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The Effect of Preparation Height And Taper on Cement Lute Stress: A Three-dimensional Finite Element Analysis

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Abstract - *Three dimensional finite element models of an upper second premolar and molar with full veneer gold crown preparations were developed from extracted samples. The cement lute width was kept constant at 40 µm, but the height and preparation taper were varied. For both models the preparation height was either 1.5 mm (short preparation) or 3 mm (long preparation). The preparation taper was either 10° or 30°, giving a total of eight models. Each model was loaded with a 10 N horizontal load, a 10 N vertical load or a 10 N load distributed across the occlusal surface. The maximum shear stress and the maximum Von Mises' stress in the cement lute of each model were recorded. For the premolar, the maximum shear stresses ranged from 0.3-5.43 MPa and the maximum Von Mises' stress ranged from 1.44-14.98 MPa. For the molar, the maximum shear stresses ranged from 0.15-5.22 MPa and the maximum Von Mises' stress ranged from 0.37-15.02 MPa. The stress fields were consistently higher in the premolar with a 30° preparation taper compared to the 10° taper. The attainment of a cavity taper of 10° is still important to minimise stress in the cement lute and is particularly important in teeth with a lower preparation surface area such as a premolar.*

KEY WORDS: Finite element stress analysis, Crown taper, Biomechanics

INTRODUCTION

Conventional crowns and bridges rely on the geometric form of the preparation for retention rather than on chemical adhesion. This is because most of the traditional cements used in fixed prosthodontics are not naturally adhesive. Whilst restorations that rely principally on adhesive retention, such as resin retained bridges, veneers and ceramic 'bonded' crowns have become established, there remains some doubt about their long term success and adhesive technology has not, as yet, been applied to crown retained bridges, particularly those with longer spans. The traditional cements, such as zinc phosphate and polycarboxylate, allow the removal of a restoration in the event of failures without damaging the whole prosthesis.

Factors that influence the retention of a "conventional" crown include the degree of preparation taper, the preparation height and width (and hence the height to width ratio), the preparation surface area and the surface roughness[1]. As far as taper is concerned, the maximum retention occurs, theoretically, when the preparation has parallel walls. However, with contemporary clinical techniques it is impossible to prepare a tooth to this ideal shape as slight undercuts may be created that prevent the restoration seating.

The relationship between crown taper and retention was first investigated by Jörgensen[2] in 1955. He cemented brass cups onto cones of varying taper and noted the force required to dislodge the brass cups. He identified that the relationship between taper and retention to be hyperbolic, with retention rapidly decreasing as the taper increased above 10°.

The effect of preparation dimension was studied by Kaufmann *et al*[3] who examined the factors influencing the retention of gold castings on metal test dies using restoration taper, height and diameter as the variables. They highlighted that retention increased significantly as the opposing walls approached parallelism, whilst a less marked effect was found with an increase in preparation height. Shillinburg *et al*[4] described the angle of convergence as a compromise between the ease of clinical application and retentive and resistive capability, stating that the optimal restoration taper was 6°. Neuhaus[5,6] provided a thorough step-by-step guide to established methods of crown preparation and suggested that an ideal restoration taper was 2°- 8°. However, a more recent study examined the relationship between restoration taper and retention using zinc phosphate cement[7]. Crown retention was greatest with a taper of between 6° and 12°. Angles greater or lesser than this range resulted in diminished retention.

Fusayama and Imamoto[8] also found that with a preparation taper of between 0° and 5°, the cement lute thickness reduced dramatically as a 0° convergence angle was approached. This suggests that a finite cement lute thickness was desirable to utilise the mechanical properties of the cement and that this thickness cannot be achieved when very small tapers are employed.

Achieving an optimal preparation taper of 5-10° within the clinical environment is challenging. Weed *et al*[9] reported

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that dental students could produce gold crown preparations with a taper of 12° on a typodont, but this taper increased to a mean of 23° clinically. Similarly, Smith *et al* [10] showed that a convergence angle of 6° was less likely to be achieved by dental students than one of 12°, due to difficulty in visualising the small angles involved.

