longevity and retention of these cavities is a day-to-day challenge for dentists. The retention rates of restorative materials significantly depend on the constant occlusal loading and their mechanical properties.^[3,4] According to the biomechanical theory, cuspal flexure leads to mechanical overloading of cervical enamel, tensile stress, and shear stress in

ABSTRACT

Objectives: Restorative materials are used in the treatment of cervical lesions and restoration of the dental tooth. The objective of this study was to assess the suitability of the three commonly used restorative materials by dentists and the evaluation of stress distribution and deformation using Von Mises stress in cervical lesions of mandibular premolars under varying loading condition. **Materials and Methods:** A computerized model of restored class V cavity of mandibular premolar tooth was created using three dimensional modeling software SpaceClaim. It was subjected to occlusal pressure load of 100, 150, 200 and 250MPa at right angle to buccal cusp and was analyzed for stress distribution and deformation in different restorative materials using Finite Element analysis, ANSYS Workbench. **Results:** The analysis carried on the class V restored tooth from biomechanical point of view indicates that restorative material glass-ionomer cement exhibited better bonding with the tooth structure using ionic bonds with the calcium ion present in the tooth structure. The variation of 8%–9% of stress concentration is observed in cavity region across varied pressure loads with glass-ionomer cement to Cention N. **Conclusion:** Glass-ionomer cement had showed better results than amalgam in terms of biomechanical property which is in agreement with the clinical findings. The stress values of Cention N were comparable to that of glass-ionomer cement.

KEYWORDS: Dental materials, dentistry, finite element analysis, restoration, stress

the cervical region, resulting in disruption of bonds between the hydroxyapatite crystals and non-carious cervical tooth loss.^[5,6] For a successful restoration, the mechanical properties of dental materials must

Address for correspondence: Dr. Vathsala Patil, Department of Oral Medicine and Radiology, Manipal College of Dental Sciences, Manipal, Manipal Academy of Higher Education, Manipal, Karnataka, India. E-mail: vathsala.mcods@manipal.edu

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withstand the stresses and strains caused by the repetitive forces of mastication.^[7]

Traditionally, the cervical lesions were managed by preparing class V cavities and restoring them directly with materials such as silver amalgam, gold, and silicates.^[7] These materials are unaesthetic, do not bond chemically, and generally require preparation of a specified cavity within the tooth structure to facilitate mechanical retention.^[8] The simple conservative treatment approach with minimal or no removal of tooth structure has become the treatment of choice for the cervical lesions.^[9] For restoring the class V lesions, various tooth-colored restorative materials with diverse mechanical properties are available that can function properly.^[7] Adhesive restorative materials, such as the composite resin, offer the advantage of both aesthetics and bonding. However, often clinicians face the problem of isolation from gingival crevicular fluid, and the inherent characteristic of polymerization shrinkage results in gap formation between the restoration and tooth margin leading to postoperative sensitivity and secondary caries.^[10,11] Glass-ionomer cement (GIC), on the contrary, bonds chemically with the tooth structure and does not possess any shrinkage. It has a good bond strength, and the coefficient of thermal expansion is comparable to that of the dentin, although, it is not superior to composite resin in terms of aesthetics.^[12] Alkasites (Cention N, Ivoclar Vivadent AG, Germany) are newer class of resin restorative materials that have comparable strength and relative bonding to the tooth structure.^[13]

Finite element analysis (FEA) is a method used to simulate and perform the biomechanical analyses in biological research. It enables modeling and simulation of complex structures and analyzes their mechanical properties and behavior when loads and boundary conditions are applied.^[14] The mechanical properties of dental restorative materials must withstand the stresses and strains caused by repetitive forces.^[15] Hence, this study aimed to evaluate and compare the stress distribution in different restorative materials used in cervical lesions of mandibular premolars, using FEA. The null hypothesis was that there is no

difference in the stress distribution among the restorative materials used for the restoration of cervical lesions.

MATERIALS AND METHODS

The study was performed over six months (December 1, 2018 to May 31, 2019) in the institutional computer-assisted designing (CAD) lab after the Institutional Ethics Committee clearance was obtained (IEC No. 883–2018).

