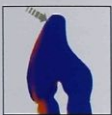
Optimization of Resilience and Stress Distribution in Porcelain Veneers for the Treatment of Crown-Fractured Incisors



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The present study was conducted to define, when restoring extensive loss of dentin, the configuration of the restoration that will best reproduce the biomechanical properties of the intact original tooth in terms of resilience and stress distribution. The treatment of ⅓-crown fractures and ⅔-crown fractures was investigated using different designs of facial porcelain veneers with and without underlying composite buildup. The stress distribution and tooth compliance were assessed in a numeric model reproducing a 2-dimensional buccolingual cross section of an incisor. A 50-N facial force was applied to simulate an incisal impact situation. The facial surface tangential stresses were calculated, and the maximum displacement (horizontal direction) at the most incisal node of the enamel surface was also recorded and used to calculate the tooth compliance (ie, displacement/load or resilience) for each test condition. Tensile stresses were generated on the facial surface of the porcelain laminates with a similar pattern for all test conditions, the cervical part of the crown being the most quiescent area. Substantial differences appeared in the incisal half of the crown, the lowest stresses being observed for extensively fractured teeth restored without composite buildup (facial peaks at ≈ 33 MPa). Fractured teeth restored with minimal veneers and a "dentin-like" composite buildup showed stress patterns similar to the intact tooth (facial peaks at ≈ 50 MPa). The natural tooth gave the highest tooth compliance or flexibility. All restorative designs featured increased tooth stiffness. However, the original tooth compliance was almost restored when composite was used to replace the missing dentin, with the porcelain acting only as a facial and incisal enamel substitute. When restoring crown-fractured incisors, tooth compliance and stress distribution can be modulated by the combination of composite and ceramics. Optimized configurations can be reached to reproduce the original biomechanical behavior of the intact tooth. The use of ceramic alone generates low stress concentrations, but also less compliant restored teeth.
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The good overall clinical behavior of porcelain laminate veneers (PV) in terms of fracture rates, microleakage, debonding, and soft tissue response is generally well recognized and attested to by numerous clinical studies.[1-7] As a consequence, the indications for PVs have been extended,[8,9] including the treatment of crown-fractured incisors[10,11] and the rehabilitation of worn down dentition.[12,13] Among these, the treatment of severely damaged incisors commands special attention. The use of PVs is particularly interesting in the presence of teeth with short clinical crowns or insufficient residual tooth structure to provide adequate stability for a conventional type of fixed prosthetic restoration (Fig 1). PVs permit above all the maintenance of tooth vitality in spite of a severe breakdown of tooth structure.

The strength of the tooth-restoration complex is an important clinical concern when restoring extensively fractured incisors. Also important is the exact definition of the restorative design, ie,

Fig 1a *Clinical case of previously fractured incisor. The patient's maxillary incisors are insufficient in length and have lost their characteristic form. The right central incisor was fractured and previously reconstructed with composite resins. Porcelain veneers were planned to reestablish anterior tooth prominence and esthetics.*

Fig 1b *Specific diagnostic approach is used to redefine tooth volume and length. A silicon index of the corresponding waxup is used by the ceramist during porcelain buildup: the volume that will be restored by the future veneer on the left central incisor, which will allow both the restoration of the facial aspect and replacement of missing incisal substance, is shown.*

Fig 1c *Ceramic only was used to restore structure and esthetics of anterior teeth (immediate postoperative view, now more than 4 years in service). (Ceramist: Michel Magne, dental laboratory Oral Design, Montreux, Switzerland.) Owing to the ceramic stratification, optimal optical transition was obtained between the intact part of the right central incisor and the bulk of the restoration.*

whether the missing tooth substance should be replaced using *(1)* the veneer alone, *(2)* a composite buildup along with the veneer, or *(3)* the fractured tooth fragment itself along with the veneer. A surprising answer was given in an assessment of strength by Andreasen et al,[11] who used veneered sheep incisors in a load-to-failure test that yielded ultimate strengths of *(1)* 28.2, *(2)* 20.2, and *(3)* 21.0 MPa, respectively. These values are well above the strength of intact teeth, since the latter fractured at an average of 16 MPa in a similar experiment by Munksgaard et al.[14] Therefore, the use of a simplified approach (veneer alone) to the restoration of crown-fractured incisors could be justified. However, one may question the biomechanical behavior of single teeth restored with extremely resistant restorations. Using in vitro simulated impacts, Stokes and Hood[15] clearly demonstrated that the excessive strength of conventional prosthetic restorations such as gold and metal ceramic crowns yields root fractures that would be very difficult to restore.