Many studies have suggested that the average life of crown and bridgework is between 10 and 15 years[11-13]. However, these restorations do eventually fail and the common causes are due to loss of retention and/or caries. Caries at the crown margin may be related to poor oral hygiene in this area, but may also be assisted by breakdown of the cement lute at the restoration margin. Therefore, the integrity of the cement lute and how this responds to occlusal loading during eating, swallowing and parafunctional activity is critical to the success of crown and bridgework.

Finite element analysis has been used to investigate many aspects of crown construction including cement microfracture[14], luting cement thickness and physical properties[15], the influence of margin design on cervical stresses[16] and the influence of crown metal thickness on cervical stresses[17]. However, the interplay between preparation taper, preparation height and tooth type on the stresses developed within the cement lute has not been investigated.

Therefore, the aim of this study was to examine the stress fields in the cement lute of crowns placed on premolars and molars with differing preparation height and taper using three-dimensional finite element analysis. The hypothesis for this study was that a reduced height and increased taper would decrease resistance to displacement.

MATERIALS AND METHODS

An upper second premolar and first molar were embedded in a low exotherm epoxy resin and sectioned bucco-lingually through the centre of the tooth using a diamond saw and photographed alongside a millimetre rule. The outline of the tooth, enamel-dentine junction and pulp was traced onto transparent paper and this was placed over the computer screen so that the outline could be captured in the finite element pre-processor (Marc, MSC Software Corporation, 500 Arguello St., Suite 200 Redwood City, California, USA). These outlines were initially used to generate two dimensional finite element meshes of the upper premolar and molar using quadrilateral elements. The tooth dimensions were also cross-checked with the tooth morphology values of Van Beek[18]. As this study was concerned primarily with the cement lute stress and the influence of preparation geometry, modelling of the supporting tissues and alveolar bone was omitted. Similarly, the effect of the pulp was considered negligible due to its comparatively low volume and the comparatively high stiffness characteristics of the surrounding dentine and cement. Furthermore, Rubin *et al*[19] and Hojjatie and Anusavice[20] have shown that modelling the pulp as a void has no effect on the magnitude of the coronal stress field.

Each two dimensional mesh was then rotated through 360° in 7.5° increments and the centre section expanded bucco-lingually to form the three-dimensional mesh using eight-noded, isoparametric hexahedral elements. The initial two-dimensional mesh for the premolar is shown in Fig. 1a and the resulting three-dimensional mesh is shown in Fig. 1b. The cement layer was 40 µm wide [21,22] and formed by three layers of elements to ensure accurate representation of stress behaviour through its thickness. As this was the specific region of interest the mean mesh density was of the order of 10^{12} elements/m^3 compared to a global mean mesh density of 10^{10} elements/m^3.

Each mesh for both the premolar and molar had a crown height of 3 mm and these are referred to as the 'long preparation'. Each mesh was then shortened for both tooth types to give a crown height of 1.5 mm these are referred to as the 'short preparations'. Both the 'long' and the 'short' preparations were further modified to give a total preparation taper (convergence angle) of 10° or 30°. A synopsis of the meshes generated are given in Table 1 and the material property values used in the study are given in Table 2.

The contact properties of the model between the cement/dentine and the cement/crown interfaces were then defined using a contact table within the software. The contact between the cement layer, the tooth and crown

