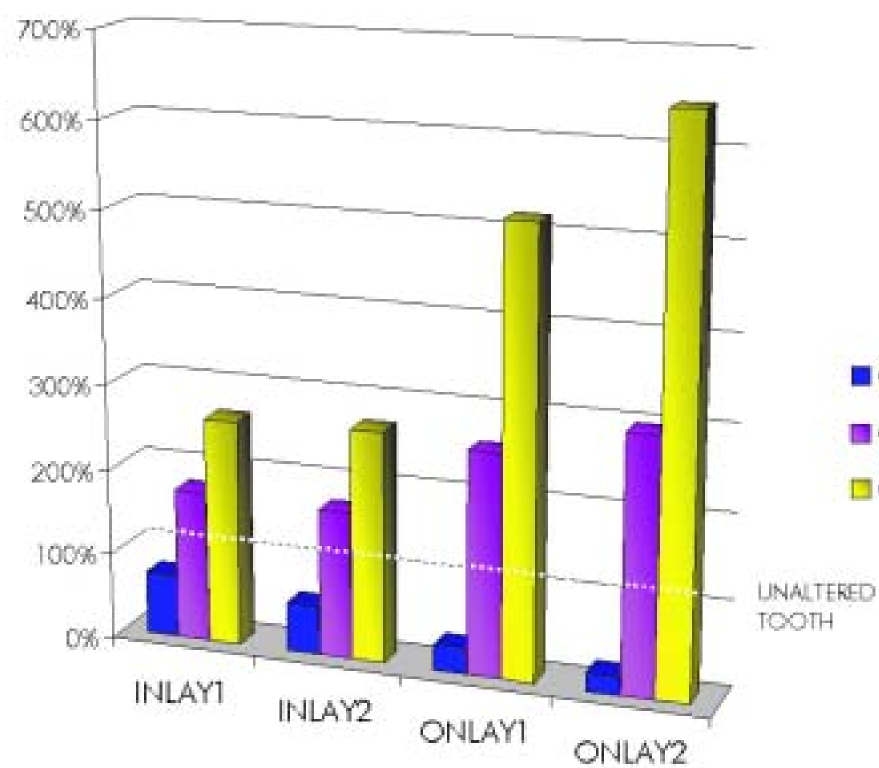
700%
600%
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CER
CPR20
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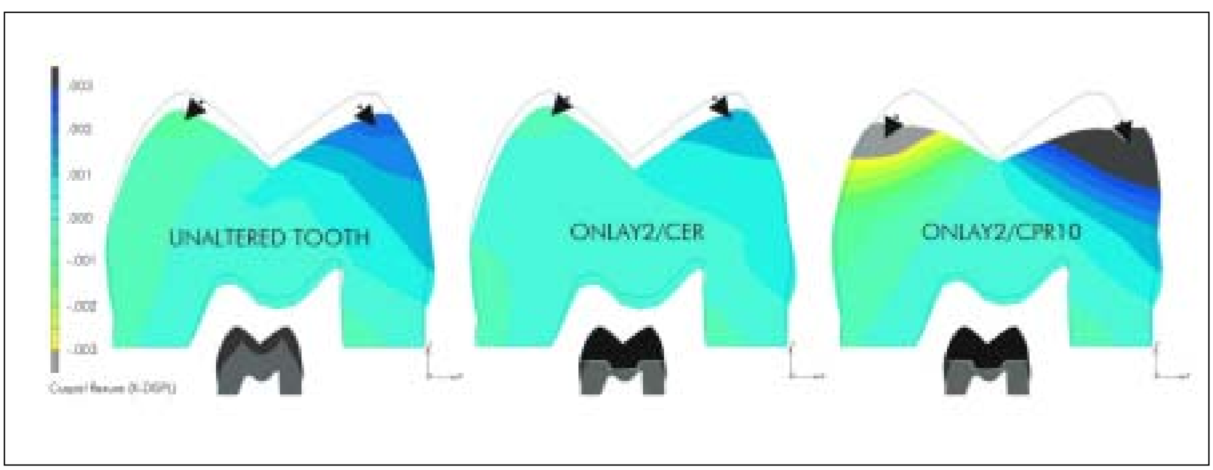
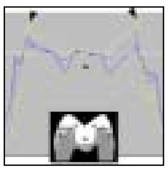
UNALTERED TOOTH
INLAY1
INLAY2
ONLAY1
ONLAY2


UNALTERED TOOTH
ONLAY2/CER
ONLAY2/CPR10

Porcelain Versus Composite Inlays/Onlays: Effects of Mechanical Loads on Stress Distribution, Adhesion, and Crown Flexure



