Original Article

Finite Element Stress Analysis of Composite Polymerisation Shrinkage in Endodontically Treated Maxillary Central Incisors

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ABSTRACT

Introduction: Resin composites are common materials used to restore anterior teeth following root canal therapy, but are accompanied with shrinkage during polymerization. The aim of this *in vitro* study was to investigate the effect of the insertion method and polymerization shrinkage of resin composite on residual tooth structure.

Materials and Methods: Stereomicroscopy and computerized Finite Element Modelling (FEM) were used to compare residual stresses in endodontically treated, extracted maxillary central incisor teeth, in which the access cavities were restored with resin composite. Theoretical stresses derived from the FEM were analyzed during preparation and after teeth were restored using either a "bulk" or a "wedge incremental" method. These data were subsequently compared with stresses measured directly using strain gauges.

Results: Results showed that intensive stresses, which had the potential to cause fracture in dental structures and composite de-bonding, were applied to teeth during polymerization.

Conclusion: According to the results of this study, the "bulk" build up led to less stress induction during restoration of teeth following root canal therapy.

Key words: Finite Element, Polymerization, Resin Composite.

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Introduction

Resin composites undergo a volume contraction of 1-3.5% during polymerization, resulting in enamel fracture, cracked cusps, cuspal movement, and eventually post-operative pain and microleakage [1]. Another consequence of polymerization contraction is residual stress. These stresses may create cusp movements, post-operative sensitivity and tooth fracture [2,3]. Some methods have been developed to limit resin composite shrinkage and resultant stresses [4]. These include the application of dentine adhesion agents with high bonding strengths and techniques involving the placement of composite in incremental layers. These methods can help to reduce the potential for microleakage, but can be associated with increased residual stress when a decrease in marginal gap is achieved without decreasing shrinkage [2]. Resin flow during curing can act to decrease residual stresses, but this phenomenon is not always effective in deep cavities and with light curing resins [5].

Polymerization shrinkage of resin composites has been improved by innovation in manufacturing [6], modification of cavity preparation design and modifications to insertion techniques [7]. At present, our understanding of stress generation associated with the placement of restorations is incomplete. In

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one study, after using finite element modelling (FEM), higher transient stress was predicted to occur during curing in class V cavities restored by a "bulk" method than was expected after complete composite curing [8]. In another study by Abbas et al [9] in 2003, incremental build up showed greater cuspal deflection. In another study carried out on class V cavities, the final stresses were found to be identical despite different cavity restoration techniques [10].

However, transient stresses during curing were different, with lowest stresses associated with a "bulk" method and the highest stresses with a "wedge incremental" placement. In explaining this phenomenon, the authors stated that the greater the linear dimension of material and the smaller the adhesion surface area, the greater the developed stresses [6]. To further investigate this problem, caries- and crack-free maxillary central incisors, which had previously received root canal therapy, were used to investigate the effect of insertion method and polymerization shrinkage of resin composite on the dental residual tissue using both computer modelling and direct observations under controlled laboratory conditions.

Materials and Methods

This *in vitro* study was divided into three stages. In stage 1 or cracks detecting, a pilot study involved the selection of three extracted, human, caries-free maxillary incisors with no evident cracks. The entire surface of each tooth, except the buccal surface, was covered with nail polish, and the teeth were placed into a solution of 10% fuchsin for a period of 24 hours. Teeth were then irrigated and stereomicroscopic examination (7 x magnification) was carried out to detect the presence of existing cracks. Access cavities were then prepared and root canal therapy was performed. A long, flame–shaped, high-speed bur was used to extend the access cavity, so that the thickness of the labial wall was reduced to 1 mm and one of the marginal ridges was removed. Root walls were also prepared to a thickness of 1 mm (thickness was checked using Bolley gauge). Cavities also were checked to detect the presence of any cracks and then were restored using dentine bond adhesive (Scotch bond multipurpose plus, Batch 70-2010-1606-3, 3M, USA), and resin composite (Herculite XVR Lot 406/33, Kerr, USA, A3 shade) was cured for 40s from buccal and palatal walls using Coltolux2 (Coltene, Switzerland) with checked output. The specimens were subsequently placed into 10% fuchsin solution for 24 hours before stereomicroscopic images were obtained. Pre- and post-treatment images were compared to provide evidence of crack formation associated with the experimental process.