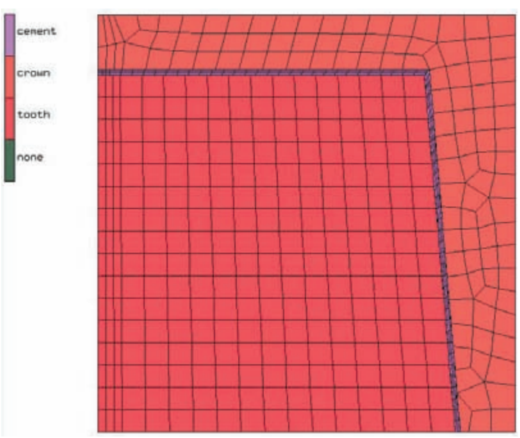

Figure 1a. *Original two-dimensional mesh*

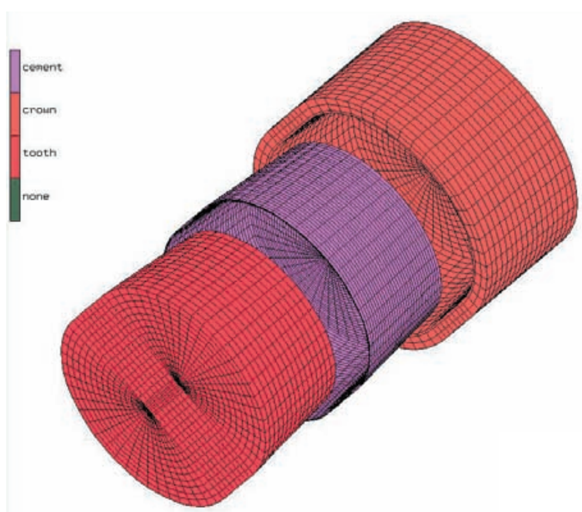

Figure 1b. *Three-dimensional mesh*

Table 1. *Overview of meshes used in the study*

Tooth type	*Preparation length*	*Preparation taper (°)*
Premolar	Short	30
Molar	Short	30
Premolar	Long	30
Molar	Long	30
Premolar	Short	10
Molar	Short	10
Premolar	Long	10
Molar	Long	10

Table 2. *Material properties used in the study*

Material	*Elastic Modulus (GPa)*	*Poisson's ratio*
Dentine[27]	15.0	0.31
Cement[28]	4.0	0.30
Gold alloy[29]	96.6	0.30

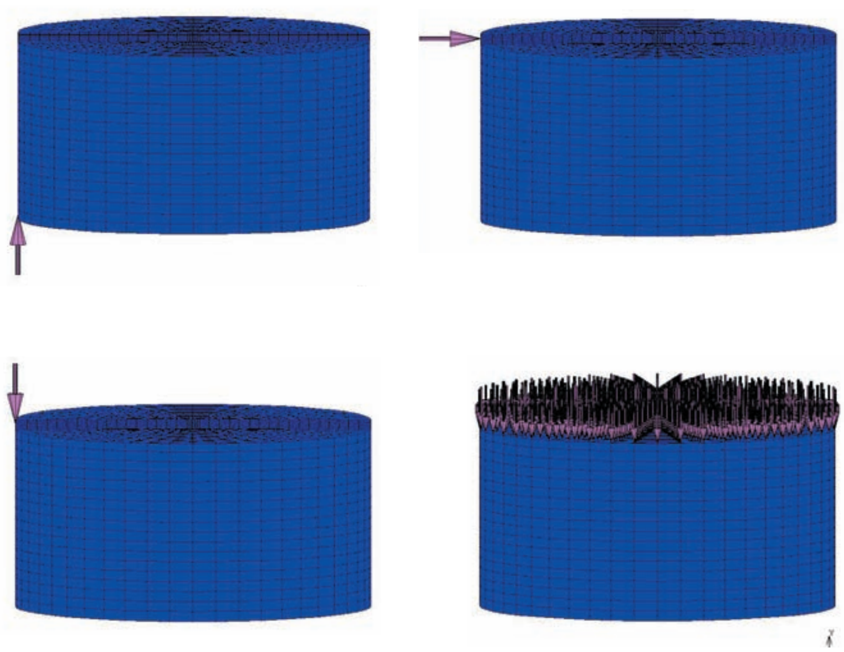

Figure 2. *Three different loading points used in the study*

were described using the 'glued contact' option. This created tying equations that described the contact, both normal and tangential to the contact segments. This contact option allowed specifications to be entered regarding the circumstances at which separation at the interfaces would take place. The separation force was set to a very high level (>500N) in order to ensure that no separation could occur.