The modulation of the strength of the tooth-restoration complex should therefore be considered to avoid stress transfer and catastrophic failures at the level of the root. The combination of both composites and ceramics seems theoretically appropriate to reproduce the original stiffness of the tooth and modulate the tooth-restoration strength. However, no scientific investigations have been conducted yet to define, when restoring extensive loss of dentin, the optimal configuration of the restoration and related thicknesses of composite and ceramic. Only a few scientific papers[16,17] specifically addressed the problems of internal stress distribution, stress transfer, and tooth stiffness after the placement of PVs.

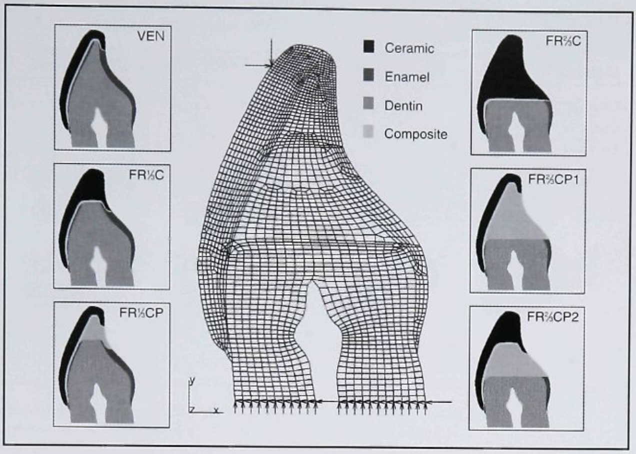

Fig 2 *Mesh developed in MENTAT and related experimental groups.*

An efficient way to access the intimate structure of the tooth-restoration complex undoubtedly is represented by finite element (FE) evaluations. New trends in research tend to combine experimental approaches and FE evaluations.[16] In an FE model, 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 undivided large structure. By solving the deformation of all the small elements simultaneously, the deformation of the whole structure can be reconstructed. Accordingly, the present study was conducted using the 2-dimensional FE method to define the optimal geometric relation between composite and ceramic materials and related thicknesses that should be reproduced to meet the physicomechanical properties of the natural tooth.

Method and materials

An extracted maxillary central incisor was embedded in a clear epoxy resin (Orthodontic Resin, Caulk/Dentsply) and sectioned longitudinally in the buccolingual plane. The sectioned surface was digitized with a computer scanner device (UMAX, Umax Data System). The contours of enamel, dentin, and pulp chamber were manually traced using a personal computer and graphic software (Freelance Graphics, Lotus). Additional lines were included to simulate different restorative designs, ie, a conventional preparation for PVs and 2 grades of traumatic injury. Point coordinates were obtained using Scion Image software (Scion). The lines were finally transferred to MENTAT 3.3 software (MARC Analysis Research), and a single mesh that included the different restorative designs was developed (Fig 2). The root was modeled to a level 2

Table 1	**Material properties**	
Material	**Elastic modulus (GPa)**	**Poisson ratio**
Composite	20	0.24[18]
Ceramic	78*	0.28[19]
Enamel	50	0.30[18]
Dentin	12	0.23[20]

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

mm below the cementoenamel junction. It is assumed that the overall stress distribution on impact is constrained to the coronal restoration. Fixed zero displacement in both horizontal and vertical directions was therefore applied at the cut plane of the root. Functional stress transfer into the jaw would have required meshing the entire root and the periodontal ligament, which was not the purpose of this investigation. A facial load of 50 N was applied to the incisal edge of the veneer (Fig 2) to simulate the equilibrium response of a tooth in an impact case. This situation was also chosen to generate tensile stresses at the facial surface of the veneer. The stress distribution was solved using the MARC Analysis solver (MARC K7.3, MARC Analysis Research). The simulation was performed with plane-strain elements (linear, 4-node, isoparametric, arbitrary quadrilateral).