In stage 2 or software designing, a finite element model (FEM, Nisa II) was developed. One caries-free maxillary central incisor with dimensions corresponding to reported averages [11] was selected. The tooth was mounted in silicone putty. CT scan images at 1 mm intervals in both the coronal and sagittal axes were prepared. An access cavity was then prepared using a long fissure bur and extended in such a way that the distal marginal ridge was removed. The cavity was finished with the following dimensions: 3 mm thickness of labial wall, 1 mm thickness of mesial marginal ridge, 1.5 mm height of palatal wall from incisal edge, 2 mm height of palatal wall from CEJ and 1 mm thickness of canal walls at the CEJ. CT scans were repeated under the same above-mentioned condition and the images were transferred to transparent paper; scanned graphical files were prepared for modelling using standard FEM software (AutoCAD, version 12). A model including 2,685 elements and 2,848 nodes using Display III software was developed for both prepared and nonprepared teeth. Enamel, dentine and composite were included in the model with the mechanical properties described in Table 1. Polymerization was modelled using a 1% change in elastic modulus between nonpolymerised and polymerised composite resins and a one degree assumed drop in temperature [12, 13]. The restoration of the cavity involved two alternative techniques, a "bulk" method, in which the entire restoration was placed in one increment, and a "wedge incremental" method, where the first increment was placed in the base of the cavity to occlude the root canal, the second increment was placed as a wedge against the labial wall of the cavity and the final increment completed the restoration. Since there are generally some cracks within dental enamel under clinical conditions, one horizontal crack involving two-thirds of the thickness of the tooth was modelled. In addition, considering both 3 mm of residual dentine on the labial wall and the situation when no dentine remained approximated the clinical variation in preparation.

Calculations for the two restoration methods ("bulk" and "wedge incremental") for cracked and crack-free teeth, for different residual dentine thickness (0 mm and 3 mm) were performed.

In stage 3 or the final stage of this study, a laboratory investigation of 12 intact central incisors, extracted human teeth with no cracks or caries and with average dimensions [11], was undertaken. Selected teeth underwent complete root canal therapy in such a way that the resultant access cavities corresponded to those designed for the FEM computerised model. The only difference was in the thickness of dentine in the labial cavity wall, which was prepared up to 3 mm in six specimens and up to 1 mm in the other six. Strain gauges (FLG-02-11, TML, Sokki Kenkyujo Co Ltd, Tokyo) were attached to the teeth in the middle third of buccal surface parallel to the long axis using cyanoacrylate cement at the location that had been previously determined by computerized calculations as a high risk region for crack generation (middle one third of labial surface of enamel). In the next step, composite was inserted into the cavities using either the "bulk" or "wedge-incremental" methods. During light curing and composite polymerization, the strain gauge data were collected and average values were calculated and plotted to follow the time-course for polymerization.

Results

The results of the first stage of the study provided stereomicroscopic evidence of an increase in the number and complexity of cracks in enamel after the preparation and restoration of cavities. This provided the basis for including the presence or absence of cracks in the subsequent modelling. Results of the FEM analysis are summarised in Table 2. These results are presented for three stages for both the "bulk" and "wedge incremental" protocols. For the "bulk" method, these stages were as follows: stage 1, half of the surface of enamel composite was cured; stage 2, the entire crown enamel composite was cured; stage 3, the composite located at the pulp entrance was cured. With the "wedge incremental" method the stages were as follows: stage 1, the first part of composite located at the pulp entrance was cured; stage 2, the first half of crown enamel composite that was attached to the labial wall of the cavity was cured; stage 3, the rest of the crown cavity composite was polymerised. Results derived from the strain gauge analysis for the "bulk" and "wedge incremental" methods with both 1 mm and 3 mm of retained labial dentine are presented in Figures 1-4. Figures show that increasing the thickness of the labial surface from 1 mm to 3 mm will decrease the induced strain.

Results of the FEM are shown in Figures 5 to 10.

