Cementation in adhesive dentistry: the weakest link
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CHAPTER 5

Reduced contraction stress formation obtained by a two-step cementation procedure for fiber posts

Abstract

Objectives: In a previous study, a 60% increase in push-out strength was obtained in vitro with a two-step cementation of fiber posts, a procedure equivalent to the layering technique of composite restorations. The aim of this study is to find the rationale for this increase in push-out strength with finite element analysis (FEA).

Methods: FE models were created of the push-out test set-up of fiber posts cemented according to a one-step and two-step procedure and of the complete root with post. The failure loads of glass-fiber posts cemented with RelyX Unicem as obtained in a previous study were used as the load in the push-out FE models. For the complete root model, a load of 100N was used. The stresses due to the shrinkage of the cement layer and the applied load were determined for the one-step and two-step procedure of the push-out test specimens and for the one-step procedure of the complete root.

Results: Even though the load in the two-step push-out model was 60% higher compared to the one-step model, the combined stresses were comparable. The stresses due to shrinkage alone in the complete root approached or exceeded the bond strength of resin cements to dentin in the coronal and apical areas.

Significance: FEA of this test set-up explains the results of the in vitro study. Two-step cementation of fiber posts leads to a decrease of internal stresses in the restoration which results in higher failure loads and possibly in less microleakage.
Introduction

Over the last years, prefabricated glass fiber posts have gained popularity. They have a number of advantages compared to metal posts [1]. One of the main problems with any type of post, including prefabricated glass fiber posts, is the bonding of the post to the root canal walls. Retention is influenced by a number of factors, such as the type, composition and shape of the post, the cement, the bonding between the different parts, the pretreatment of the different substrates, contamination with other chemicals, etc. [2, 3]. The adhesion of cement to the root canal walls is mainly of micromechanical nature, based on infiltration of the demineralized dentin and the formation of a “resin dentin interdiffusion zone” [4]. Shrinkage and contraction stress of the cement, and the unfavorable configuration factor (C-factor) within the root canal influence the quality of the bond negatively [5, 6]. This is illustrated by the observation that debonding is the most common mode of failure for fiber posts clinically [7, 8].

A problem with composite materials in general, and with the cementation of fiber posts with resin cements in particular, is the polymerization contraction stress. The shrinkage and the accompanying contraction stress for different restorative techniques for direct resin composites have been studied extensively [9, 10]. The composition of the restorative materials, chemical vs. light curing, and different light curing programs on the curing devices are aimed to reduce the contraction stress within a restoration.

The contraction stress is related to the so-called C-factor, which is defined as the ratio between bonded and unbonded surface of a restoration. The higher the C-factor, the higher the contraction stresses can become. It has been shown that in high C-factor geometries, contraction stress values can exceed the bond strength [11] and even the cohesive strength [12, 13] of the resin composite itself.

In intracoronal restorations, the problem of a high C-factor has been addressed by filling cavities in increments instead of using a bulk technique. This is suggested to reduce the contraction stress and microleakage, but others do not confirm these results. Using layers (C < 1) instead of using a bulk technique (C = 3-5) results in a more favorable configuration and, in principle, to less contraction stress [5, 14-16]. In the root canal, which in many ways can be regarded as a very deep Class I cavity, with a calculated C-factor that can exceed 200 [5] [17] an incremental layering technique has
not been practiced until recently. In a recent study, an incremental layering cementation technique for the cementation of fiber posts (two-step cementation) has been developed and tested in vitro [17]. This technique consists of cementing a Teflon post, with a diameter 30 μm larger than the fiber post, in the root canal. The cement is then cured and the Teflon post removed, leaving a post-space with a perfect fit for the fiber post. The corresponding fiber post can therefore be cemented with a thin and uniform cement layer. This technique significantly decreases the C-factor, since the surface of the cement in contact with the Teflon post can be considered unbonded surface. The second cement layer used for cementing the glass fiber post is so thin that the stresses in this layer will have little effect on the total restoration. In this study, a 60% increase in push-out strength was achieved with this two-step cementation procedure compared to the normal one-step procedure. Significant differences were found for all cements tested.

The aim of this study was to gain insight in the theoretical background of this two-step cementation procedure. Finite element analysis (FEA) was performed both on models representing the specimen used for in vitro push-out testing and on the entire restoration, the human canine root with a glass fiber post cemented in it.

