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Finite Element Stress Analysis of Diastema Closure with Ceramic Laminate Veneers

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Abstract

Purpose: The purpose of this study was to use finite element stress analysis to examine the relative importance of variables such as porcelain laminate veneer (PLV) extensions, loading angle, and loading level for the case of feldspathic ceramic veneering of teeth to manage diastema.
Materials and Methods: A 3D maxillary central incisor including its internal anatomy and morphology was constructed with ANSYS software for different extensions of PLV. Internal boundaries defining the dentinoenamel junction, the pulp-dentinal junction, the interface between the enamel-luting cement, and the porcelain-luting cement were well defined. The von Mises stresses distribution and stress intensity were analyzed on the free extension of PLV for varying extensions, various angulations (0°, 30°, and 60°) on the incisal edge, and for different loading levels (50, 150, and 250 N).
Results: The numerical values of stress were recorded. A significant difference in stress was observed. Increased stresses occurred with increased extensions, angulations, and loading levels. At 0° angulation, compressive stresses were visualized in finite element analysis for various magnitudes of force. Higher stress values of 182 MPa and 211 MPa were obtained for the 2.5-mm extension in the mesial surface and in both proximal surfaces for 0° angulation at 250 N magnitude of force. The stress occurring at 30° and 60° angulations was the combination of compressive and tensile stress. Higher values of 261 MPa and 232 MPa were observed when forces were applied on the mesial extension of the PLV and on both the proximal surfaces for 2.5 mm at 30°, 250 N magnitude of force. A maximum stress value of 507 MPa was observed when PLV were increased in mesial width by 2.5 mm for 60° angulation at 250 N magnitude of force.
Conclusion: The extensions of PLV in diastema closure have more of an esthetic than functional consideration, but critical factors such as angulations and the loading level acting on the free extension of PLV are important.

Porcelain laminate veneers (PLVs) have been used to mask discoloration or staining, accidental loss of an incisal edge, or diastema and to achieve improved esthetics.[1] The success rate for PLVs varies between 75% and 100%.[2-9] The properties of conventional dental ceramics have shown certain clinical shortcomings in adverse conditions, including excessive brittleness, crack propagation, low tensile strength, wear of antagonists, and restoration fracture. The poor tensile strength of ceramics may affect the clinical success of the PLV when used in diastema closure, because of the increase in stress on the free extension of ceramic from the tooth structure into the interproximal area. This factor, which has not been studied, was analyzed using finite element analysis (FEA).

FEA, as a numerical and simulative study, has definite advantages over other experimental approaches, such as photoelastic studies or the use of a strain gauge. In FEA, the exact stress distribution pattern and areas of fracture potential can be determined and visualized.[10] Unlike the models of a photoelastic study, which are magnified, the models used in this finite element study were simulations of natural models. In studies using a strain gauge, the stress distribution pattern cannot be visualized.[11]

The accuracy of FEA has been demonstrated and validated by several reports in the literature. Morin et al[12,13] compared the use of the strain gauge on photoelastic studies with FEA. The results confirmed that FEA is more accurate than strain gauge

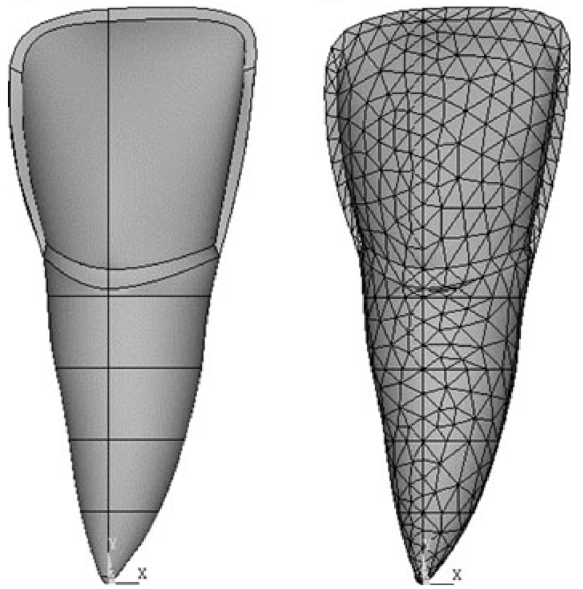

Figure 1 (A) Tooth preparation, FE model. (B) Tooth preparation, FE meshed model.