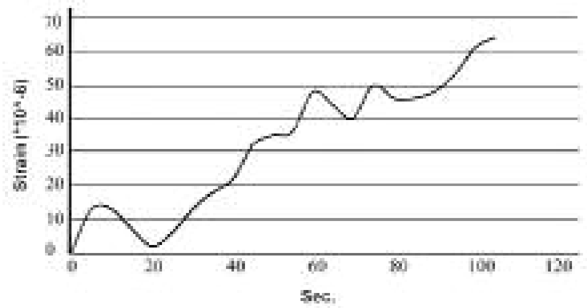

Figure 1. Strain measured on the labial surface of experimental tooth with 1 mm thick labial wall during restoration using the "bulk" method.

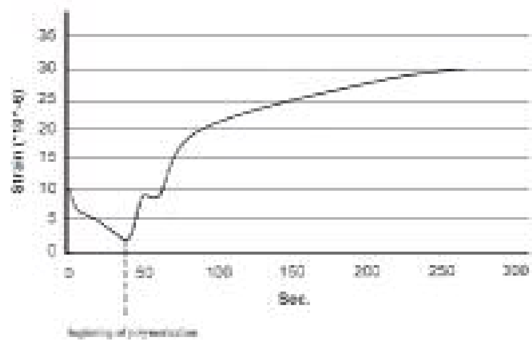

Figure 2. Strain measured on the labial surface of experimental tooth with 3 mm thick labial wall during restoration using the "bulk" method.

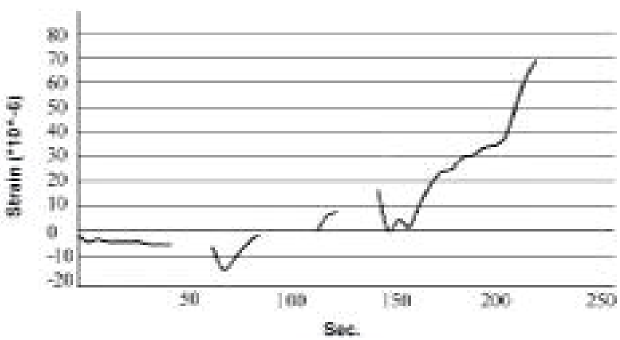

Figure 3. Strain measured on the labial surface of experimental tooth with 1 mm thick labial wall during restoration using the "wedge incremental" method. Breaks in trace represent the duration of addition of increments.

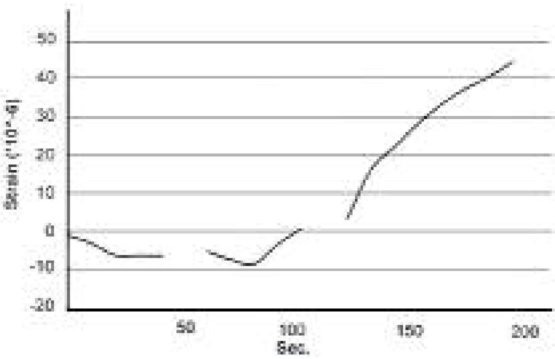

Figure 4. Strain measured on the labial surface of experimental tooth with 3 mm thick labial wall during restoration using the "wedge incremental" method. Breaks in trace represent the duration of addition of increments.

Discussion

Restoration of a central incisor with resin composite following root canal therapy sometimes fails. Stress resulting from polymerization shrinkage can be an important factor in this failure. This study was designed to investigate the amount of strain that develops under different conditions. In bulk method restoration with 2 mm of remained dentine, the induced stress is due to contraction of composite and transfers some stresses to the walls adjacent to the composite, in addition to causing bending along the longitudinal axis of the tooth [14,15]. In this state, the tooth acts mechanically as a beam and transfers these stresses on the labial wall of the cavity, as a tension upon the external surface (enamel) or as a pressure upon deep surfaces (dentine). In dentine adjacent to the cavity (dentine attached to the composite), some tension was observed that was due to the effect of tension from the composite attached to this surface. But in the body of the dentine, some compressive force was observed. In the incisal part of the cavity, some higher tensile stress was applied to the composite at the tooth interface. It is most likely that this tensile stress would cause de-bonding of small segments in this area. Compressive stresses at the marginal ridges appeared to increase with promotion of polymerization immediately after the initiation of curing (Table 2). Up to the time of polymerization of half of the surface of composite, this force is lower, but the progress of curing and the bending of the crown significantly increase the compressive force on the marginal ridge. Here again, the marginal ridge functions as a beam and mostly bears the forces generated from bending. As a result, some stresses exist upon external parts (towards the palatal surface) and some tension at internal parts (towards deep dentine).