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This study used 2-D finite element modeling to simulate cuspal flexure and stresses at the surface and tooth-restoration interface of a restored maxillary molar using three restorative materials; the influence of four inlay/onlay preparation configurations on stress distribution within the complex was also investigated. A buccolingual cross-section of an intact molar was digitized and used to create 2-D models restored with different restorative materials (feldspathic porcelain, high– and low–elastic modulus composites) and tooth preparations (small and large inlays, small and large onlays). Two simulated 25-N oblique loads were applied to the cusps. The tangential stress for each finite element node located at the tooth surface, interfacial stress, and relative cuspal flexure were analyzed. All materials and tooth preparations exhibited similar surface tangential stress patterns, with a definite compressive area at the external cusp ridges, a tensile zone at the occlusal surface, and compression stress peaks at the CEJ. The low–elastic modulus composite showed reduced tensile stresses at its surface but increased tension at the dentin-adhesive interface when compared to ceramics. All types of onlays demonstrated a majority of compressive interfacial stresses, while inlays showed a majority of tensile stresses. The interfacial tension at the dentin level increased with the flexibility of the restorative material. Only the large ceramic onlay displayed almost pure compression at the interface. Composite-restored teeth exhibited increased crown flexure, while porcelain-restored teeth showed increased crown stiffness. Porcelain inlays/onlays featured more detrimental stresses at the occlusal surface but better potential protection against debonding at the dentin-restoration interface compared to composite inlays/onlays. Ceramic onlays/overlays seem to represent an effective answer to restore severely damaged posterior teeth.
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Tooth-colored materials in combination with adhesive technology are increasingly used in practice. Although anterior bonded porcelain restorations have proven not only to be extremely reliable[1–6] but also superior to composite veneers,[7–12] there are still controversies regarding the performance of ceramics versus composites in the posterior dentition (inlays/onlays). Most long-term data are related to ceramic materials; some of these studies account for the excellent behavior of porcelain inlays/onlays generated either indirectly[13] or by computer-aided design/manufacturing.[14] No such long-term data are available for indirect composites, and it is extremely difficult to find clinical studies comparing ceramic and composite inlays/onlays. A recent work[15] revealed the significantly better anatomic form and integrity of ceramic restorations. Accordingly, ceramic inlays seem to perform well in the long term.[13,14] However, their high cost and extreme technique sensitivity explain why clinicians restrict their use to specific clinical situations. As a result, there has been a growing interest in "more convenient" or "easy to handle" composite inlays/onlays.[16]

The aforementioned bonded restorations not only offer a tooth-colored alternative to metal restorations, but also contribute to reproducing the performance of the intact tooth by influencing cuspal flexure and plastic yielding, key parameters in the performance of the tooth-restorative complex.[17,18] Subclinical cuspal microdeformation was identified in the early 1980s,[17,19,20] and it is now well accepted that intact teeth demonstrate cuspal flexure because of their morphology and occlusion. Restorative procedures can increase cuspal movement under occlusal load,[17,21] which may result in altered strength, fatigue fracture, and cracked tooth syndromes.[22–24] Such knowledge led to the development of methods, especially the adhesive techniques,[18,25,26] to improve fracture resistance of teeth.[27,28]

In view of the above biomechanical facts, and because of the lack of evidence to solve the ceramic/composite dilemma, fundamental experimental data should be reconsidered. Traditional "load point" experiments provide insight into a number of biomechanical issues but do not reveal the stress distribution within the tooth-restoration complex and often fail to show significant differences. One reason might be that in spite of important differences in their physical properties, no difference could be found in vitro between Class II composite and ceramic inlays in terms of their marginal and internal adaptation[29] or fracture resistance.[30,31]

Knowledge of stress distribution is of paramount importance in the biomimetic approach (mimicking of intact tissues), especially in the optimization process of adhesive restorative techniques, but it requires complex modeling tools such as the finite element (FE) method. In FE analysis, a large structure is divided into a number of small, simple-shaped elements, for which individual deformation (strain and stress) can be more easily calculated than for the whole undivided structure. By determining the deformation of all the small elements simultaneously, the deformation of the structure as a whole can be assessed. Using the traditional biophysical knowledge database in a rational validation process, FE analysis has been significantly refined during recent years.[32] Experimental-numeric approaches undoubtedly represent the most comprehensive in vitro investigation methods. Two-dimensional FE models, the accuracy of which, considered in a buccolingual cross-section, has been demonstrated and validated on several occasions by experimental strain measurements on both anterior and posterior teeth, were used in the present work.[19,20,33]

The aim of this study was to describe the biomechanical response of a restored maxillary molar in terms of stress and strain distribution based on 2-D FE simulations. Current literature provides little information about the effect of restorative material properties (ceramics vs composites) and restoration configurations (small vs large inlays/onlays) on the resulting biomechanical behavior of posterior teeth. Special attention was therefore given to the simulation of various materials and preparation configurations.

Method and materials

Two-dimensional FE models derived from a buccolingual cross-section of a natural maxillary molar were subjected to a 50-N occlusal load to compare the intact tooth with three different restorative inlay/onlay materials and four restorative designs. The postprocessing files allowed the calculation of surface tangential stresses, tooth-restoration interfacial stresses, and relative cuspal flexure.