and photoelastic studies. Studies by Magne et al[14] on the natural central incisor also came to the same conclusion. Although numerous studies have been made on the modifications of tooth preparation,[15-20] effects of margin designs and load angles,[21-23] ceramic materials,[24-28] and cement polymerizations,[29-34] fewer studies have examined the unsupported PLV material in diastema closure specifically. The purpose of this study was to use finite element stress analysis to examine the relative importance of variables such as PLV extensions, loading angle, and loading level, for the case of feldspathic ceramic veneering of teeth to manage diastema.

Materials and methods

Finite element stress analysis was performed on a maxillary central incisor to examine the stress distribution resulting from varying the extensions in seven ways for a PLV to mimic the conditions of diastema closure. A maxillary central incisor, including its internal anatomy and morphology, was modeled. Internal boundaries defining the dentinoenamel junction, the pulp-dentinal junction, the interface between the enamel-luting cement, and the porcelain-luting cement were well defined. The pulp chamber was modeled as a hollow volume with a shell element of negligible elastic modulus, which does not affect the stress distribution significantly. The gingiva, periodontal ligament, and bone were not modeled, as studies have shown that no significant changes occur in the stress distribution.[22,32,33] The tooth preparation design was standardized and performed on the simulated models[7] (Fig 1). The labial surface was reduced by 0.5 mm. Preparation on the proximal surface was extended to half the labiopalatal thickness of the tooth. The finish line extended up to the cervical line of the teeth on the labial and proximal surfaces of the teeth, simulating a subgingival tooth preparation.

Table 1 Description of FE models

Model number	Model
M0	Natural central incisor
M1	Central incisor tooth preparation for PLV
M2	Central incisor tooth model restored with PLV
M3	0.5 mm increase in extension on mesial surface of central incisor
M4	1.5 mm increase in extension on mesial surface of central incisor
M5	2.5 mm increase in extension on mesial surface of central incisor
M6	0.5 mm increase in extension on mesial and distal surface of central incisor
M7	1.5 mm increase in extension on mesial and distal surface of central incisor
M8	2.5 mm increase in extension on mesial and distal surface of central incisor

To create increased enamel width and bonding potential, a 45° bevel to the long axis of the central incisor was prepared on the incisal edge of the labial surface. No palatal reduction was made. A modified chamfer finish line was placed at the margins of the prepared teeth. Over the natural tooth model, a PLV was modeled by using line or arc segments at the distance of 0.5 mm from the labial to the proximal surface of the tooth. The modified chamfer finish line with a width of 0.5 mm was terminated at the cervical line of the labial surface and half the proximal surfaces. The finish line and the PLV areas were created as separate volumes. The composite cement layer of 100 μm was modeled by offsetting.[22] The studies of Seymour et al[22] and Morin et al[12,13] demonstrated that luting cement thickness does not affect stress distribution significantly. The remaining tooth structure (other than the PLV, finish line, and cement layer) was modeled as a separate layer. This model, which simulated the PLV-restored central incisor, was designated M2. From model M2, other models (M3, M4, M5, M6, M7, M8) were made, with an increase in the extension (mesiodistal thickness) of PLV (Table 1). There were approximately 15,000 nodes and 11,000 elements per model. The PLV extension was increased by 1 mm in each model, mesial surface, and both the proximal surfaces to replicate the possible clinical situations of diastema closures. The extension of PLV was created as a separate volume and joined with the main PLV model. With the incorporation of material properties[35-42] (Table 2) the model behaved as a tooth restored with PLV. The simulated model was meshed with tetrahedral elements (solid 3D, structural, 10-node tetrahedral), as they are better suited to the geometric structure of the tooth.

The material properties were incorporated into the model to simulate the clinical condition. To estimate the least expected target for success, the properties of feldspathic porcelain was used as a control material.

