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Modeling of ultrathin occlusal veneers☆

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ABSTRACT

Objective. The purpose of this investigation was to compare stresses within bonded porcelain and composite resin ultra-thin occlusal veneers to restore advanced erosive lesions.
Materials and methods. A sound maxillary molar was digitized with a micro-CT scanner. The 2D image data were converted in a 3D model using an interactive medical image processing software (Mimics). Standard triangle language files (STL files) of enamel and dentin surfaces were then exported to the software 3-matic to execute design and meshing operations. Solid 3-dimensional (3-D) models acquired in a finite element software (Marc/Mentat) were subjected to nonlinear contact analysis to simulate occlusal loading at 200N and 800N. Values of maximum principal stress and ultimate tensile strength were used to calculate the risk of fracture and for validation with existing experimental data.
Results. There were marked differences in stress distributions both at 200N (maximum peak values of 21.59, 28.63, 31.04 MPa) and 800N (96.16, 115.73, 134.90 MPa) for all restorative materials (MZ100, Empress CAD and e.max CAD, respectively). High tensile stresses (measured in the central groove) were found at 800N with the ceramic occlusal veneers showing occlusal stress peaks 17–29% higher than composite resin. The estimated risk of fracture was decreased for ultrathin composite resin occlusal veneers, which correlated with the existing validation data.
Significance. Ultra-thin composite resin (MZ100) and lithium disilicate (e.max CAD) occlusal veneers represent a conservative alternative to traditional onlays and complete coverage crowns for the treatment of severe erosive lesions in the posterior dentition.

1. Introduction

Enamel, as the outer barrier, is designed to resist the wide array of aggressions from the oral environment (mechanical, chemical, biological and thermal) for one's entire life. It acts as a shield protecting the softer vital underlying dentin against wear [1]. The reduction of the enamel's thickness along its life is a biological condition resulting from the aging process [1]. However, the premature and accelerated loss of enamel by gastro-esophageal reflux disease (GERD) or bulimia nervosa may happen in adolescence or even in childhood, with destructive consequences [2,3].

Ultra-thin bonded posterior occlusal veneers have been demonstrated as a conservative alternative to traditional onlays and complete coverage crowns for the treatment of

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severe erosive lesions [4,5]. Evidence and common sense seem to indicate that severely eroded teeth require nonretentive preparations and stronger materials. The combination of CAD/CAM technologies and a state of the art bonding protocol (such as immediate dentin sealing) seems to be the right approach for this paradigm shift [4,5].

Only bonded ceramics and composite resins can potentially conform with the aforementioned requirements for utmost tissue conservation and esthetics [6–8]. The development of ceramics that are stronger (e.g. lithium disilicate glass ceramic) [9] but still etchable and machinable [10] has extended the spectrum of indications for bonded ceramic restorations. The performance of composite resins have also improved considerably during the last decade [11,12], through superior bond between the different constituting phases (enabling appropriate stress transfer) [13,14] and various post-cure treatments [11,15].

It is noteworthy that knowledge of stress distribution under cyclical activity in a highly complex and anisotropic structure such as a restored tooth is quite important, particularly for the clinical prediction of novel restorative procedures. Experimental load-to-failure should be accompanied by non-destructive approaches [16] such as fatigue tests and finite element (FE) method.

Therefore, the aim of the present study was to assess the influence of CAD/CAM restorative material (ceramic vs. composite resin) on the stress distribution of ultra-thin veneers. The null hypothesis was that there would be no influence of material selection on the stress distribution of ultra-thin (0.6 mm thick) occlusal veneers.

2. Materials and methods

A 3-D FE model of an extracted human maxillary first molar was generated in three steps according to a previous and validated protocol [17]. A raw micro-CT set of slices was provided by Digisens (Ferney-Voltaire, France) with a voxel dimension of 13.67 microns.

Second, an interactive medical image processing software (Mimics 9.0; Materialise, Leuven, Belgium) allowed identifying the different hard tissues visible on the scans. Mimics features extended visualization and segmentation functions based on image density thresholding. Each 3-D object is created by growing a threshold region on the entire stack of scans. Each resulting mask (enamel, dentin) is then converted into a 3-D file (STL, bilinear and interplane interpolation algorithm) using Mimics STL + module. The pulp chamber and root canals were generated as an empty space (no elastic modulus) in the dentin.

Because of the aspect ratio and connectivity of the triangles in the native STLs, these files are improper for use in FEA. Reducing the amount of triangles and simultaneously improving the quality of the triangles while maintaining the geometry is automatically achieved with the Remesh module included with Mimics.

