Porcelain veneers have demonstrated excellent clinical behavior in terms of longevity, periodontal response, and patient response.\textsuperscript{1–4} Because the confidence in bonded ceramic restorations has increased, the indications for their use have been broadened significantly,\textsuperscript{5–9} resulting in newer preparation designs.\textsuperscript{7,10,11} However, as a possible consequence, postbonding cracks represent new problems experienced by practitioners.\textsuperscript{12,13} Only a few scientific investigations have specifically addressed the problem of internal stress distribution and the parameters responsible for the craze-line formation.

One of the new restorative designs, an extension of the veneer for the interdental area, has become a common procedure. Highton et al\textsuperscript{14} claim that the use of wraparound laminates can provide an improved stress distribution within the restoration when it is subjected to incisal loading. The safety and innocuousness of...
interdental wrapping can be supported by other investigators who indicate that the most important mechanical events in incisors appear within the buccolingual plane.\textsuperscript{15,16} Stresses and strains within the crown seem to be minimally affected by interdental preparations.

Mechanical loading is not the only source of stress. Additional factors can be considered, such as the curing contraction of the luting composite and the extremes of thermal changes. It has been shown that thermal changes are able to create harmful stresses and initiate cracks within porcelain veneers.\textsuperscript{13,17} Anterior teeth are directly subjected to the different temperatures of ingested food and drinks, and thermal records of the oral environment show that temperatures can range between 0 and 67°C.\textsuperscript{18} Problems related to thermal stresses can get worse in the presence of composite resin restorations. Actually, some of these restoratives may exhibit high thermal expansion coefficients when compared to teeth and ceramics.\textsuperscript{19} In this context, extending the veneer into the interdental area could be detrimental if one considers that it is common to veneer teeth that feature preexisting interdental composites.

It is difficult to find accurate recommendations that define the correct amount of interdental wrapping in relation to the presence of preexisting interdental composites. More information is required about the intimate structure of the tooth-restoration complex, especially if postbonding cracks and internal stress distribution are to be explained. For such an analysis, the finite element (FE) method has become a well-accepted modeling tool.\textsuperscript{20}

The purpose of this FE study was to define the effect of thermal stresses on different types of veneers. This study focused on the interdental extension of the restoration and the simulation of a preexisting interdental composite.

**Materials and Methods**

**Model and Analysis**

The anatomic shape of a horizontal cross section of a natural maxillary central incisor (Fig 1a) was digitized using a charge-coupled device camera (Sony DXC-151A) attached to a stereomicroscope (Olympus SZH10) and an image-analysis software program (Optimas 5.22, Optimas). The contours of the enamel, dentin, and pulp areas were manually traced using graphics software (Freelance Graphics, Lotus). This template was used to create the FE computerized model. Additional curves were added to provide a simulated Class III composite and standard laminate preparation with 3 different degrees of interdental penetration: (1) short wrapping—the veneer was extended only to the facial margin of the preexisting interdental composite; (2) medium wrapping—the veneer was extended into the bulk of the preexisting interdental composite, penetrating \textasciitilde 50\% of the interdental area; and (3) long wrapping—the veneer covered the entire interdental area. Because the contours between the mesial and distal aspects of the section were symmetric, only half of the section was used. The geometric data were then transferred to a personal computer workstation. A single mesh, which included the 3 different restorative designs (Fig 1b), was generated using Mentat software (MARC Analysis Research).
Although teeth are 3-dimensional structures, a 2-D FE model with plane strain elements (linear, 4-node, isoparametric, and arbitrary quadrilateral) was chosen. A 3-D model, although more realistic, would have resulted in coarser meshes. The increased memory requirements for the 3-D model would not have allowed the thin layers, such as the luting composite or preparation details, ie, marginal chamfers, to be finely represented. The 2-D plane strain analysis has been demonstrated by Morin et al.\textsuperscript{21} and validated in a companion paper by experimental strain measurement.\textsuperscript{22} The application and effectiveness of thermal load application using such models was revealed by other companion studies.\textsuperscript{13,17} For this FE simulation, 4 material properties were required: the modulus of elasticity, the Poisson’s ratio, the coefficient of linear shrinkage, and the thermal expansion coefficient (Table 1). All nodes on the symmetry axis (y axis) were fixed only in the x direction (Fig 1b). Sliding along the y axis was possible for all of these nodes except for the first node on the palatal surface, which was also fixed in the y direction.