**Materials and methods**

Three-dimensional finite element simplified models were created according to the dimensions and with the material properties of a previous study in which an incremental layering technique for the cementation of fiber posts (two-step cementation) was investigated [17]. In the latter study, the difference in push-out bond strength between a conventional one-step cementation procedure where the post was placed directly, and the experimental two-step cementation procedure was determined. For the one-step procedure, the fiber posts were cemented 9 mm into the canal according to manufacturers’ instructions, and the cement was cured. With the two-step procedure, a Teflon post (special design RTD; 30 μm thicker than the # 2 post) was used instead. The Teflon post was removed after the recommended curing time according to manufacturers’ instructions, and freshly mixed cement was inserted into the space left by the Teflon post, followed by the definitive placement of the fiber post.
Per root, four cross-sections with a thickness of 0.7 mm were prepared. The differences in push-out strength between cementation procedure and cement were determined. Simplified models with the same geometry as these cross-sections were used as models for the finite element analysis. The experimentally determined loads for the one- and two-step cementation procedure of 45.8 N and 75.9 N, respectively, were used as input for the FE models.

Two models represented the dentin discs as used in the push-out test of fiber posts cemented in a single-rooted human canine tooth, according to a one-step and two-step cementation procedure. A third model represented a simplified model of the root portion of a fiber post restoration cemented with a conventional one-step cementation procedure. The Finite Element modeling and post processing were carried out with FEMAP software (FEMAP 10.02; Siemens PLM Software, Plano, Texas, USA), while the analysis was done with NX Nastran software (NX Nastran; Siemens PLM Software, Plano, Texas, USA).

**Push-out test models**

The specimens of the push-out test are symmetrical in geometry. Therefore, in order to limit the number of elements, models were realized that represented half specimens, with the nodes in the centric plane allowing for sliding in the surface only. The nodes of the bottom of the model, with the exception of the nodes in an inner circle of \( d = 3.28 \) mm, were prevented from moving in the vertical direction. The nodes in the center were prevented from moving in the horizontal plane. The models were composed of 21,448 parabolic tetrahedron solid elements; the cement layer along the post was 3 layers thick. The dimensions of the test models are shown in Figure 5.1.

In the push-out test, the specimens were cut from a root with cemented post. Cutting slices from the entire post-root system will have an effect on the stress distribution due to the shrinkage of the cement layer in the sliced specimens. This was mimicked in the FEA models by increasing the top and bottom part of the model by 0.2 mm during the calculations of the shrinkage of the cement layer. Hereafter, the material properties of the increased parts were changed into the properties of air, leaving the model with the dimensions as shown in Figure 5.1.

For the two-step procedure, the shrinkage of the cement layer was calculated while the fiber post was given material properties of air to simulate the non-adhesion to the Teflon post. The shrinkage of the second cement layer was not taken into
account, because the influence of this shrinking would have been minimal given the thickness of this final cement layer. The stresses due to the shrinkage of the cement layer were calculated using a time independent non-linear elastic-plastic material model [18]. Hereafter, calculations were done with the push-out test models with the loads of failure from the in vitro tests for the one-step and two-step procedure of 45.8 N and 75.9 N, respectively. The output of the shrinkage of the cement layer and the output of the load of failure in the cut model were combined using the linear combination facility of FEMAP. The solid maximum principal stresses were calculated to establish the maximum stress in the dentin at the cement-dentin interface, and the maximum stress in the cement layer.

Figure 5.1  Dimensions of the FE model of the push-out test specimen.

Complete root model
A simplified model of the complete post-root system was also evaluated (see Figure 5.2). The root was modeled in a periodontal ligament with properties from literature
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[19] as shown in Table 5.1. Since the model is symmetric in two directions, a quarter model was made in order to limit the number of elements, with the nodes in the centric planes in the two directions allowed sliding in the surface only. The model was composed of 45,045 parabolic tetrahedron solid elements; the cement layer along the post was 3 layers thick. The nodes in the bottom and side planes of the ligament were fixed and for the nodes in the center of the model the movement in the horizontal plane was fixed. The stresses due to the shrinkage of the cement layer were calculated using the time independent non-linear elastic-plastic material model [18] and a calculation was done with a vertical load of 100 N.

The output of the shrinkage of the cement layer and the output of the load to failure in the cut model were combined using the linear combination facility of FEMAP. The solid maximum principal stresses were calculated to establish the maximum stress in the dentin at the cement-dentin interface and the maximum stress in the cement layer.

Figure 5.2 Dimensions of the FE model of the complete root with cement layer and fiber post. (A) Dimensions of the root. (B) Dimensions of the cement layer. (C) Dimensions of the fiber post.
Material properties

The material data used are shown in Table 5.1. The data for the post are supplied by the manufacturer. The data for the dentin [20] and the cement [18, 21] are from literature. The anisotropy of the dentin was not taken into account; although due to the structure, the mechanical properties of the dentin do vary with orientation and location as shown by Konishi et al. [22]. For the data of the cement the parameters for a layer thickness of 0.250 mm were used [18], although the thickness of the cement layer along the post varied from 0.100 mm to 0.300 mm.