THREE-DIMENSIONAL FINITE ELEMENT MODELING OF THE TOOTH

The three-dimensional (3D) model of mandibular premolar was developed by importing the digital imaging and communications in medicine images generated by cone beam computed tomography (CBCT) imaging technique into ANSYS SpaceClaim:

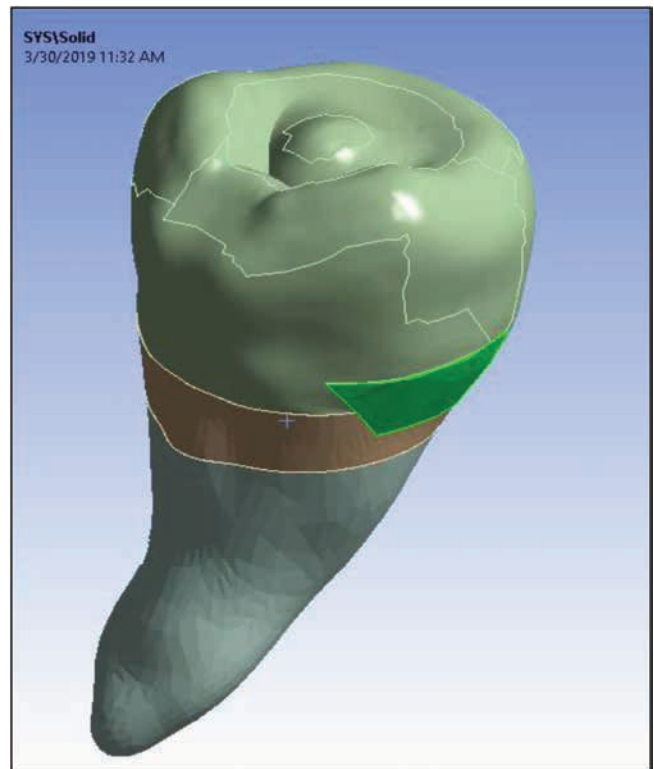


Figure 1: Three-dimensional finite element model of premolar tooth with cavity

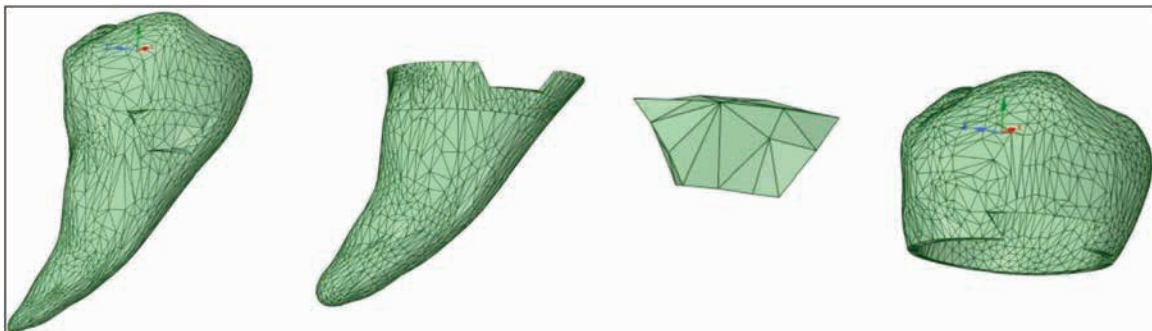


Figure 2: Three-dimensional model showing layers of tooth dentin, cementum, cavity, and enamel

3D Modeling Software, ANSYS, Inc. Delaware, USA, CAD modeling software. The design of external contours, cusps, and occlusal anatomy was refined using CAD software tool. The anatomy of the premolar, including dentin, cementum, cavity, and enamel,