Analysis was performed with three level of loads (50, 150, 250 N), and at three angulations (0°, 30°, 60°) on the labial

Table 2 Material properties

	Elastic modulus (MPa)	Poisson's ratio
Enamel	84,100[35]	0.33[36]
Dentin	14,700[37]	0.31[36]
Pulp	2[38]	0.45[38]
Composite	9500[39]	0.24[40]
Porcelain	74,000[41]	0.19[42]

surface of the incisal edges. The angulations (Fig 2) and forces simulated some of the masticatory forces that act on the restored teeth. The force was distributed on the incisal edge of models M2, M3, M4, M5, M6, M7, and M8. Stress distribution and stress intensities in the finite element model were represented both in numerical values and color coding. The results were interpreted after the models were subjected to analysis. The degrees, angulations, and level of loads were chosen to simulate the occlusal forces acting on the maxillary central incisor during mastication.[22,23] The range of PLV extensions were chosen to cover normal clinical conditions.

Results

Table 3 demonstrates the numerical value of the maximum stress acting on the unsupported PLV for different extensions, angulations, and loading levels applied. The lowest stress

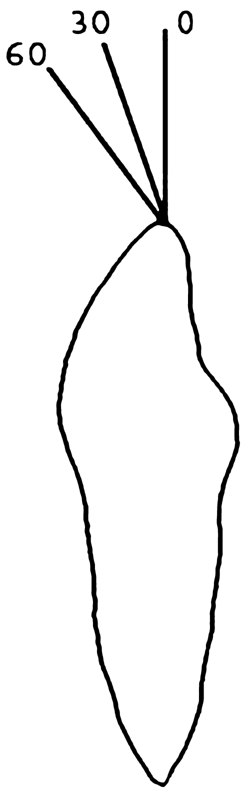

Figure 2 FE model depicting angle of loading. Plates 1: FEA of 0 mm PLV for varying angulations and loading levels.

Table 3 Maximum stresses (MPa) within the unsupported PLV for varying extensions, loading angles, and loading levels

Model number	Angulations PLV extensions	50 N			150 N			250 N		
		0°	30°	60°	0°	30°	60°	0°	30°	60°
M2	0 mm	9	10	21	27	28	63	45	47	106
M3	0.5 mm M	6	31	43	37	94	129	61	157	146
M4	1.5 mm M	23	32	45	45	95	134	75	159	223
M5	2.5 mm M	44	52	134	109	157	327	182	261	507
M6	0.5 mm M+D	13	17	29	33	69	78	53	115	129
M7	1.5 mm M+D	14	23	45	40	88	93	66	147	155
M8	2.5 mm M+D	18	47	101	64	140	304	211	232	471

recorded was 6 MPa for 0.5 mm Mesial (M), 0° angulation at 50 N force. There was a progressive increase in the stress when the extension, angulations, and magnitude of application of force were increased. At 0° angulation, compressive stresses were visualized in FEA for various magnitudes of force. Higher stress values of 182 MPa and 211 MPa were obtained for the 2.5 mm extension in the mesial surface and in both proximal surfaces for 0° degree angulation at 250 N magnitude of force. The stress occurring at 30° and 60° angulations was the combination of compressive and tensile stress. Higher values of 261 MPa and 232 MPa were observed when forces were applied on the mesial extension of PLV and on both the proximal surfaces for 2.5 mm at 30°, 250 N magnitude of force. Maximum stress values of 507 MPa and 471 MPa were observed when PLV was extended mesially by 2.5 mm in both proximal surfaces for 60° angulation at 250 N magnitude of force.

Discussion

This study examined stress distribution in PLV under different conditions. The results showed medium to moderate stress in most situations and signs of mechanical failure occurring in higher magnitude, greater angulation, and increased extension of PLV; however, FEA is a numerical tool, and any results obtained should not be extrapolated to the clinical situation unless verified. In contrast to the standardized protocol, there are clinical variations in biological and mechanical properties of teeth, ceramic materials, bond strength of luting materials and clinical variations in size and shape of the teeth. The use of such an analysis should be restricted to comparisons of relative effects of material properties, microstructure, and treatment conditions that may enhance resistance to fracture. The results of the study (Table 3) suggest that stress levels increase on the incisal edge and increase more in mesiolabial incisal angle with an increase in extension, angulation, and level of load. The increase in stress value was observed with an increase in the angulation and extension of the PLV. A considerable decrease in stress value was noted when the tooth was restored on both the proximal surfaces when compared to restoring the mesial surface. This is probably because stress is load divided by area, and an increased area with extended PLV helps to distribute the load and produce lower stresses