Mesh generation and material properties (preprocessing)

A buccolingual cross-section of a natural maxillary molar 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). The contours of the enamel, dentin, and pulp areas were manually traced using a PC and graphic software (Freelance Graphics, Lotus). Additional lines were drawn to simulate four different tooth preparations and their corresponding inlays/onlays. The following configurations were considered (Fig 1):

- INLAY1: small inlay (~ 3.0-mm occlusal width)
- INLAY2: large inlay (~ 4.5-mm occlusal width)
- ONLAY1: small onlay (~ 2.5-mm cusp coverage)
- ONLAY2: large onlay (~ 4.0-mm cusp coverage)

An image-processing program (NIH Image, developed at the Research Services Branch of the National Institute of Mental Health) was used to record the coordinates of all structures and defined contours. These geometric data were then transferred to an interactive FE program (MENTAT 2001, MSC Software) for the generation of a single mesh (1,320 nodes, 1,274 elements; Fig 1) and preprocessing steps. A 2-D FE model with plane strain elements (linear, four-node, isoparametric, and arbitrary quadrilateral) was chosen. Two mechanical material properties were required for this FE simulation: the Poisson's ratio and the modulus of elasticity (Table 1). A variety of values have been recorded in the literature. A correct ratio of moduli (enamel:dentin) is necessary for qualitative linear analysis.[34] Moduli of 50 GPa and 12 GPa were chosen for enamel and dentin, respectively, yielding a ratio of 4.2. The influence of restorative material was investigated by simulating three different esthetic products:

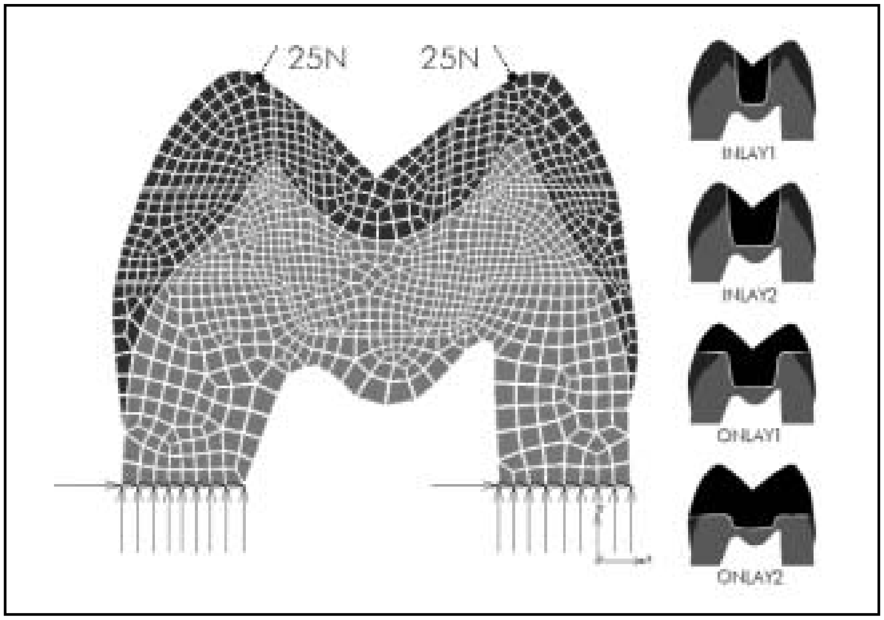

Fig 1 *Original natural contours and mesh developed in MENTAT* (left). *The two 25-N occlusal loads are applied to cusp tips, just within occlusal table* (dotted lines = *load direction). Horizontal and vertical fixed displacements are shown at cut plane of root* (arrows). *Four restorative designs* (right) *were reproduced using same original mesh.*

Table 1 Material properties

Material	Experimental label	Elastic modulus (GPa)	Poisson's ratio
Feldspathic ceramic	CER	78*	0.28[35]
Stiff composite	CPR20	20[36]	0.24[37]
Elastic composite	CPR10	10[38]	0.24
Enamel		50	0.30[35]
Dentin		12	0.23[39]

*Data from manufacturer of Creation Dental Porcelain (Klema).