A baseline temperature of 37°C was chosen because this condition corresponds to the luting of the veneers in clinical conditions. The change of state was applied in 2 consecutive increments: (1) composite shrinkage at 37°C; and (2) thermal load, either from 37 to 60°C (23°C positive thermal load) or from 37 to 5°C (32°C negative thermal load). MARC Analysis Solver was used to calculate the stress distribution within the cross section of the tooth. The effect of thermal change was also assessed without composite shrinkage to identify the respective effects of shrinkage and thermal variation. This represents a unique advantage of numeric modeling and reveals the otherwise inaccessible stress distribution within the tooth-restoration complex. The FE calculations generated the values of stress. The surface tangential stress $\sigma_s$ for each node located at the outline of the veneer was calculated from the values of stress in the x and y directions ($\sigma_x$ and $\sigma_y$) and $\tau_{xy}$ shear stress integrated into a transformation equation.\textsuperscript{23}

### Restoration

The facial contour of all veneers was identical and was defined by accentuating the contour of the natural tooth. This precaution is relevant to the clinical application because the preservation of enamel thickness during tooth preparation often leads to overcontouring of the final restoration.\textsuperscript{24,25} The luting composite thickness was maintained at 200 µm at the facial level, whereas 50 µm were produced for the proximal margins. The decision to use these thicknesses was based on measurements and recommendations made during a simulated operatory evaluation.\textsuperscript{13} The different designs were meshed and assessed, assuming that the invasion of the proximal area was a determinant in stress distribution and, consequently, in the formation of postbonding cracks.

### Results

#### Effect of Luting Composite Shrinkage Alone

Within this FE environment, stresses created by shrinkage appeared to be compressive for the porcelain, except for a minor tensile stress peak at the interface of the short-wrap veneer (near the margin). Few differences between the 3 types of veneers were detected, either along the free surface or the luting interface of the ceramic (Fig 2). Independent of the restorative design, the stresses were more compressive at the interface than at the surface of the ceramic.

For all 3 designs, acute stress levels were found at the margin of the restoration. A major difference was

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**Table 1** Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Linear shrinkage (o/L/L)</th>
<th>Thermal expansion (°C^{-1} 10^{-6})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite</td>
<td>20.00</td>
<td>0.24^26</td>
<td>0.0014^29</td>
<td>30^19</td>
</tr>
<tr>
<td>Ceramic</td>
<td>78^*</td>
<td>0.28^27</td>
<td>13.5^*</td>
<td></td>
</tr>
<tr>
<td>Enamel</td>
<td>50.00</td>
<td>0.30^26</td>
<td>17^20</td>
<td></td>
</tr>
<tr>
<td>Dentin</td>
<td>12.00</td>
<td>0.23^28</td>
<td>11^30</td>
<td></td>
</tr>
</tbody>
</table>

*Data from the manufacturer of Creation Dental Porcelain (Klema).
found between the margin of the long-wrap veneer subjected to a compressive stress of \(-15\) MPa, and the short-wrap and medium-wrap veneers (9 and 10 MPa of compressive stresses, respectively).

**Effect of Thermal Changes Alone**

Whereas shrinkage of the luting composite generated almost pure compressive stresses in the veneer (Fig 2), simulation of thermal loads alone was responsible for both the tensile and compressive stresses (Fig 3). Differences between the 3 types of veneers were detected either along the surface or the interface of the restoration.

The short-wrap and medium-wrap veneers exhibited a similar behavior (Figs 3a and 3b). Stresses created by a temperature increase always subjected the restoration interface to tension, while compression was generated at the ceramic surface. Stresses created by a temperature drop always subjected the restoration interface to compression, while tension developed at the ceramic surface. The most adverse effect of temperature variance was observed on the short-wrap veneer (\(-8\) MPa of tensile stress at \(5^\circ\)C for the ceramic surface). The behavior of the long-wrap veneer markedly differed from the others (Fig 3c). The surface and interface of this restoration were simultaneously either mainly under tension at \(60^\circ\)C or under compression at \(5^\circ\)C. The margin of the long-wrap veneer exhibited the highest stresses in both compression (\(\sim 13\) MPa at \(5^\circ\)C) and in tension (9.5 MPa at \(60^\circ\)C).