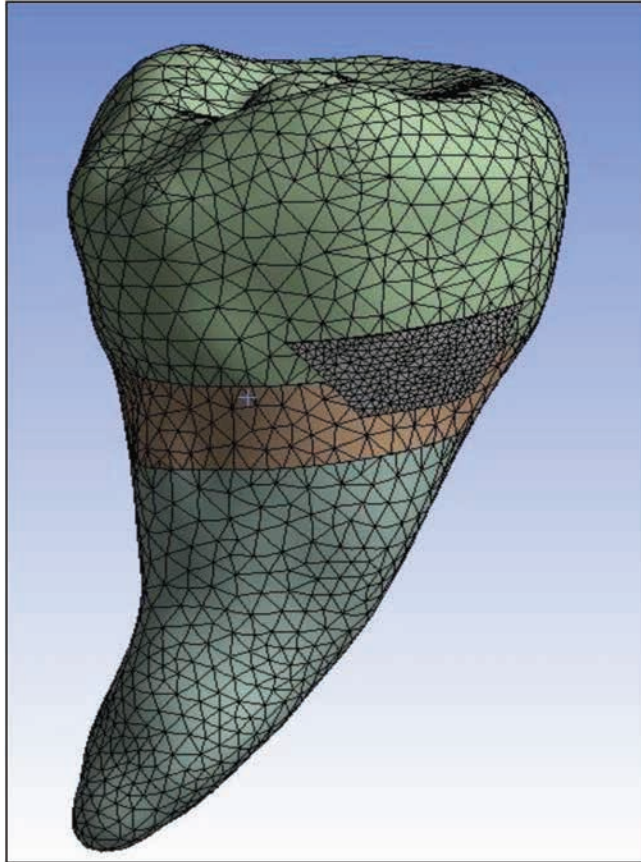


Figure 3: Meshed finite element model of premolar tooth

was assembled and positioned to perform analysis using ANSYS Workbench, version 19.0, as shown in Figure 1. Figure 2 shows the 3D model with layers of tooth dentin, cementum, cavity, and enamel.

PREPARATION OF THE CAVITY

A cavity with trapezium cross section of dimension 3mm (mesio-distally-occlusal wall), 2mm (mesio-distally-gingival wall), 1.5mm (occluso-gingival-mesial and distal walls, such that 0.5mm rests on the cementum), and depth of 1mm was prepared in the cervical aspect of the buccal surface of the modeled tooth.^[3] All the internal line angles were rounded off to prevent any stress concentration. The element type selected for analysis was program controlled. A meshed FE model of premolar tooth with tetrahedron elements is shown in Figure 3.

RESTORATION AND LOAD APPLICATION

The cavity was restored with three different restorative materials in the computer model according to the mechanical properties of the tooth and restorative materials and classified into the following three groups:

- Group I: Restored with a Alkaside (Cention N; Ivoclar Vivadent AG, Germany)
- Group II: Restored with a GIC (Fuji II GC America)
- Group III: Restored with dental amalgam (Dentsply Caulk, Milford, USA)

The class V restored tooth was subjected to occlusal pressure load (pressure in megapascal) of 100, 150, 200, and 250N at right angles to the lingual slopes buccal cusp (45 degrees oblique to the long axis) generally experienced by the patient on biting.^[16] Figure 4 shows the tooth

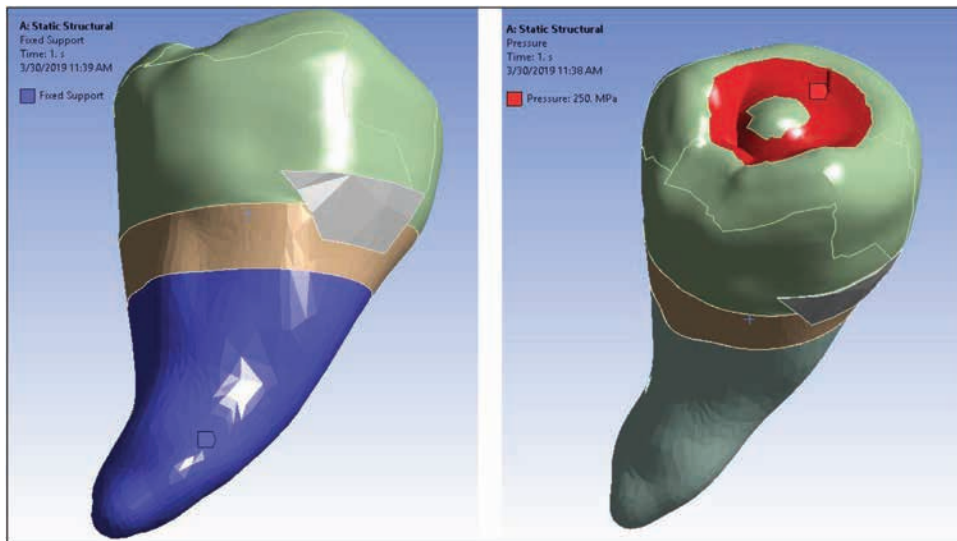


Figure 4: Load and boundary conditions applied on the restored tooth

applied with the pressure load and boundary conditions. The mechanical properties of the tooth and the restorative materials used in the study are given in Table 1.

The premolar tooth within the bone region was constrained for motion with all degrees of freedom. The fulcrum was applied at the bone, and the Von Mises stress and total deformation were observed in the restored area.