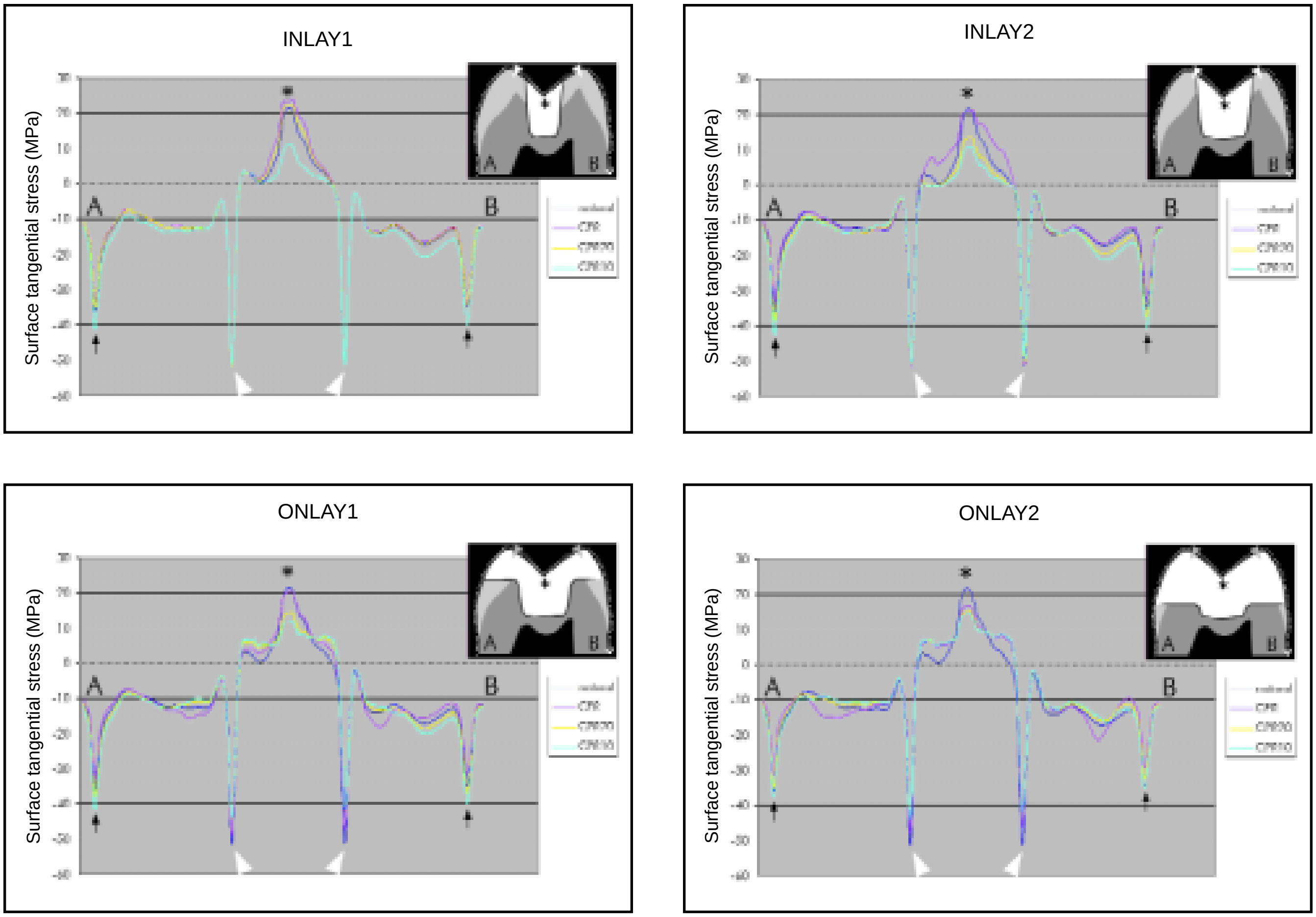

Fig 2 *Tangential stresses along tooth surface for each experimental design. Path plot proceeds from palatal* (A) *to buccal* (B) *across tooth surface* (dotted arrow *in insets*). * = *central groove*; arrowheads = *load points; arrows = CEJ compression peaks.*

- CER: a regular feldspathic porcelain (elastic modulus of 78 GPa)
- CPR20: a stiff composite (Z100, 3M/ESPE; elastic modulus of ~ 20 GPa)
- CPR10: a more elastic composite (Herculite XRV, Kerr; elastic modulus of ~ 10 GPa)

Boundary conditions, load case, and data processing

Fixed zero displacement in both the horizontal and vertical directions was assigned to the cut plane of the root, approximately 1.5 mm beyond the cementoenamel junction (CEJ).

A realistic biting load can be separated into horizontal and vertical components. The horizontal components induce cuspal flexure and represent the major challenge for a posterior tooth. Therefore, two point loads of 25 N each were applied to cusps just within the occlusal table, perpendicular to the tooth surface (Fig 1). A static load case that corresponded to a situation of a slow loading, assuming absence of vibration or dynamic effects, was used.

The stress distribution was solved using the MARC Analysis solver (MARC 2001, MSC Software). The postprocessing file was accessed through MENTAT software. MENTAT was used to select the node path along the tooth surface and to extract the values of stress in the x and y directions, the x,y shear stress, and the node coordinates. After the transfer of these data to a spreadsheet, the surface tangential stress for each FE node located at the tooth surface was calculated by using a specific transformation equation.[40,41] Similar data collection and transformation were used to calculate the interfacial stress (perpendicular to the tooth–luting composite interface) along the node path corresponding to the preparation outline (adhesive interface). The "relative cuspal flexure" was also recorded by measuring the x-displacement (displacement along the x-axis) of the palatal cusp tip of the restored tooth in a selected experimental condition and dividing this number by the x-displacement of the unaltered cusp tip.

Results

Surface tangential stress

The analysis of surface tangential stress is plotted in Fig 2. The general pattern of the plots was similar for all test conditions, with only minor differences between configurations or materials. The values were highly positive (tensile stresses) between the load points, with a tensile stress peak always found in the central groove (20 MPa for the unaltered tooth). As expected, the stress was highly negative (marked compression peaks at –50 MPa) in the area of the load points. Both palatal and buccal external cusp ridges were subjected to compression, with well-defined peaks around –40 MPa (regular composite inlay/onlay) always found at the CEJ.

For the small intracoronal cavity (INLAY1), the main difference was found at the restoration surface. The low elastic modulus of the regular composite (CPR10) showed reduced tensile stresses (maximum 11 MPa); both the ceramic and stiff composite ensure a stress distribution similar to that of the intact tooth. In the large intracoronal cavity (INLAY2), the main difference was again found at the restoration surface. Both composites showed reduced tensile stresses (maximum 11 to 13 MPa), while the ceramic plot was somewhat similar to that of the intact tooth, with a trend for more tensile stresses at the restoration surface. For the extracoronal cavities (ONLAY1 and ONLAY2), the small onlay followed the same trend as the large inlay, with reduced tensile stresses in the central grooves for both composites (maximum 12 to 14 MPa) and more tooth-like behavior for the porcelain. The plots of the large onlay displayed only minor differences between materials.