By considering the situation after curing half of the total volume of composite and then at subsequent stages, it was expected that the tension would increase proportionally as the volume of contracting composite increased. In practice, it was seen that this proportionality did not exist and the rate of increase in tension was less than expected. There are two possible reasons for this phenomenon. First, surface adhesion increases in parallel with the curing. As previously noted, if the amount of flow of resin composite is not considered, a larger bonded surface area and a smaller length of cured material results in less tension [16]. Furthermore, during curing at the second stage, the tooth acts as a column instead of beam. Therefore, the magnitude of tooth bending in this stage was less. This is illustrated in Figure 6, which shows composite with significant tension at the incisal margin during polymerization; cured composite from a previous stage acted as a base, preventing excessive tooth bending in the longitudinal axis. Therefore, the amount of bending and tensile stress was less than expected. During resin curing in the root canal entrance, there is no remarkable change in crown tensions, but there is pressure on external areas and tensile stress on internal parts of the root as a result of inward directional forces. A similar pattern of forces was evident at the completion of the polymerization (Figure 7). When teeth with a transverse crack in enamel were restored by the "bulk" method, the FEM analysis showed tension across the entire surface of enamel (Figure 8). The amount of tension was similar to that for a tooth without any crack. However, there was a marked increase in tensile stress at the depth of the crack, which was due to concentration of tension in this area. This tension can cause widening of cracks, which is very high at the beginning of curing and decreases with progressive curing. Even though the volume of contracted composite was increased, tensile stress on enamel, marginal ridges, and incisal edge was similar to the situation with no cracks. Clinically, widening of cracks can reduce the stress. Therefore, in the presence of cracks, the amount of stress may be less than required for debonding and can reach the limit required for new cracks initiation or remains as residual stress.

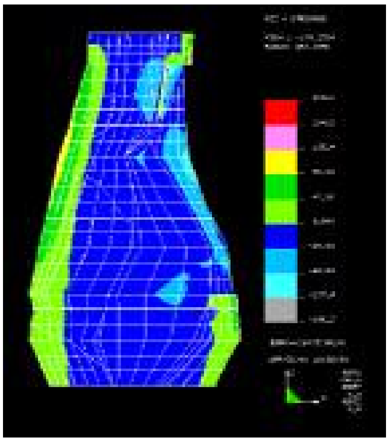

Figure 5. FEM diagram illustrating stresses after stage 1 of resin curing when the tooth is restored by the "bulk" method.

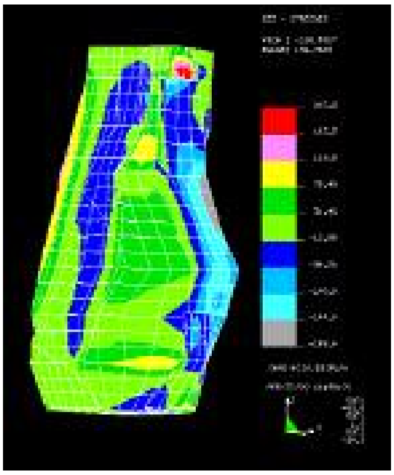

Figure 6. FEM diagram illustrating stresses after stage 2 of resin curing when the tooth is restored by the "bulk" method.

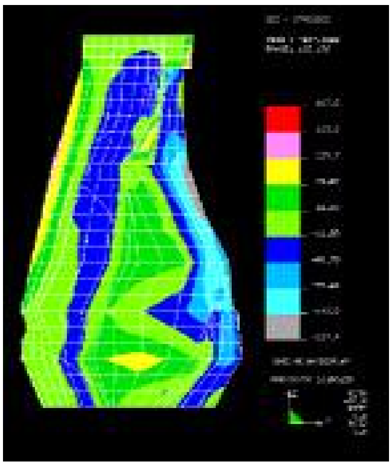

Figure 7. FEM diagram illustrating stresses at the completion of resin curing when the tooth is restored by the "bulk" method.