RESULTS

MESH CONVERGENCE STUDY

The mesh convergence test plays a vital role in establishing the accuracy of the solution with the reduced computation.

The coarse, medium, and fine mesh density were considered to perform mesh convergence study. The study evaluated and determined the effect of mesh quality on the simulation results. All the layers of the tooth were successively meshed by using size function as adaptive and varying the relevance center to coarse, medium, and fine mesh as shown in Table 2, with the maximum pressure load of 250 N applied.

The values of variation in the stress concentration and the total deformation varied in the range of approximately less than 2% and 3%, respectively, as shown in Table 2. Further, the element size was

considered for mesh convergence study in the cavity region. The analysis was carried out with the optimum mesh density considered with an element size of 0.5 mm for cavity region and medium for rest of the region from the mesh convergence study.

STRESS ANALYSIS

The Von Mises stress was evaluated for enamel, dentin, and in the region of class V restoration with different materials under the occlusal forces when a load of 100, 150, 200, and 250 N was applied. The maximum Von Mises stress value (357.78 N) in the inlay material of restored cavity region among the three materials was seen in amalgam [Table 3]. The least stress (160.3 N) was seen with GIC when the respective loads were applied. Stress distribution (Von Mises) in restored cavity with pressure load (250 MPa) for Cention, GIC, and amalgam is shown in Figures 5, 6, and 7, respectively. In all the groups, the Von Mises stress values increased as the pressure load applied increased. The variation of 8%–9% of stress concentration was observed in cavity region across varied pressure loads with GIC to Cention.

The maximum Von Mises stress values were compared across the three materials and also across different pressure levels using an analysis of variance (ANOVA) and *post hoc* test, and the results are shown in Table 4. A significant difference in the Von Mises stress values was seen across the three materials at the 0.2% level of significance and across the four pressure levels at the 1% level of significance. Cention N and GIC had similar stress values.

TOTAL DEFORMATION

The total deformation was evaluated for enamel, dentin, and in the region of class V restoration with different materials under the occlusal forces. The total deformation values in the inlay material of restored cavity region for all the materials as shown in Table 4 were observed to be least in group III at the loads of

Table 1: Mechanical properties of the tooth and supporting structures used in the study^[3,17,18]

Materials	Modulus of elasticity (MPa)	Poisson's ratio(μ)
Enamel	84100	0.33
Dentin	13700	0.31
Cementum	18600	0.31
Cention N	13000	0.3
Glass-ionomer cement	10800	0.3
Amalgam	35000	0.35

Table 2: Mesh convergence study

Type	Nodes	Elements	Von Mises stress in MPa		Total deformation in mm	
			Maximum	Minimum	Maximum	Minimum
Coarse	40160	23000	169.42	30.099	0.112	0.03501
Medium	55037	31011	160.3	29.79	0.11307	0.0358
Fine	79453	45153	160.35	30.315	0.11333	0.03603

Table 3: Distribution of Von Mises stress in restored tooth

Groups	Element	Nodes	Vertical load (N)				
			100 N	150 N	200 N	250 N	
I	Von Mises	55037	31011	64.122	96.182	128.24	160.3
II	Stress	55037	31011	58.491	87.629	116.84	146.05
III	(MPa)	55037	31011	143.11	214.67	286.23	357.78

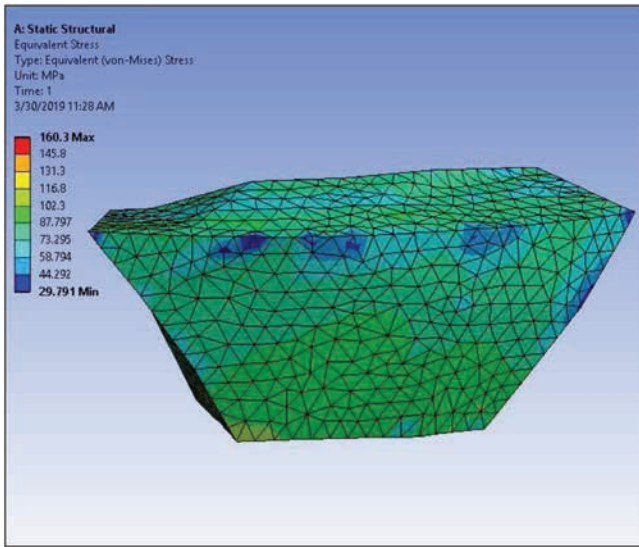


Figure 5: Stress distribution (Von Mises) in restored cavity (Cention) with pressure load (250 MPa)