Interfacial stress

The analysis of interfacial stress is plotted in Fig 3. For all test conditions, the pulpal floor (center of the plots) was almost stress free. Except for this central area, there were significant differences between test conditions, with major discrepancies between configurations. Overall interfacial stresses were mainly tensile for intracoronal restorations, while major compression was found in both types of cusp coverage. Porcelain inlays/onlays systematically exhibited the least amount of interfacial tension; there was an increase of interfacial tensile stresses for composite inlays/onlays, especially those with the low elastic modulus. The following peculiar behaviors could be observed.

In intracoronal cavities (INLAY1 and INLAY2), the composite inlays seemed to produce smaller tensile peaks than did the porcelain in the marginal area. The plots for the small inlays were characterized by inverted peaks located where the interface passed the dentinoenamel junction (DEJ), which even resulted in compressive peaks for the interface of the small porcelain inlay. The crossing of the DEJ did not seem to have a major effect on

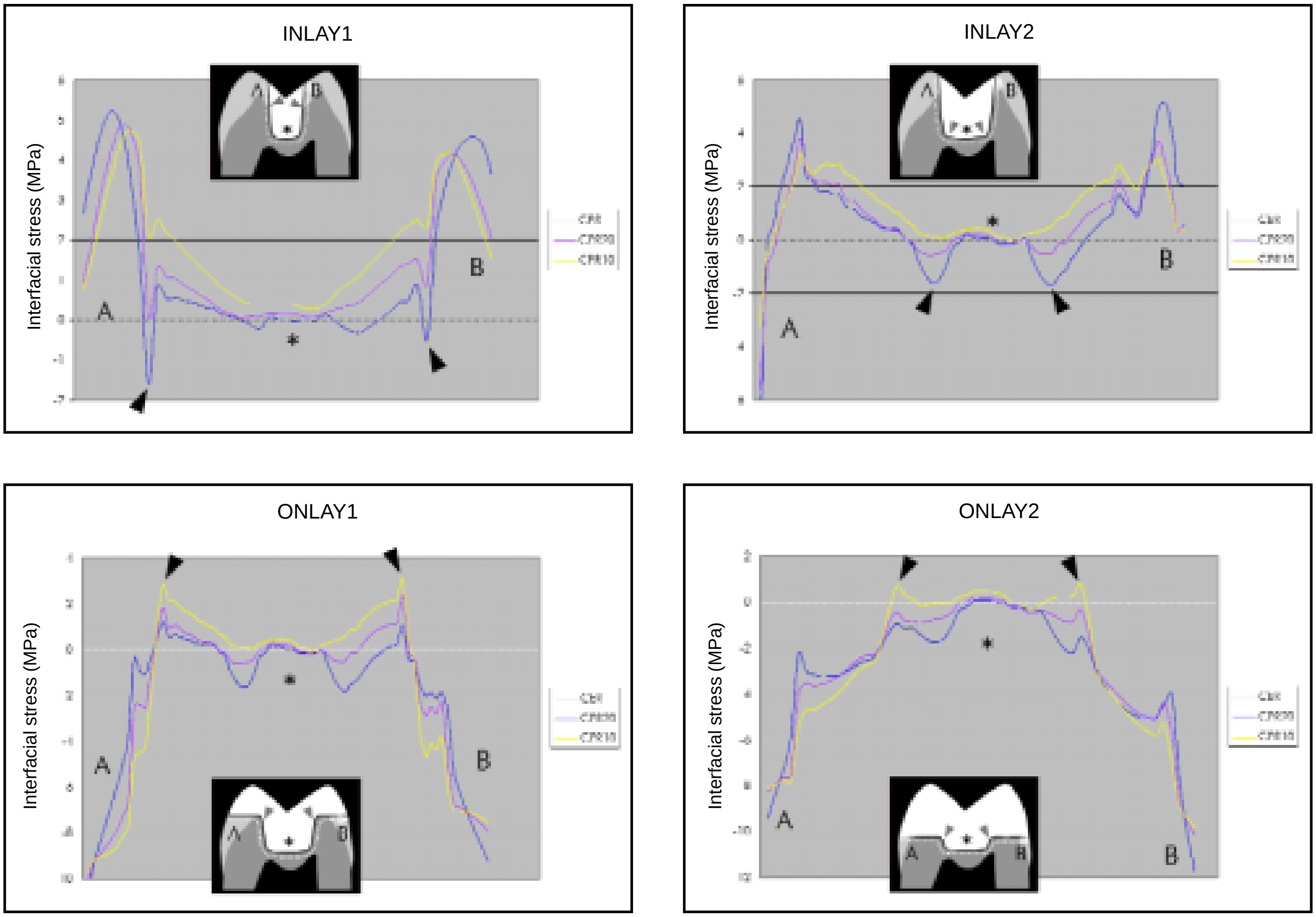

Fig 3 *Interfacial stresses between preparation surface and luting composite for each experimental design. Path plot proceeds from palatal* (A) *to buccal* (B) *along tooth-restoration interface* (dotted arrow *in insets*). ** = pulpal floor;* arrowheads in INLAY1 *= inverted stress peaks at crossing of interface and DEJ;* arrowheads in INLAY2 *= compressive stress peaks at internal cavity angle for porcelain inlay;* arrowheads in ONLAY1 and 2 *= tensile stress peaks at transition line angle between occlusal coverage and vertical wall of cavity for composite onlays.*