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (MPa)</th>
<th>Hardenings modulus (MPa)</th>
<th>Transition Stress (MPa)</th>
<th>Poisson’s ratio</th>
<th>Linear shrinkage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber post</td>
<td>5100</td>
<td>5100</td>
<td>18000</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement during hardening</td>
<td>1552</td>
<td>5082</td>
<td>5.578</td>
<td>0.27</td>
<td>0.01237</td>
</tr>
<tr>
<td>Cement hardened</td>
<td>9500</td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Dentin</td>
<td>18300</td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Ligament</td>
<td>0.25</td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
</tr>
</tbody>
</table>

Results

Push-out test models

The load at failure for the one-step model was 45.8 N while the load at failure for the two-step model was 75.9 N, as found in the in vitro study of Jongsma et al. [17]. Note that the load of failure of the two-step model is 60% higher than the load of failure for
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the one-step model. Figure 5.3 shows the solid maximum principal stresses calculated by FEA in a section of a slice of the push-out test model. The calculated stresses are the combination of stresses due to the loads at failure and the stresses caused by the shrinkage of the cement layer. The stresses in the dentin in the cement-dentin interface are distributed rather uniformly across the dentin surface and are somewhat higher in the top part of the model. The maximum stresses at these locations and in the cement layer are shown in Table 5.2.

Figure 5.3   Solid maximum principal stresses in MPa in the push-out models of the one- and two-step cementation procedures combining the load at failure as depicted and the stress caused by the shrinkage of the cement layer. (A) One-step procedure. (B) Two-step procedure
Complete root model

Figure 5.4 shows the solid maximum principal stresses due to the shrinkage of the cement layer for the one-step procedure in the model of the complete root. The highest stress (41.2 MPa) in the cement layer is in the coronal part of the cement layer. In the apical areas, the stresses are also high. The highest stresses in the dentin are at the coronal margin of the model at the cement-dentin interface, where the dentin is rather deformed due to the shrinkage of the cement.

Figure 5.4  Solid maximum principal stresses in MPa due to the shrinkage of the cement layer for the one-step procedure in the model of the complete root with fiber post. (A) Stresses in all layers. (B) Detail of (A) showing scaled deformation of the layers as a result of the shrinkage of the cement layer. (C) Stresses in dentin and ligament.
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The maximum stresses at these locations are summarized in Table 5.2. The mid-coronal areas of the cement layer demonstrate the lowest stress values. It can be seen in Figure 5.4 that the stresses from the cement do not stop at the cement-dentin interface. The stresses are distributed deeply into the dentin and in the fiber post itself.

Table 5.2  Solid maximum principal stresses in MPa in the dentin at the cement-dentin interface and in the cement layer of the FEA models.

<table>
<thead>
<tr>
<th>Solid maximum principal stress (MPa)</th>
<th>Dentin layer</th>
<th>Cement layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One-step procedure (load 45.8 N)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined stresses</td>
<td>20.6</td>
<td>51.0</td>
</tr>
<tr>
<td>Composed of:</td>
<td></td>
<td></td>
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<tr>
<td>Stress due to the applied load</td>
<td>10.6</td>
<td>12.4</td>
</tr>
<tr>
<td>Stress due to the shrinkage of the cement</td>
<td>16.3</td>
<td>37.3</td>
</tr>
<tr>
<td><strong>Two-step procedure (load 75.9 N)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined stress</td>
<td>20.4</td>
<td>54.9</td>
</tr>
<tr>
<td>Composed of:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stress due to the applied load</td>
<td>17.8</td>
<td>20.9</td>
</tr>
<tr>
<td>Stress due to the shrinkage of the cement</td>
<td>11.8</td>
<td>39.6</td>
</tr>
<tr>
<td><strong>Complete root (load 100 N)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined stresses of applied load and shrinkage of the cement</td>
<td>34.2</td>
<td>59.6</td>
</tr>
<tr>
<td>Stress due to the shrinkage of the cement</td>
<td>34.9</td>
<td>41.2</td>
</tr>
<tr>
<td>Apical</td>
<td>41.0</td>
<td>36.8</td>
</tr>
</tbody>
</table>

Discussion

The stresses in the models of the push-out test specimen show many differences between the one-step and two-step cementation procedure. The load of failure was inserted in the model from the results of the previous in vitro study by Jongsma et al. [17]. The models in Figure 5.3 represent the maximum stresses at the moment of failure of the specimens. The combined stresses of the load at failure and the shrinkage of the cement layer are similar for both models, even though the load at failure for the
two-step model is much higher than that of the one-step model. In other words, the two-step model needed a higher failure load to achieve these stresses, because the stresses due to the shrinkage of the cement are lower, especially in the dentin at the cement-dentin interface. This higher load of failure for the two-step procedure caused higher and deeper compression stresses in the fiber post, as can be seen in Figure 5.3.