The finite element model was rigidly constrained in the x, y and z directions at the base of the model. In clinical reality this set of boundary conditions is likely to represent a crowned tooth that has been loaded by a relatively high occlusal load causing the tooth to 'bottom out' in the alveolar housing.

The finite element model was loaded in three ways (Fig 2):

- Loadcase 1: Point load of 10 N acting sideways applied to the top edge of the crown. This would mimic a load applied in lateral excursion;
- Loadcase 2: Point load of 10 N applied vertically to the occlusal surface. This would mimic a load applied in chewing or swallowing (23);
- Loadcase 3: Distributed load of 10 N place across the entire occlusal surface acting apically; this would mimic the effect of biting into a food bolus.

For each model and load case the maximum shear stress and Von Mises' stress within the cement lute were recorded. The shear stress was chosen as this would be greater numerically than the local tensile or compressive stresses. The Von Mises' stress was chosen as it provides an overall picture of the stress field, since it contains components of both the local tensile and shear stresses. Both of these stress parameters are likely to predict failure[24].

RESULTS

The results for loadcase 1 are shown in Table 3, for loadcase 2 in Table 4 and for loadcase 3 in Table 5. In each results table the highest peak stress is highlighted in bold. For loadcase 1, which depicts a lateral force applied near the occlusal surface of the crown, the maximum shear stresses ranged from 1.63-5.43 MPa, while the maximum Von Mise's stresses were in the range 13.32-15.02 MPa. For loadcase 2, which depicts an apically directed occlusal load, the maximum shear stresses were in the range 1.94-2.96 MPa, while the maximum Von Mises' stresses were in the range 4.36-5.60 MPa. For loadcase 3, which depicts the load applied by a food bolus, the maximum shear stresses were in the range 0.15-0.36 MPa, while the maximum Von Mises' stresses were in the range 0.37-3.69 MPa. A representative stress plot is shown in Fig. 3. This is for the load case 1 and shows the maximum shear stresses in the cement lute for each combination of tooth type, taper and preparation height.

Table 3. *Maximum stress values for load case 1 (10 N applied laterally to the top edge of the crown)*

Tooth	*Preparation length*	*Preparation taper*	*Max. shear stress (MPa)*	*Max. Von Mises' stress (MPa)*
Premolar	Short	30°	2.25	13.86
Molar	Short	30°	1.92	13.95
Premolar	Long	30°	5.43	13.32
Molar	Long	30°	5.22	13.37
Premolar	Short	10°	1.89	14.10
Molar	Short	10°	1.63	14.16
Premolar	Long	10°	2.27	14.98
Molar	Long	10°	2.19	15.02

Table 4. *Maximum stress values for load case 2 (10 N applied vertically to the occlusal surface)*

Tooth	*Preparation length*	*Preparation taper*	*Max shear stress (MPa)*	*Max Von Mises' stress (MPa)*
Premolar	Short	30°	2.80	5.20
Molar	Short	30°	2.51	4.67
Premolar	Long	30°	2.96	5.60
Molar	Long	30°	2.78	5.21
Premolar	Short	10°	2.44	5.02
Molar	Short	10°	2.21	4.58
Premolar	Long	10°	2.09	4.68
Molar	Long	10°	1.94	4.36

Table 5. *Maximum stress values for load case 3 (10 N distributed occlusal load)*

Tooth	*Preparation length*	*Preparation taper*	*Max shear stress MPa)*	*Max Von Mises' stress (MPa)*
Premolar	Short	30°	0.36	1.44
Molar	Short	30°	0.22	0.40
Premolar	Long	30°	0.34	3.69
Molar	Long	30°	0.23	0.49
Premolar	Short	10°	0.30	1.76
Molar	Short	10°	0.19	0.37
Premolar	Long	10°	0.32	3.45
Molar	Long	10°	0.15	0.52