the plots of large inlays, but marked compressive peaks of –1.7 MPa characterized the porcelain inlay at the level of the internal cavity angle. For the extracoronal cavities (ONLAY1 and ONLAY2), the small onlay was characterized by marked tensile stress peaks at the transition line angle between the occlusal coverage and the vertical wall of the cavity (maximum 3 MPa for the regular composite) and compressive peaks in the porcelain onlay at the level of the internal cavity angle. In large onlays, porcelain seemed to be the only material for which interfacial stresses were purely compressive, while the interface of the regular composite still exhibited mild tensile peaks at the transition line angle with the vertical wall of the cavity.

Relative cuspal flexure

The relative cuspal flexure is presented in Fig 4a for each cavity configuration and restorative material. Composites and porcelain seemed to act in opposing trends. In composite inlays/onlays, restored teeth featured increased crown flexure (range 176% to 646%; Fig 4b), the amount of which

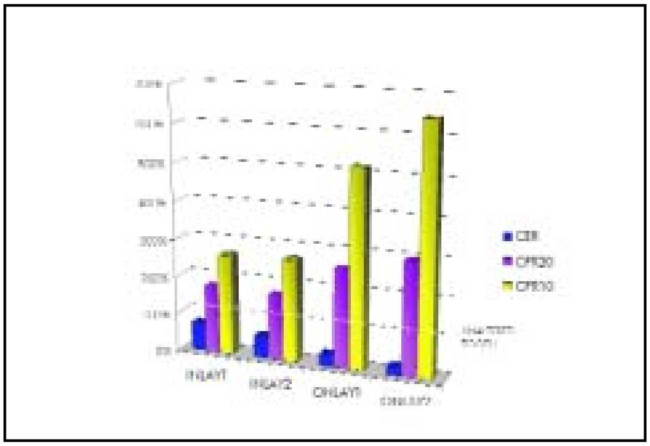

Fig 4a *Relative cuspal flexure for each cavity configuration and restorative material. Lateral displacement of palatal cusp in selected test condition is expressed as percentage of same displacement given by unaltered tooth.*

Fig 4b *Comparative cuspal flexure (displacement along x-axis) of intact tooth* (left) *and teeth restored with large porcelain onlay* (center) *or large regular composite inlay* (right). *Flexure mode is visible because of magnification of deformation (factor 200×).*

seemed proportional to the amount of tissue replacement and inversely proportional to the elastic modulus. In porcelain inlays/onlays, restored teeth were characterized by reduced crown flexure (range 21% to 73%; Fig 4b); this reduction seemed proportional to the amount of tissue replacement.

Discussion

The results presented here might be questioned because they have been produced in an FE environment. The methods used in this study, however, are based on several validation studies that have proven the relevance of these concepts.[19,20,33] Even though some differences can remain between the reality and the FE environment, at least two reasons still justify the use of numeric modeling. First, numeric modeling is able to reveal the otherwise inaccessible stress distribution within the tooth-restoration complex. Second, it has proven to be an essential tool in the thinking process for the understanding of tooth biomechanics and the biomimetic approach. The root was not modeled, as it may be assumed that the overall stress distribution in the coronal portion is only marginally affected by the root area under the simulated boundary conditions. Generally, when local stress distributions in a crown are studied, fixation of the model is prescribed along the cross-section of the root. The model being fixed at the cut plane of the root, a stress is generated in this area. Normally, this stress would be diffused throughout the periodontal membrane and, as here, not influence coronal events. No conclusions can be drawn from the stresses encountered at the CEJ and in the root portion of dentin.

Inversely to anterior teeth, cusps do not deform under load as simple cantilever beams.[42,43] The deformation mode is complicated by the numerous possibilities in the application of loads (working, nonworking, closure).[43] The load configuration applied in the present study was selected because it creates a maximum challenge for cuspal flexure,[27] which seems to represent an important biomechanical feature of posterior teeth, and it has been used in a number of FE model validation studies and load-to-failure tests (simulating axial loading with a steel ball).