The maximum microtensile bond strength of a resin cement to dentin is between 5 MPa and 70 MPa, depending on which cement and bonding system is used [23]. Therefore, the maximum stresses due to the shrinkage of the cement layer only, found in the FE model at the cement-dentin interface may cause debonding of the cement layer seen the level of these stresses.

The two-step model showed low stresses compared to the one-step model, due to the combined influences, present in both the cement-dentin interface as in the dentin itself. On the higher edge of this model, however, a high peak stress is observed, which is caused by the higher load of failure causing stresses more concentrated at the top of the model, bringing the maximum stresses to the same level as in the one-step model. In the one-step model, the higher stresses are observed throughout the cement-dentin interface. The stresses also penetrate further into the dentine; this is the result of the higher cement contraction stresses in the interface. In the two-step model the stresses due to the shrinkage of the cement layer in the cement layer are of the same magnitude as the stresses in the cement layer in the one-step model. However, in the one-step model the contraction stresses are located throughout the cement layer, whereas in the two-step model these stresses are concentrated at the interface of the cement layer and the post. This observation can be explained by the development of a surface tension in the unbound surface of the cement layer.

In the complete root model, the middle part of the fiber post restoration demonstrates relatively low stresses. The apical part, however, shows higher stresses than the mid-coronal and mid-apical sections. In the clinical situation, the stress values in this part approaches or exceeds the bond strength of resin cements to dentin as described in literature [23], which could mean debonding of the cement. The highest stresses are observed in the coronal part of the restoration. The stresses observed here between the cement layer and the dentin are a lot higher than the ones observed in the push-out models at failure. This implicates that spontaneous debonding takes place at the coronal margin of the restoration. This debonding is likely to travel along the post surface. This will not result in debonding of the post, as the debonding of cement on
one side will cause relaxation of stresses at the other side of the restoration. It will, however, cause (micro)leakage with all its detrimental effects.

In this study, an independent non-linear elastic-plastic material model was used [18]. This model accommodates the material properties of composite materials better than the linear models that are used in most FEA studies concerning fiber post restoration. However, an FE model cannot be regarded reality. No matter how well the model is designed, it is never exactly conform the reality. As a consequence, it is not possible to implement the results obtained in this study directly into the clinical situation. However, we did our best to design the model in such a way that it mimicked the real situation as closely as possible.

This study implies that very high stresses are present in a fiber post restoration, even before loading. The stresses achieved by shrinkage stresses alone could be high enough to disrupt the cement-dentin interface. This would result in microleakage, which would cause endodontic failure, debonding, and secondary caries. This would seriously compromise the fiber post restoration, to the point that maintaining or repairing the restoration is no longer possible. Cementing the fiber post using a two-step cementation procedure, as described in the study of Jongsma et al. [17], results in lower stresses in the restoration. The pre-stresses in the restorative system are lower, and this might prevent debonding of the cement-dentin interface and results in higher stresses needed for catastrophic failure of the system. This could very well lead to better clinical results, less microleakage and therefore less clinical failure due to secondary caries, endodontic failure or debonding of the fiber post.

With this FEA study, the differences between stresses in the restoration after cementing a prefabricated fiber post with either a classical one-step or a new experimental two-step cementation procedure have been evaluated. This has been a useful theoretical approach. To find out what the possible clinical benefits of this method would be, more research is needed. It would be useful to assess the difference in micro-leakage between the one- and two-step cementation procedures in an in vitro study. Furthermore, randomized clinical trials are needed to assess the differences between the one- and two-step cementation procedures of fiber post restorations clinically.
Conclusion

Two-step cementation of fiber posts leads to a decrease in internal stresses in the restoration compared to one-step cementation, which results in higher failure loads and possibly to less microleakage. This is in accordance with a previous in vitro study, in which a 60% increase in push-out bond strength was reported when using a two-step cementation procedure compared to a classical one-step cementation procedure.
Reduced contraction stress obtained by a two-step cementation procedure

References