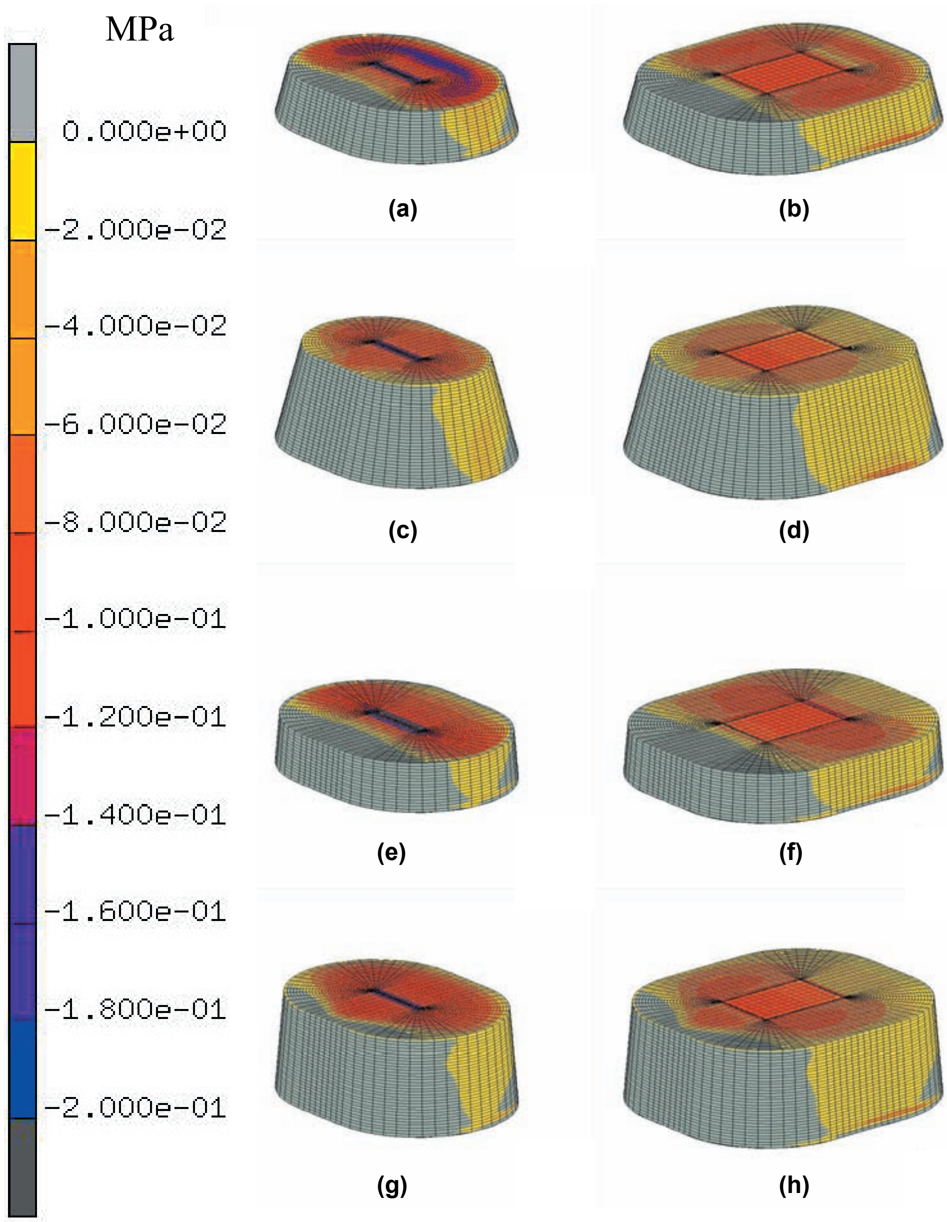

Figure 3. *Shear stress distibutions for loadcase 1*

DISCUSSION

Load case 1

The first load case, where the load was applied horizontally near the occlusal surface, represents a load that could well displace a crown by rotation, particularly where the preparation height was low. The maximum shear stress values for both the premolar and the molar crowns with the 10° preparation taper were very low, ranging from 1.89 to 2.27 MPa and the effect of a short or long preparation seemed to have little influence on the stress field.