Stresses created by shrinkage of the luting composite were not reproduced here; they can be expected to be temporary because all resin-based materials show significant water uptake.[44] Over time, this phenomenon can totally compensate for the initial shrinkage of the material,[45,46] leading to the complete relief of shrinkage stresses.[47]

Despite extreme variations in material properties and cavity configurations, there were only minor differences at the surface of restored teeth. For a given load configuration, it appears that overall stress distribution within the tooth-restoration complex was more influenced by geometry and hard tissue arrangement (convex vs concave)[41] than by composition (eg, enamel-dentin distribution and restorative material type/thickness). The general pattern of stresses did not depend on the exact load magnitude (confirmed by preliminary testing using different loads). This explains the similar surface tangential stress observed for all materials and configurations, with the most critical areas represented by the occlusal surface (concavities). Enamel, dentin, and esthetic restorative materials are brittle and present a higher strength in compression than in tension. Tensile stresses must therefore be regarded as the most harmful. It is precisely in the area of tensile stresses where differences were found (ie, the area of the central groove). In this specific zone, low–elastic modulus restorative materials showed reduced stresses, which can be explained by the stress redistribution into the more flexible composite. Ceramic inlays represented the only conditions with a slightly greater amount of surface tensile stresses when compared to the intact tooth. However, this should not be regarded as a potential threat, knowing that enamel bridges and crests crossing the occlusal surface from buccal to lingual (which should be reproduced in the restoration) prove to be essential biomechanical elements to protect the crown from harmful tensile stresses.[43]

The simulation assumed a perfectly bonded interface, which, at the level of dentin, would require precuring the dentin bonding agent[48,49] and applying an optimized clinical protocol.[33,50–52] Despite an extremely demanding load configuration, all types of onlays exhibited a majority of compressive-type interfacial stresses, which can be assumed to prevent potential debonding. This behavior contrasts with that of inlays, which showed a majority of tensile interfacial stresses challenging the adhesive bond and generating a higher potential risk for postoperative dentin sensitivity (especially with the more flexible composites). The amount of interfacial tensile stress was highly related to the elastic modulus of the material.

Porcelain inlays featured more detrimental stresses at the occlusal margins but better potential protection against debonding at the dentin interface. There were even compression peaks at the internal line angle of large porcelain inlays (transition between vertical walls and pulpal floor of the cavity) and an almost stress-free pulpal cavity floor. Composite inlays showed an opposite trend (especially large inlays made of flexible composites), with reduced stresses at the enamel margins and increased tension at the dentin interface. Large onlays were characterized by an extremely favorable stress pattern, with an almost pure compression of their interface. Stress peaks were found at the transition line angles between the occlusal coverage and the vertical wall of the cavity. At this level, more rounded line angles are always preferred, and the clinician must remember that acute edges will consistently generate increased focal stresses, especially when using composite onlays.

It could be questioned whether the selected loading configuration was influential in the positive interfacial response of teeth restored with onlays. To explore this effect, additional computations were carried out using large inlays/onlays in a simulation of a nonworking contact (single 50-N load point at the inner ridge of the palatal cusp; Fig 5). Even though the general stress pattern seems to be influenced by this new load direction, the conclusions regarding the differential response of inlays and onlays remain unchanged: The majority of interfacial stresses were in compression for onlays and in tension for inlays; this difference was mainly observed within the supporting cusp, while the response at the buccal side of the interface was identical for both cavity configurations and materials. As for the standard load configuration, interfacial stress peaks always characterized the cavity transition line angles, which should be made as smooth and blunt as possible.

A number of studies[19,20,27,28] analyzing biophysical stress and strain have shown that restorative procedures can make the crown more deformable, and that teeth could be strengthened by increasing their resistance to crown deformation. The standard load case applied in the present analysis constitutes the most discriminating technique to study crown deformation; the results obtained with composite-restored teeth are in agreement with earlier conclusions[28] stating that their strength falls off with increasing cavity size and can only approach that of the unaltered tooth in the case of small, conservative cavities. The opposite can be said about ceramic-restored teeth, the stiffness of which is increased with increased cavity size. Adhesive technology has proven its efficiency in simultaneously reestablishing crown stiffness and allowing maximum preservation of the remaining hard tissue (intracoronal strengthening).[18,25,26] These studies demonstrated that bonded composite restorations permit the recovery of tooth stiffness, which was not possible with amalgam.

However, it should be remembered that the physical properties of composites are somewhat limited. One limitation is the elastic modulus, which for an average microfilled hybrid can be up to 80% lower (~ 10 to 20 GPa) than the elastic modulus of enamel (~ 80 GPa). The enamel shell proves to be instrumental in the way stresses are distributed within the crown.[6,41,43] When a more flexible material replaces the enamel shell, one can expect only