**Effect of Combined Shrinkage and Thermal Changes**

Generally speaking within the present simulation, the preexisting stresses created by the composite shrinkage were markedly modified by thermal changes (Fig 4). An increase in temperature increased compressive stresses at the restoration surface while decreasing them at the interface. Inversely, a temperature drop decreased compressive stresses at the restoration surface while increasing them at the interface. As mentioned above for the effect of shrinkage alone, the margin of the long-wrap veneer was always subjected to higher compressive stresses when compared to the short-wrap and medium-wrap veneers. Independent of temperature, stresses remained mostly compressive for both medium-wrap and long-wrap veneers. However, adverse effects of temperature were observed on the short-wrap veneer, where marked tensile peaks were found (\(\sim 7\) MPa).
**Discussion**

Bonded-to-tooth ceramic restorations undergo various types of mechanical strain. Curing contraction of the luting composite and significant thermal changes in the oral environment must be considered in addition to functional loads.

Within the FE environment, shrinkage of the luting composite did not show important differences between groups. All veneers were put under compression. The maximum compressive stress generated without thermal variation was recorded at the restoration margin, the geometry of which seemed to play an important role. Generally speaking, smooth and convex surfaces demonstrated smaller stress levels than highly curved concavities or acute angles, at least on the numeric model of an incisor. The feather-edged design inherent to the long-wrap veneer was responsible for the substantially higher stresses compared to the marked chamfer of shorter veneers. For all 3 types of veneers, more compressive stresses were found at the interface when compared to the restoration surface. Here again, geometry can explain these differences because the restoration interfaces show more curvature and concavity, unlike the ceramic surface.

The question can be raised as to whether shrinkage of the luting composite alone can initiate cracks within the restoration. Interestingly, in a previous study on the parameters related to crack propensity of porcelain veneers, ceramic cracks were not found after a 21-day storage in saline, but only after thermocycling. Two factors can explain this behavior:

1. The static stress produced by shrinkage of the luting composite was not directly related to the development of flaws, but its combination with the
repeated thermal loads may have played a key role, considering that feldspathic porcelains demonstrate cumulative damage with cyclic mechanical fatigue.

2. Stresses created by shrinkage of the luting composite can be expected to be temporary because all resin-based materials show significant water uptake. Over time, this phenomenon can totally compensate for the initial shrinkage of the material, leading to the complete relief of shrinkage stresses.

It was therefore essential to consider, within the present FE environment, the simulation of thermal stresses alone (without composite shrinkage). In this situation, a given thermal load had opposite effects on the restoration surface and the interface, creating pure

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**Fig 4a** Surface tangential stress created by combined luting composite shrinkage and temperature changes for short-wrap veneer. Same path plot as in Fig 2; * = proximal margin.

**Fig 4b** Surface tangential stress created by combined luting composite shrinkage and temperature changes for medium-wrap veneer. * = proximal margin.

**Fig 4c** Surface tangential stress created by combined luting composite shrinkage and temperature changes for long-wrap veneer. * = proximal margin.
compressive stresses on one side of the restoration while generating pure tensile stresses on the other side. This typical behavior of short-wrap and medium-wrap restorations can be easily understood by studying the deformation mode of the veneer. This approach is illustrated in Fig 5, where displacements of the restoration are magnified by a factor of 500. Because of the nearby expanding/contracting composite filling, the edge of the veneer is either pushed away from the tooth (at 60°C) or pulled against the tooth (at 5°C). The veneer acts as a cantilever beam under bending conditions—a neutral axis delineates 2 portions subjected to opposite stresses (compression vs tension). This phenomenon was not found on the long-wrap veneer, the surface and interface of which were simultaneously under tension at 60°C or compression at 5°C. This distinct behavior can be explained by the reduction of the volume of the composite filling. Actually, in the long-wrap veneer, at least 1/3 of the composite bulk was replaced by the extension of the ceramic, which reduces the influence of the expanding/contracting composite filling. As a consequence, deformation of the tooth-restoration complex is more uniform (Fig 6) and this kind of veneer is subjected to less bending.

When shrinkage of the luting composite was included in the simulation, thermal changes exhibited differential effects on stress distribution within the porcelain. As mentioned for thermal stresses simulated alone, a given thermal load always had opposite effects on the restoration surface and the interface, this time increasing preexisting compressive stresses on one side and partially relieving them on the other. Marked tensile peaks were generated only in the case of the short-wrap veneer. To understand the possible detrimental effect of stresses on the restoration, one must be aware that ceramics are brittle materials. They present a higher strength in compression than in tension. The strength differential effect, the ratio between compressive and tensile strengths, has been incorporated in a failure criterion for brittle types of materials: the modified Von Mises criterion (mVM). Maximum values of the mVM are shown in Fig 7 for each restorative design at each experimental condition. When combining shrinkage and thermal changes, the short-wrap veneer showed significantly

**Fig 5** First principal stresses (ps1) in the medium-wrap veneer subjected to thermal changes alone. Deformation caused by temperature changes (60 to 5°C) was magnified by a factor of 500. Negative values of stress delineate the area of compressive stresses. A “bending effect” can be observed. Arrows = relative displacement of the restorative margin.