Third, an advanced STL design and meshing software (3-matic 4.2, Materialise, Leuven Belgium) was used to generate additional intersection parts simulating the occlusal veneer preparation and establish perfect congruence of the interfacial mesh between the different objects (enamel, dentin, restorative material, cylindrical fixation base simulating the bone). The following sequence was applied, starting by the merging of all 4 parts into a single STL file, called assembly. Self-intersecting curves were then created and used to split all triangles at the intersections within the assembly. Using a section view to look inside the assembly, all unwanted surfaces were deleted. The definitive assembly was then remeshed using the Remesh module of 3-matic. Self-intersecting curves were maintained and the tolerance variation from the original data was specified (quality of triangles does not mean tolerance variation from the original data). As in Mimics Remesh, the quality is defined as a measure of triangle height/base ratio (defined at 0.3) so that the file can be imported in the finite element analysis software package without generating errors. Finally, the remeshed assembly was split again by indicating the proper surfaces constituting each part (occlusal veneer, enamel, dentin and bone), separating them and copying them as a new and definitive STL part.

Table 1 – Material properties.

Source	Elastic modulus (GPa)	Poisson's ratio
Enamel	84.1[a]	0.30[b]
Dentin	18.6[c]	0.3[d]
Base (cortical bone)	14.7[e]	0.30[d]
MZ100	16[f]	0.24[f]
Empress CAD	62[g]	0.21[h]
e.max CAD	95[g]	0.30[i]

[a] Craig et al. [18].
[b] Anusavice and Hojjatie [19].
[c] McGuiness et al. [20].
[d] Farah et al. [21].
[e] Moroi et al.[22].
[f] Ferrari M [23].
[g] Data from manufacturer of Empress CAD and e.max CAD (Ivoclar Vivadent, Schaan, Liechtenstein).
[h] Gonzaga et al. [24].
[i] Aboushelib MN et al. [25].

The exact design and dimensions of the occlusal veneer reproduced an existing experiment [5], which was used in the validation process of the FEA model (see Section 3). The assembly consists of a prepared tooth (occlusal reduction by the complete removal of the occlusal enamel) and a 0.6 mm-thick onlay restoration (Fig. 1 A and B)

Fourth, the definitive STL files of all parts were then imported in a finite element analysis software package (MSC.Marc/MSC.Mentat; MSC Software, Santa Ana, Calif) for the generation of a volumetric mesh (total 131,853 elements/26,770 nodes) and attribution of material properties according to existing data (Table 1). Automatic mesh generation using a tetrahedral mesher (tetrahedron elements with pyramid-like shape and 4 nodal points) is ideally achieved using the triangulated files generated in 3-matic.

The nodes at the bottom surface of the fixation base were assigned fixed zero-displacement in the 3 spatial dimensions. To simulate usage of adhesive luting cements, the tooth and restorative materials were considered to be bonded. A uniform ramp loading was applied to the mesiobuccal, mesiolingual and distobuccal cusps (tripod contact) through a rigid body, that is a 7 mm-diameter ball positioned as close as possible