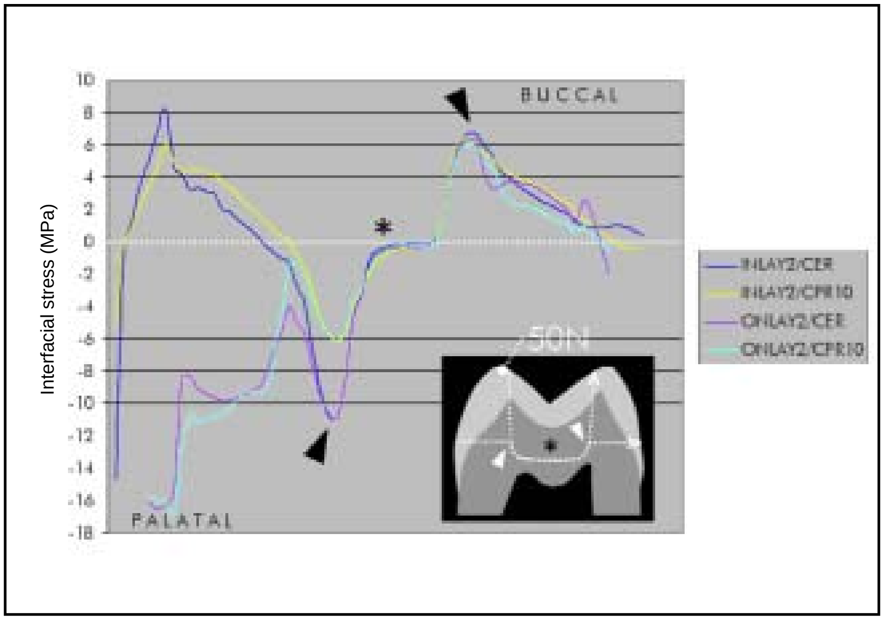

Fig 5 *Interfacial stresses between preparation surface and luting composite with nonworking load configuration* (dotted line = *single palatal 50-N load point). Same path plot as in Fig 3. * = pulpal floor;* arrowheads = *stress peaks at transition line angle between occlusal coverage and vertical wall of onlay preparation.*

Fig 6a *Insufficient remaining thickness of buccal cusps and extensive wear at palatal cusps justified coverage of the complete tooth, but the latter was kept vital.*

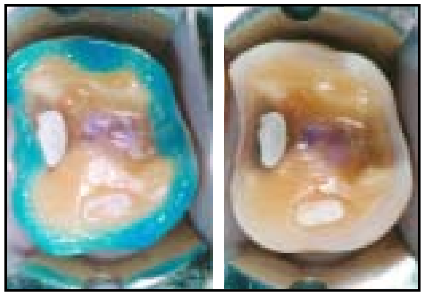

Fig 6b *No effective dentin bonding agents were available at time of placement. Dentin was isolated with calcium hydroxide and varnish.*

Fig 6c *Complete occlusal restoration with ceramic overlay at 10-year follow-up. Sole adhesion to marginal enamel using acid-etch technique (Fig 6b) is responsible for this long-term clinical success.*

partial recovery of crown rigidity. Studies showed a recovery of 76% to 88% in crown stiffness after the placement of composite restorations and veneers.[53,54] On the other hand, 100% crown rigidity can be recovered when feldspathic porcelain (elastic modulus ~ 70 GPa) is used as an enamel substitute, as is the case in porcelain veneer restorations.[33] Porcelain can be regarded as an enamel-like material. Extensive dentin replacement using porcelain (large porcelain onlays) logically results in excessively reduced cuspal flexure. The stiffness of the crown was instrumental in the reduction of tensile stresses at the dentin interface as well. Figure 6 depicts a clinical case with a 10-year follow-up of a large porcelain onlay. No effective dentin bonding agents were available at the time of placement, and dentin was isolated from the restoration with a varnish. The sole adhesion to marginal enamel could be held responsible for this clinical success; however, in view of results from the ONLAY2/CER design, it is logical to assume that the bulk and stiffness of the restoration diminished the impact of the missing dentin bonding as well. Marginal ridge integrity is also an important anatomic feature limiting cuspal flexure, which is the most significant contribution to stiffness and strength of the posterior crown.[55]

A number of posterior teeth can be treated ultraconservatively using freehand composites,[16,56] especially in the presence of intact proximal ridges that ensure the biomechanical integrity of the crown. The comparatively low elastic modulus of most composites, however, can never fully compensate for the loss of strong proximal enamel ridges, especially in extremely large Class II restorations. In these situations, including eventual cusp coverage or complete occlusal coverage in vital teeth with a short clinical crown, indirect ceramic inlays/onlays seem to be best indicated.[16,56] Adequate stiffness of the porcelain material potentially allows for 100% recovery of crown rigidity. Current composites suffer not only from low elastic modulus and limited toughness, but also from high thermal expansion (~ 20 to 50^{-6}/°C)[57] when compared to tooth substance and ceramics (~ 11 to 17^{-6}/°C).[58]

Conclusions

The realization of posterior bonded porcelain restorations in the form of ceramic onlays and overlays is a judicious way to prevent traditional prosthetic procedures that would require root canal therapy and surgical crown lengthening.[6] Maximum tissue preservation and biomimetics, the driving force of modern restorative dentistry, are enabled. Within the limitations of this simulation experiment, it can be concluded that:

- All materials and tooth preparation designs exhibited similar surface tangential stress patterns, with a definite compressive area at the external cusp ridges and a tensile zone at occlusal surfaces.
- The low–elastic modulus composite showed reduced tensile stresses at its surface (including margins) but increased tension at the dentin-adhesive interface when compared to ceramics.
- Both types of onlays exhibited a majority of compressive interfacial stresses, while inlays showed a majority of tensile stresses.
- The amount of interfacial tension at the dentin level increased with flexibility of restorative material.
- Composite-restored teeth exhibited increased crown flexure, while porcelain-restored teeth showed increased stiffness.
- Among all experimental designs, only the large ceramic onlay exhibited almost pure compression at the interface; because of their extreme stiffness and optimal interfacial behavior, ceramic onlays/overlays offer the most promising solutions for restoration of severely damaged posterior teeth.

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