The introduction of a 30° taper increased the maximum stress by approximately 50% with the long preparation (5.22-5.43 MPa). However, this effect was not seen for the short crown preparation, which is in direct opposition to the traditional teaching of fixed prosthodontics[25].

The Von Mises' stresses, which provide an overview of the stress field, showed very little difference in the maximum stress values for all of the different preparation types.

Load case 2

The second load case, where a point load was applied to the occlusal surface in an apical direction, represents a typical swallowing load. The magnitude of the maximum shear stresses with this load case were similar to load case 1 (1.94-2.96 MPa). Firstly, it was a consistent feature that the peak stresses in the premolar were always higher than in the molar for both stress types. Presumably this is just a reflection of the much smaller surface area of the premolar available for retention compared to the molar.

Secondly, the highest stresses were again found for the premolar with the 30° taper and the long preparation. The lower surface area of the premolar preparation compared to the molar and the 30° taper would partly explain this high stress field, as the crown would be more likely to flex and rotate under the 'compressive' load. It would seem logical that the combination of a short preparation with a 30° taper in a premolar would present the most unfavourable stress field. However, the combination of a

30° taper in a premolar with a long preparation had the most unfavourable stress field. One possible explanation for this finding may be the juxtaposition of the 30° taper with the maximum shear stress plane, which occurs at 45° to the vertical axis of the preparation[24]. Therefore, as the taper increased from 10° to 30°, the sampling plane in the cement lute became increasingly influenced by the maximum shear stress.

Finally, with this vertical load it was noted that the maximum stresses with the 10° preparation taper were consistently smaller than with the 30° taper. In terms of magnitude, the stresses were between 0.4 and 0.8 MPa lower when comparing these two tapers. This pattern was also repeated with the Von Mises' stresses. Standard texts on Operative Dentistry[1,25] suggest that the optimal taper for a crown preparation is between 5 and 10°, this assumption being based on laboratory based biomechanical studies carried out in the 1950s and 1960s [2,3,8]. The results from this study seem to suggest that a smaller preparation taper of 10° is also biomechanically more acceptable than a 30° taper, as the stress distribution is more favourable. Although the differences in the magnitude of these stresses were small (< 1MPa) it is possible that after many years of function, the slightly higher stress field of the 30° taper crown would result in crack initiation and propagation[14] and ultimately loss of retention.

Load case 3

The third load case, where the load was distributed uniformly over the entire occlusal surface of the crown was used to simulate the effect of crushing a food bolus. Not surprisingly, the magnitude of the stresses were rather smaller than the previous two load cases, as a result of distributing the load over a wider area.

The highest value for the maximum shear stress was found for the combination of a premolar with a 30° taper and a short preparation, as would be expected from first principles. This was not the case for the Von Mises' stresses, where the highest stress was again found with the combination of 30° taper in a premolar with a long preparation. The reason for this may be the systematic anomaly described above.

Once again, the shear stress and Von Mises' stresses for the 10° taper preparations were smaller than for the 30° taper, which again highlights the importance of small preparation taper.

In spite of these findings, the results of this study must be interpreted with a certain amount of caution. First, the finite element meshes were developed from tooth sections rather than from µCT scans which could lead to minor errors in tooth morphology. Second, the root, periodontal ligament and supporting alveolar bone were not modelled which could introduce some errors. However, Rees[26] has recently shown that it is not essential to model the root and supporting structures if the region of interest is the crown of the tooth. Finally, these models examined just one crown in isolation. In the mouth, teeth contact their near neighbours and will dissipate some load to them via the approximal contact areas. Finally, there is biological variation in many intra-oral factors such as tooth size, arch shape and occlusal load.

In conclusion, this study showed that:

- A 10° preparation taper produced a more favourable stress field in the cement lute compared to a 30° preparation taper;
- The stress field was generally higher in the premolar than the molar which suggests that it is vitally important to produce an optimal taper when preparing a premolar, due to the lower surface area.

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