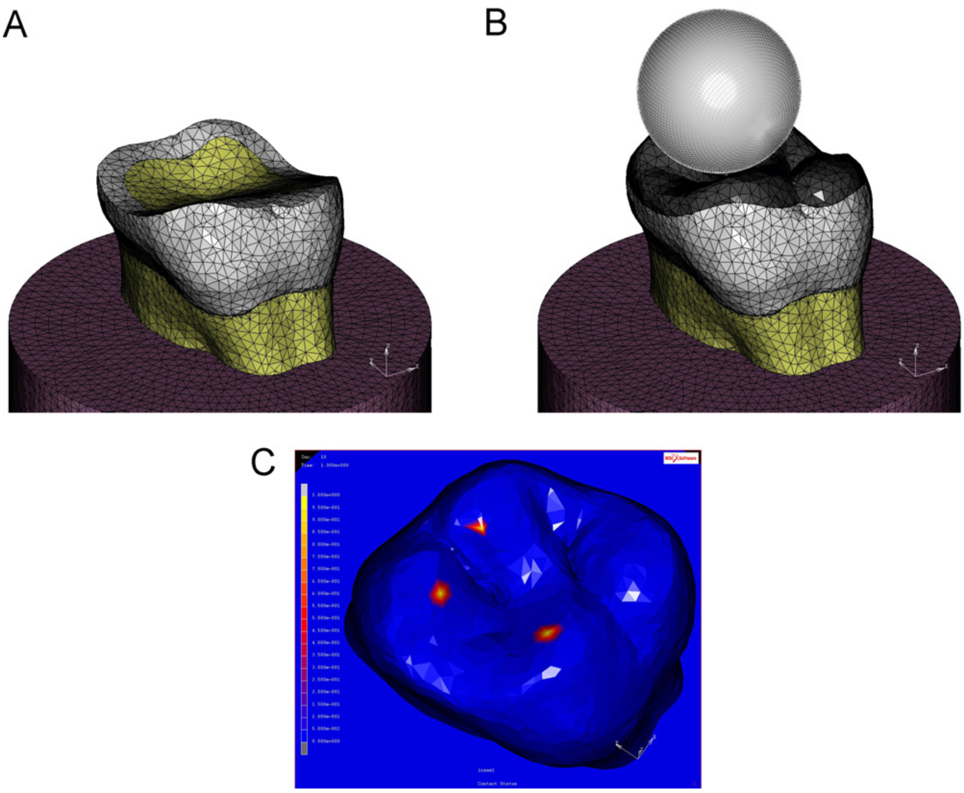

Fig. 1 – View of final mesh used for automatic volume mesh generation in Mentat. (A) Tooth preparation simulating advanced occlusal erosion. (B) Restored tooth with ultrathin occlusal veneer and load sphere as seen in Mentat (preprocessing); all nodes at bottom of cylindrical fixation base were assigned fixed zero displacement in 3 spatial dimensions. (C) Load sphere was set to move against tooth along z-axis while touching mesiobuccal, mesiolingual, and distobuccal cusps.

to the tooth (Fig. 1B and C). The tooth was defined as a deformable contact body. Contact between these bodies was determined automatically by the FEA simulation during the static mechanical loadcase (no inertia effects). A motion was applied to the rigid ball along the z-axis until the target load was obtained, measured by 200N or 800N on the ball. The stress and strain distributions were solved using the MSC.Marc solver (MSC Software). These specific boundary conditions, load protocol and configuration were selected because they reproduce a previous experiment [5].

3. Results

The post-processing file was read through MENTAT. Values of maximum principal stress (located at the central groove and oblique ridge) are available in Table 2 and illustrated in Figs. 2 and 3. Similar stress distributions were observed at low load (200N) with maximum peak values ranging from 28.6 to 31 MPa (central groove) for both ceramic materials while composite resin stresses reached no more than 21.6 MPa. Noticeable differences were experienced at high load (800N), with the ceramic occlusal veneers showing stress peaks 17–28.8% higher than composite resin. All restorations illustrated stress concentrations in concave areas such as central and secondary grooves with dissipating stress as the region moved toward a more convex shape.

Table 2 – Maximum principal stress (MPa) at central groove.

	200-N Occlusal load	800-N Occlusal load
Restorative material		
MZ100	21.6	96.0
Empress CAD	28.6	115.7
e.max CAD	31.0	134.9

The FEA model in the present study is a reproduction of restorative conditions simulated in a previous experiment, in which the ceramic occlusal veneers were the first to fail, at 800N for 0.6 mm thick restorations [5]. Fig. 4 shows the difference in survival rates for all three restorative materials when subjected to cyclic loading. While none of the Empress CAD and only 20% of the e.max CAD occlusal veneers survived the load of 800N at 0.6 mm thickness (average failure load of 800N), composite resin onlays did not fail in 90% of the specimens. Because all fractures appear to start at the occlusal surface, the margin of safety in the corresponding FEA model can be evaluated quantitatively by the following equation:

$$\text{Margin of safety} = \frac{\text{ultimate tensile strength (UTS)}}{\text{maximum principal stress (occlusal surface)}} - 1.$$

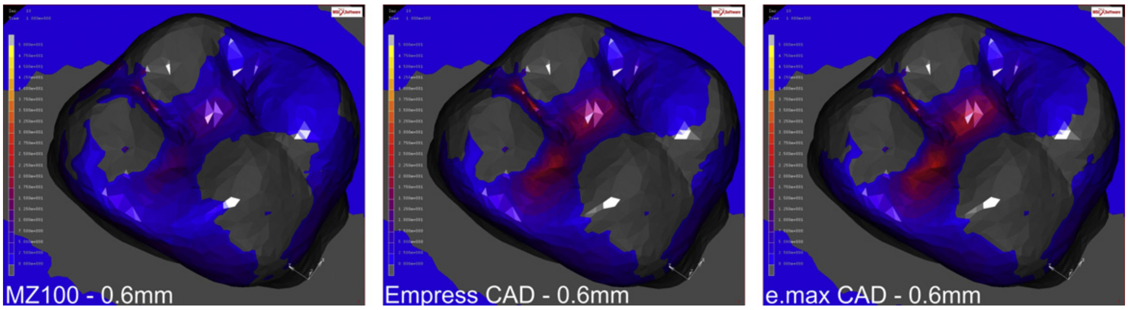

Fig. 2 – Maximum principal stress (MPa) as observed in Mentat with 200-N occlusal loading. Note slight different stress distribution with higher tensile stresses at occlusal surface (central groove and oblique ridge) for ceramic restorations. Colors, tensile stresses; gray, compressive stresses.