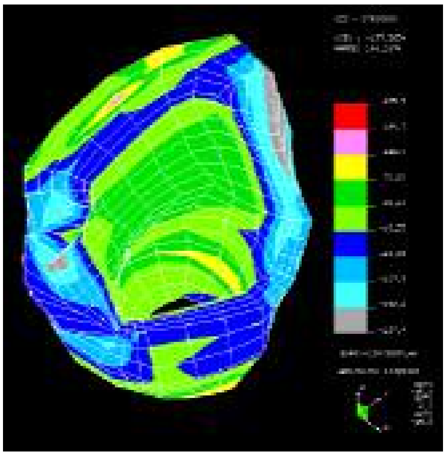

Figure 8. FEM diagram illustrating stresses at the completion of resin curing in a tooth with a transverse labial crack when the tooth is restored by the "bulk" method.

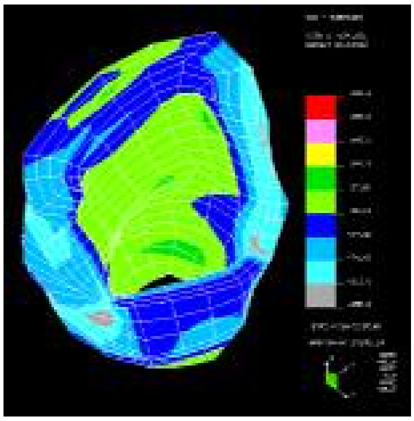

Figure 9. FEM diagram illustrating stresses after stage 2 of resin curing when the tooth is restored by the "wedge incremental" method.

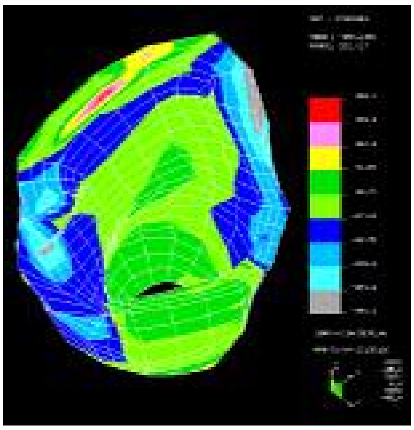

Figure 10. FEM diagram illustrating stresses at the completion of resin curing when the tooth is restored by the "wedge incremental" method.

Based on theoretical calculations, the de-bonding of resin composite from dentine after the promotion of polymerization should happen for all conditions. Practically, de-bonding does not always occur, as tension is not applied on a smooth surface. When a force is applied on a surface with depressions and projections, tension is applied in different directions and de-bonding in some areas happens before general de-bonding. This can reduce the amount of stress in some areas, but still result in forces that are higher than the tensile strength of enamel, and therefore can result in cracks and even cuspal deflection.

Using the "wedge incremental" method, no tension was recorded for the first stage (Table 2). At the second stage, tension in the crown was evident (Figure 9), but tended to be lower than tension for teeth restored with the "bulk" method at the second stage, and as a result, pressure on dentine was less. After curing the third layer, tension increased markedly (Figure 10) and was higher than observed with the "bulk" method. This could be due to reduced support for the labial wall at the second stage using the "wedge" method compared to the support provided for the incisal wall using the "bulk" method, which can prevent bending of the tooth.

Table 1. Physical properties of enamel, dentine and composite.

Material	Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Poisson's Ratio
Enamel	400	10.0	83	0.30
Dentine	297	98.0	18.6	0.23
Composite	455	60	13.8	0.24

Table 2. Maximum stresses (MPa) derived from FEM analysis for three stages for each experimental protocol. In "Bulk method" these were when (1) half of surface of enamel composite was cured, (2) the entire crown enamel composite was cured and (3) composite located at the pulp entrance was cured. For the "wedge incremental" method the stages were when (1) first part of composite located at the pulp entrance was cured, (2) the first half of crown enamel composite which is attached to the labial wall of cavity was cured and (3) remaining crown cavity composite was polymerised.