**Fig 6** Simulation of negative thermal stress (5°C) for the short-wrap and long-wrap veneers. Deformation of the tooth-restoration complex was magnified by a factor of 400. Deformation is less uniform with the short-wrap veneer: the bulk of the composite filling creates a contracting pole and induces bending of the veneer. Deformation is more uniform in the case of the long-wrap veneer because of the smaller volume of the contracting composite.

**Fig 7** Maximum modified Von Mises stresses for each veneer in the 5 experimental conditions.
higher risks of failure when compared to others. Risks of failure of the short-wrap restoration are even higher when shrinkage of the luting composite is not considered. It must be mentioned that maximum mVM values were systematically found around the restoration margin, proving again the nearby influence of the expanding/contracting composite filling. Coincidently, in an experiment simulating Class III composites and the design of the short-wrap veneer, \(^1^6\) temperature-induced ceramic cracks were found precisely at the restoration proximal margin (Fig 8).

It can be concluded from Fig 7 that shrinkage of the luting composite has a protective effect. This questions the usual assumption that shrinkage may be responsible for ceramic cracks. Actually, it is possible that the use of a so-called “ideal nonshrinking” composite would not solve the problem of stress concentrations. If the thermal expansion of such a material is not lowered to the level of enamel and dentin, the stress distribution within the ceramic will still be impaired by the harmful tensile stresses generated during thermal loads.

Overall performances of the 3 experimental designs can be evaluated in light of the practical and clinical parameters. The short-wrap veneer corresponds to a traditional and conservative proximal veneer preparation that stays facial to the contact. This often precludes the need for temporization, but ultimately leaves the tooth-restoration interface visible. Lately, extended preparations into the contact area have been popular—they hide the margin and provide a positive seat for cementation. \(^3^7\) In light of these clinical advantages, and knowing the negative influence of the intact bulk of preexisting interdental composites on thermal stress distribution, avoidance of short-wrap veneers is recommended. Practitioners and dental technicians, however, should know that long-wrap veneers are difficult to fabricate and manipulate as a result of the extension of ceramic, delicate insertion axis, and margin definition. Such maximum wraparound is absolutely indicated only when major changes of form or closures of diastemata (or interdental triangles) are planned, \(^1^0\) provided that an adequate margin (marked chamfer) and ceramic thickness are achieved. In other situations, a partial wrap (medium wrap) may represent the best compromise between stress distribution and clinical practicality when placing porcelain veneers on teeth restored with Class III composites.

Conclusions

A finite element model reproducing a 2-D horizontal cross section of an incisor restored with a bonded porcelain veneer and a Class III composite was used to assess the effect of luting composite shrinkage and thermal loads on the stress distribution in the ceramic with different interdental wraparound. Within this finite element environment, the following conclusions can be drawn:

- Shrinkage of the luting composite resin alone generated mostly compressive stresses at both the surface and the interface of the restoration.
- Because of the nearby expanding/contracting composite filling, temperature changes had opposite effects on the restoration surface and interface, creating pure compressive stresses on one side of the restoration while generating pure tensile stresses on the other side. Because ceramic is a brittle material, these tensile forces were more detrimental than the compression caused solely by the luting composite shrinkage.
- In the long-wrap veneer, \(\frac{1}{3}\) of the Class III composite bulk was replaced by the extension of the ceramic, which reduced the influence of the expanding/contracting composite filling. Deformation of the tooth-restoration complex was more uniform.
- The thermal changes, when combined with the luting composite shrinkage, had the most harmful effects on the short-wrap veneer, where marked tensile peaks were generated because of the high thermal expansion of the nearby composite filling. Longer wraparound seemed to “protect” the restoration from the tensile stresses generated at high and low temperatures.
• Because of the high thermal expansion of resin restoratives, wrapping an interdental filling can lead to a reduction of the thermally induced stresses, provided that an adequate margin definition (marked chamfer) and a proper ceramic thickness are achieved.

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References