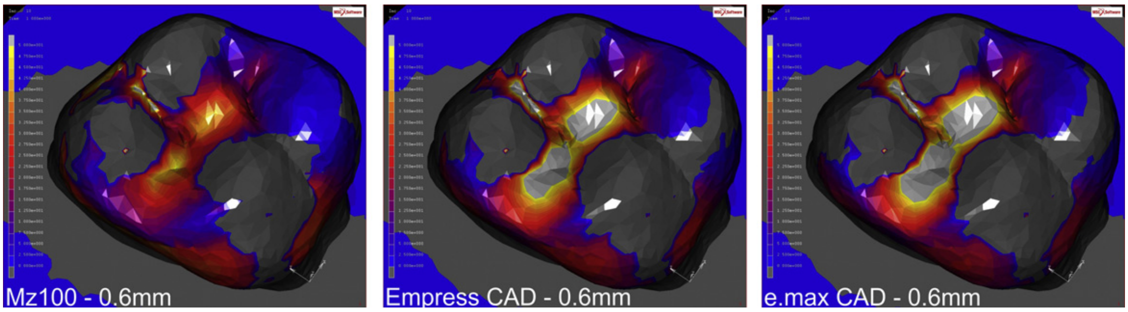

Fig. 3 – Maximum principal stress (MPa) as observed in Mentat with 800-N occlusal loading. Note different stress distribution with higher tensile stresses at occlusal surface (central groove and oblique ridge) for ceramic restorations.

Margin of safety represents how much of the structure's total capacity is detained "in reserve" during loading. If the margin is 0, the structure will not take any additional load before failing. In case of 1, it can resist one additional load of equal force to the maximum load it was designed to support (Table 3). Those results are in agreement with the survival analysis in the fatigue experiment.

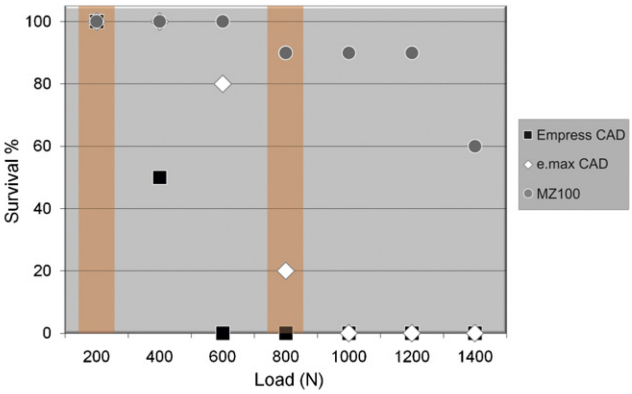

Fig. 4 – Life table survival scatter plots for 0.6 mm-thick of composite resin (MZ100; 3M ESPE, St. Paul, Minn;) and ceramic (Empress CAD and e.max CAD; Ivoclar Vivadent AG, Schaan, Liechtenstein) occlusal veneers in advanced eroded molars with same restorative design as in present FEA study. The hatched area represents the step loads reproduced in FEA. Reproduction of the Figure titled "Life table survival distributions by materials at each load step (*n* = 10)" in this chapter were approved by the Editorial Council for The Journal of Prosthetic Dentistry, Incorporated, on October 25, 2011.

4. Discussion

The null hypothesis was rejected, because according to the results of this simulation study, the choice for composite resin MZ100 had lower stress concentration when compared to the ceramics Empress CAD and e.max CAD. The study also supports the results from previous studies [4,5] showing the feasibility of treating severe erosion lesions in posterior teeth with minimally invasive CAD/CAM ceramics and composite resins.

Table 3 – Margin of safety.

	200-n Occlusal load	800-N Occlusal load
Restorative material		
MZ100 (110[a] UTS)	4.09	0.14
Empress CAD (41[b] UTS)	0.43	−0.64
e.max CAD (124[c] UTS)	3	−0.08

UTS = ultimate tensile strength (diametral tensile strength).
[a] Data from manufacturer of MZ100 (3M ESPE).
[b] Katz (US patent # 4798536) [26].
[c] Davis [27].