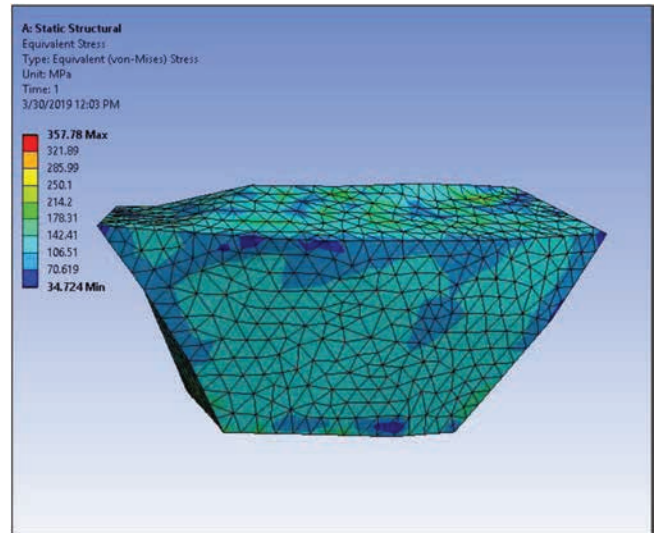


Figure 7: Stress distribution (Von Mises) in restored cavity (amalgam) with pressure load (250 MPa)

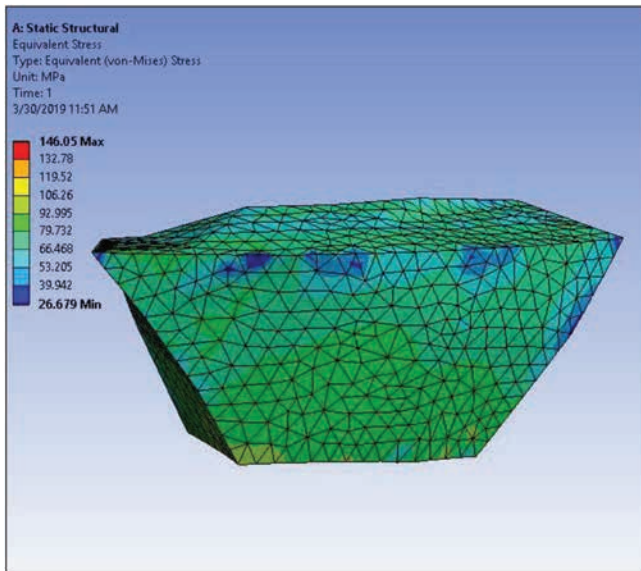


Figure 6: Stress distribution (Von Mises) in restored cavity (glass-ionomer cement) with pressure load (250 MPa)

100, 150, 200, and 250 N, whereas the deformation of group I and II was comparable. The variation of 15%–19% in total deformation was observed in cavity region across varied pressure loads with GIC to Cention. The maximum deformation was compared across the three materials and also across four different pressure levels using an ANOVA and *post hoc* test, and the results are depicted in Table 5. The maximum total deformation was statistically similar in the case of Cention as well as GIC. It was observed that the maximum total deformation was significantly different for all the different pressure levels as shown in Table 6.

DISCUSSION

A higher rate of retentive failure of restorations is found in the mandibular arch as compared to the maxillary arch. This increased failure rate of restorations is because of the lingual orientation of the mandibular teeth where there is concentration of tensile stresses at the cervical cross section, particularly the premolars, thereby contributing to the failure to withstand tensile stress.^[19] Different layering used to simulate enamel, dentin, and cementum is a unique feature in this study, which is not incorporated in many FEA studies. In this study, a conventional cavity was prepared for silver amalgam with box-shaped cavity and well-defined internal angle. There were no secondary retentive features given, such as locks or grooves. GIC and Cention N did not mandatorily need a box-shaped cavity because of their chemical adhesion to dentin.^[20,21]

In this stress analysis study, when the loading angle and the restorations sizes were kept fixed in the restored tooth, the Von Mises stress in the close vicinity of the restored area increased proportionally to the load applied and inversely to the Young's modulus value of the restorative material. The total deformation of the material was also found proportional to the load applied and was comparable. The stress pattern did not increase by increasing the load but only shifted the value to a higher scale. This was in agreement with the previous FEA studies.^[21,22]

This study showed the highest stress in the vicinity of cavities restored with amalgam. Toparli *et al.*^[23] had also concluded the same in his study.^[23] These data can be