The results of the study (Table 3) establish that high stress values were observed on the PLV for different extensions, various angulations, and levels of loads. The results were compared with the normal compressive and flexural strength values of feldspathic porcelain, a conventional ceramic, which was chosen for control because it has more standard values than the other ceramic systems. The standard compressive and flexural strengths of feldspathic porcelain are 149 MPa and 65 MPa, respectively.[43]

At 0° angulation, compressive stresses were visualized in FEA for various magnitudes of force. Higher stress values of 182 MPa and 211 MPa were obtained at 250 N for the 2.5 mm extension in the mesial surface and in both proximal surfaces for 0° angulation. Fracture of the PLV occurs because the stress value was higher than the compressive strength of the porcelain. The added extensions of PLV for other magnitudes of force at 0° did not fracture, because the stresses were within the compressive strength of the ceramic.

The stress occurring at 30° and 60° angulations was the combination of compressive and tensile stress. Troedson and Derand[23] compared the stress value with the flexural strength of ceramic material. At 30° angulation, no fracture of the PLV occurs at 50 N, because the stress values were below the flexural strength of the material. At forces of 150 N and 250 N, fracture of PLV was expected in all the extensions of PLV.

At 60° angulation, fracture of the PLV was expected at 2.5 mm extension on the mesial and both proximal surfaces for 50 N forces. The other stress values for 50 N force were below the strength values, and no fracture was expected. With 150 N and 250 N forces, fractures of the PLV were expected in all specimens, because the stress value is greater than the flexural strength of ceramic.

The results of the study show that the load angle was an important factor for principal stress distribution. The increase in the angulation increases the fracture potential of free extension of PLV. The location of maximum stresses at 60° angulation may be due to an increase in tensile stress. At 0°, maximum compressive stress occurs. As the angulation increases, the tensile stress increases. According to Anusavice,[44] ceramic material fails in areas of tension because of decreased or poor tensile strength of the material. The outcome of this study also showed that the stress distribution pattern in all models resulted in increased stresses in the incisal edge and more in the mesiolabial incisal angle with increased magnitude and angulation. The increased fracture rate or chipping of the incisal edge could be compared to the Magne et al,[45] Aristisidis and Dimitra's[46] and Meijering et al[47] findings from of clinical studies.

The result of the study implies that the PLV can be used in the closure of wider diastemas, but critical factors such as the extensions, angulations, and the magnitude of forces acting on the unsupported free extension of the PLV have to be considered. Patients with unfavorable inclination of teeth and parafunctional habits show a greater increase in angulation and magnitude of force, and utmost care is essential in selection of cases for positive long-term results. Castelnuovo et al,[16] Stappert et al,[19] Zarone et al,[20,21] Addison et al,[24,25] Magne et al,[28,32,33,45] and Matsumara et al[29] compared tooth preparation designs, luting cement thickness, properties, and ceramic materials used in PLV. Unfortunately, the available literature provides limited information on diastema closure. This study was a simulative analysis; a long-term clinical study is essential to obtain better inferences. Modifications in tooth preparation for PLV and properties of advanced ceramic systems with long-term clinical reviews will aid us in obtaining more concrete solutions. Most clinical situations fail not because of catastrophic loads, but rather by fatigue, and so failure might occur at much lower stress levels. That is one of the reasons stress distribution is crucial.

Conclusion

FEA was used to analyze the stress distribution pattern of a maxillary central incisor restored with varying extensions of PLV. For the analysis, the models were loaded on the incisal edge at 0, 30, and 60 degree angulations palatally for 50 N, 150 N, and 250 N magnitudes of force. Within the limitations of the study, the following can be concluded:

1. Stress is concentrated on the free extension, incisal edge, and the mesiolabioincisal point angle.
2. Increase in the extension of the PLV increases the stress distribution and intensity on the free extension of the PLV.
3. Increase in the extension of the PLV on both surfaces to one surface has no significance, except for a marginal decrease in stress value when both surfaces are restored.
4. Differing angulations and differing level of loads induced different stress patterns.
5. Increase in angulations increases the fracture potential of the PLV.
6. Increase in loading levels increases the fracture potential of the PLV.

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