The present study borrows a design utilized in a previous simulated fatigue experiment [5], with three simplifications. First, the resin cement layer and adhesive were omitted in the numeric model because a pre-heated light-polymerized composite resin restorative material (Filtek Z100, 3M-ESPE) was used as a luting agent in the experiment. Unlike the usual luting materials, the elastic modulus of the Filtek Z100 (16 GPa) is similar to that of dentin (18.6 GPa), which justifies its absence in the numeric analysis. Regarding the adhesive layer, (approximately 5 GPa, 100 μm-thick), it seems to work mechanically as a stress absorber and improves significantly the adaptation to dentin. This is, however, an extremely thin layer to be included in this analysis. In fact, it was also omitted in previous publications, and the strong correlation achieved between the virtual environment and the reality in those studies encouraged the authors to follow the same methodology. Second, the ball (actuator) was assumed to be a rigid body (undeformable, infinite modulus of elasticity) in order to remove a variable that was found to be insignificant (based on previous similar validated models) and that would have complicated and slowed the analysis. Third, only the step loads of 200N and 800N simulated (instead of 200 N to 1400 N in the experiment), which covers realistic occlusal load in the posterior region, namely 8N to 880N [28], from mastication and swallowing to bruxism, respectively. Both at 200N and 800N there were strong correlations between the numeric model and the fatigue experiment (Fig. 4 and Table 3). For example: the margin of safety presented for MZ100 at 200N predicts a load reserve of 4 times what is confirmed in the Life table survival scatter plot of the fatigue experiment (Fig. 4). In the same way, at 800N, the ceramic e.max CAD presents a negative margin of safety, i.e., the tensile stresses slightly overcame the UTS confirmed by the survival rate of only 20% in the fatigue experiment. Therefore, the model can be considered valid.

The numeric model indicated that composite resin yielded more stress dissipation, as confirmed by the fatigue experiment. Indeed, the intrinsic strength, as well as the thickness of the material, has limited influence on the failure triggered by the development of tensile stresses, which is much more sensitive to the ratios of elastic moduli between the restorative material and the luting material and dentin [29]. The relative similarity of elasticity moduli of the composite tested (16–20 MPa) and dentin (18.5 GPa) [18] may have a key role in the tooth-restoration performance. Besides, both findings (numeric model and fatigue experiment) seem to correlate with the work of fracture of the various materials (K1c2/Emod): Paradigm MZ100 (141 J/m2) > e.max CAD (83 J/m2) > Empress CAD (21 J/m2) (obtained from additional testing). The work of fracture represents the energy used within the fracture process where a new surface is generated and considers the elastic modulus of the material. Because of their higher strength, e.max CAD restorations started cracking at a step above that of Empress CAD restorations. Among ceramic groups, only e.max CAD successfully underwent the first part of the fatigue test (confirmed in the numeric simulation) and can be deemed indicated for ultra-thin occlusal veneers under normal occlusal conditions. The CAD/CAM composite resin (MZ100) can be recommended for fabricating ultra-thin occlusal veneers in posterior teeth even in patients with high load requirements. From a practical standpoint, additional advantages of such a material include friendly wear properties to antagonist enamel [30], easier color matching [31] and improved millability in thin layers [32] over ceramic materials.

Perfect static occlusion was simulated in this study. Additional works should include the loading of a single cusp in order to explore dynamic load effects. Further numeric studies should also evaluate the ultra-thin occlusal veneers after crack propagation (fracture mechanics), since no specimen underwent catastrophic failures in the remaining tooth structure in the fatigue experiment [5]. Cracks were restricted to the restorations and remaining enamel, regardless of the material used. The numeric simulation did reflect the same pattern as peripheral enamel displayed very low stresses at 200N (Fig. 2) but tensile stresses in the range of 20–25 MPa at 800N (Fig. 3). Enamel was completely removed for the occlusal surface in the present work. Additional numeric simulation could also evaluate the influence of the material for ultra-thin occlusal veneers bonded to severely eroded teeth in the presence of residual enamel left on the occlusal surface. Finally, clinical studies are needed to confirm the validity of this ultraconservative approach.

5. Conclusion

This investigation describes the use of a finite element model for the analysis of a newly proposed restorative design. The model was validated by comparing the generated outputs with recently observed data from simulated occlusal loading. Within the limitation of the numeric simulation, minimally invasive CAD/CAM composite resin and lithium disilicate glass ceramic performed well to treat severe erosion lesions in posterior teeth using ultrathin occlusal veneers.

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