Table 4: Post hoc analysis of variance for Von Mises stress distribution

(I) Material	(J) Material	Mean difference (I-J)	Std. error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
Amalgam	Cention	138.23650*	21.613333	0.001	85.35058*	191.12242
	Glass-ionomer cement	148.19500*	21.613333	0.000	95.30908*	201.08092
Cention	Amalgam	-138.23650*	21.613333	0.001	-191.12242*	-85.35058
	Glass-ionomer cement	9.95850	21.613333	0.661	-42.92742	62.84442
Glass-ionomer cement	Amalgam	-148.19500*	21.613333	0.000	-201.08092*	-95.30908
	Cention	-9.95850	21.613333	0.661	-62.84442	42.92742

*The mean difference is significant at the 0.05 level

Table 5: Post hoc analysis of variance for total deformation

(I) Material	(J) Material	Mean difference (I-J)	Std. error	Sig.	95% Confidence interval	
					Lower bound	Upper bound
Amalgam	Cention	-0.00695900*	0.001190801	0.001	-0.00987279*	-0.00404521
	Glass-ionomer cement	-0.00852775*	0.001190801	0.000	-0.01144154*	-0.00561396
Cention	Amalgam	0.00695900*	0.001190801	0.001	0.00404521*	0.00987279
	Glass-ionomer cement	-0.00156875	0.001190801	0.236	-0.00448254	0.00134504
Glass-ionomer cement	Amalgam	0.00852775*	0.001190801	0.000	0.00561396*	0.01144154
	Cention	0.00156875	0.001190801	0.236	-0.00134504	0.00448254

*The mean difference is significant at the 0.05 level

Table 6: Total deformation in the restored tooth

Groups	Element	Nodes	Vertical load (N)				
			100 N	150N	200N	250N	
I	Total deformation (mm)	55037	31011	0.045228	0.067842	0.090456	0.11307
II		55037	31011	0.046125	0.069187	0.092249	0.11531
III		55037	31011	0.04126	0.0619	0.0825	0.1031

correlated in clinical conditions where the cervical area being subjected to occlusal loading will not immediately lead to failure in the tooth, but may create cracks in the tooth structure, which over a period may progress into a complete failure. In a recent systematic review, it was found that the GICs most effectively and durably bond to tooth tissue in the cervical areas.^[24] This was in agreement to this study where the least amount of stress was seen with the GIC. Therefore, FEA as such contributes to the selection of restorative material.

Cention N is a new dental material, which is an Alkaside consisting of a special patented filler (Isofiller), which acts as a shrinkage stress reliever. When the material polymerizes, there is a cross-linking between the monomer chains located on the fillers and the silanes.^[13,25] These forces between the individual fillers come into play, which place stress on the cavity walls. As this study is the first of its kind, which analyses the stress around Cention N using FEA, this could be the reason for the lesser amount of Von Mises stress.

The FEA is significantly used as a research tool in biomechanical analysis. It is a widely used and accepted

noninvasive tool that enables simulation of biological system to study, visualize, and analyze the effects of mechanical forces and behavior of material in the dental system, with a repeatable set of experiments with modified designs. However, FEA being an *in vitro* study should be supplemented with clinical evaluation.^[26] Therefore, a further scope of this study includes different *in vitro* models to study the retention of Cention N in cervical cavities.

CONCLUSION

The results of this study indicate the following:

- The effect of pressure load applied may lead to gradual development of cracks in the restored zone causing failure of the tooth over a time.
- A virtual model cannot completely mimic a real biological model, where the teeth is cushioned by periodontal ligament and is actually being subjected to various types of loading stresses.
- Within the limitations of the study, GIC has shown best results and is in agreement with the clinical results. It has shown better values than amalgam.

Cention N has superior aesthetics and has shown stress values comparable to that of GIC. Hence, it may be considered as a restoration of choice in cervical area.

ETHICAL POLICY AND INSTITUTIONAL REVIEW BOARD STATEMENT

This study was approved by the institutional ethics committee, IEC No. 883–2018, dated December 11, 2018. All the procedures have been performed as per the ethical guidelines laid down by the Declaration of Helsinki (2013).

DATA AVAILABILITY STATEMENT

Data will be available on request from Nithesh.naik@manipal.edu.

FINANCIAL SUPPORT AND SPONSORSHIP

Nil.

CONFLICTS OF INTEREST

There are no conflicts of interest.

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