Method	Group	Stage	Incisal Edge	Marginal Ridge	Labial Wall Dentine	Labial Wall Enamel
BULK	* No Crack	1	203	-107.4	-68.61	125.4
		2	207.5	-188.6	-100.6	163.5
		3	207.5	-187.4	-99.62	163.6
	** Crack	1	201	-146	-68.86	123.9-162.5
		2	205.5	-197.4	-63.09	116-160.7
		3	205.5	-196.2	-69.29	116-160.8
	▪ No Dentine	1	193.6	-167.3	-	113.4
		2	238.9	-297.5	-	238.9
		3	244.4	-381.3	-	174.9
WEDGE	* No Crack	1	0.0	0.0	0.0	0.0
		2	0.0	-124.5	-80.21	141
		3	190.9	-219.2	-116.7	242.2
	** Crack	1	0.0.	0.0	0.0	0.0
		2	0.0	-155.3	-70.03	57.80-100.4
		3	196.2	-250.4	-138.8	140.4-252

* No cracked enamel with 2 mm supportive dentine.

** Cracked enamel with 2 mm supportive dentine.

▪ No cracked enamel without supportive dentine.

When teeth with horizontal cracks in the enamel were restored with the "wedge incremental" method, there was no tension in enamel at the first stage, but interestingly, after insertion and curing of the second layer, tension on enamel and dentine and even tension on the base of cracks were less than those with the "bulk method". This tension was even less than that for crack-free teeth restored with the "wedge incremental" method. In fact, distribution of tension in different surfaces depends on the rigidity of the surfaces and therefore, because rigidity of the intact surface is higher compared to surfaces with cracks; during curing the second layer there is less tension on the labial surface of a tooth with cracks. Higher tension on the orifice of the canal was also observed. Also, using the "wedge incremental" method it was observed that at the second stage, tension on the enamel and dentine of the labial and marginal ridges was less than that with the "bulk" method. After insertion and curing the third layer, a support was created on the incisal edge, which could result in severe bending of the tooth and subsequently, widening of the cracks.

In the absence of dentine in the labial wall of the cavity restoration, using the "bulk" method resulted in increased tension over time, particularly at the marginal ridge. Labial surface enamel also showed higher tension, which increased with the degree of polymerization of the coronal composite. Results obtained from strain gauge measurement confirmed the results obtained from the FEM showing strain following promotion of the polymerization of resin composite. However, the amount of strain measured was much less than the amount calculated by computer. This difference can be due to composite flow, which can relieve part of the tension during polymerization and is not included as a factor in the finite element model. It can also involve small areas of de-bonding during the polymerization, which can reduce the amount of stress on other areas of the tooth. Anatomical irregularities in the tooth associated with the occurrence of discontinuations in dental structure and the orientation of the effects of polymerization could also contribute to these differences.

Under clinical conditions, resin composite polymerized towards the light source [17, 18]. As a result of this negative strain, general deformation is reduced on tooth structure, which can not be simulated and calculated with computer, and therefore can result in differences between the results obtained by the two techniques. Plots of the development of strain over time also revealed some interesting information. For example, with the "bulk" method and the thicker labial wall (Figure 2), there was an initial reduction in strain between times 0 to 50, which was related in part at least to force generated by insertion of the material.

By studying graphs of strain development with the "wedge incremental" method (Figures 3 and 4) it is evident that at the stage of curing of composite at the entrance of the canal, there is a compressive strain, which changes to tensile strain after insertion and curing subsequent layers. This is consistent with results obtained from FEM studies.

Conclusion

Results of this study showed that contraction due to resin composite polymerization seems to generate destructive forces and tensions on residual dental tissues. It also appeared that the "bulk" method resulted in less strain, suggesting that it is advisable to use a "bulk" method where this method is not contraindicated because of the thickness of the composite to be cured.

Despite general agreement between the FEM data and the measured strain, and the fact that computerized studies can produce beneficial information because they must represent controlled laboratory conditions, the obtained results do require confirmation in subsequent clinical studies.

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