Restorative designs

The intact original tooth and 3 different preparation designs were reproduced, generating the following situations (Fig 2):

- Natural tooth (NAT): intact original tooth.
- Veneer (VEN): traditional veneer preparation with its corresponding porcelain laminate.
- Fractured (FR): FR⅓ situations correspond to a preparation following fracture of the incisal third of the crown; FR⅔ situations correspond to a preparation following the fracture of two-thirds of the crown.

Two treatment modalities could be assessed for each situation of the fractured incisal edge (Fig 2): *(1)* the replacement of enamel and dentin using the ceramic veneer alone (FR⅓C, FR⅔C (C = ceramic)) or *(2)* the enamel replacement by the veneer, the lost dentin being replaced by a composite buildup (FR⅓CP, FR⅔CP1, FR⅔CP2 (CP = composite)). The restoration of the most extensive fracture (FR⅔) was explored either with a large composite buildup (FR⅔CP1) or a reduced composite buildup (FR⅔CP2). A total of seven conditions was tested (Fig 2), including the natural tooth.

The luting composite thickness averaged 200 µm at the axial and incisal level, whereas 50-µm thicknesses were produced for both buccal and palatal margins and 100-µm thicknesses were used at the level of the palatal chamfer. Three extra layers of elements (approximately 400 µm) were meshed to accentuate the facial contour of the natural tooth. This feature corresponds to relevant clinical conditions because the desirable preservation of

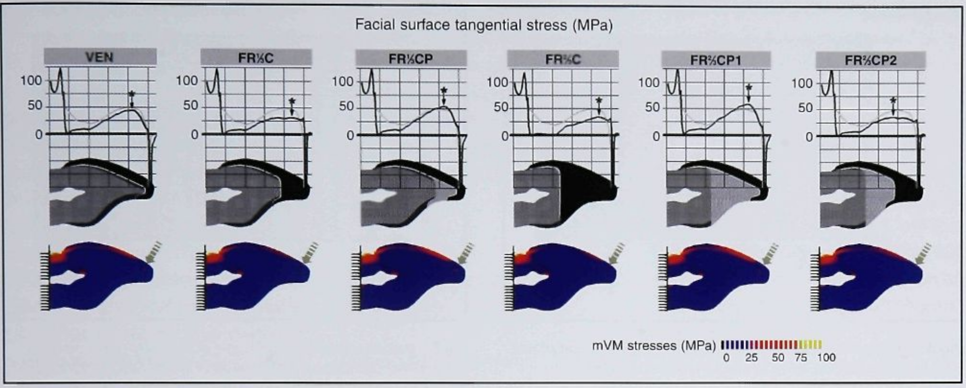

Fig 3 Surface tangential stresses (upper part) and modified Von Mises stresses (lower part) for each experimental design. The gray line on the plots corresponds to the surface tangential stress distribution of the intact tooth. * = maximum values (Fig 4).

enamel during tooth preparation often leads to the overcontouring of the final restoration.[21] Two mechanical material properties were required for this FE simulation: the Poisson ratio and elasticity modulus are listed in Table 1. Both of these properties for the luting agent and the composite buildup materials were assumed to be the same. The FE calculations generated the values of stress in the x and y directions (σ_x and σ_y) and the xy shear stress (τ_{xy}). The surface tangential stress σ_t for each node located at the facial surface of the tooth was calculated using the following transformation[22]:

$$\sigma_t = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

where θ is the angle between the x axis and the surface of the element. The maximum horizontal displacement (x displacement) at the most incisal node of the enamel surface was also recorded and used to calculate the tooth compliance (ie, displacement/load or resilience) for each test condition.

Results

The surface tangential analysis of stress was plotted for each experimental design, along with the distribution of modified Von Mises stresses (mVM) across the section of the restored tooth (Fig 3). The original Von Mises stress is an integral value that incorporates both tensile and compressive components within one number, making it easier for the observer to appreciate the total stress distribution in most materials. However, such a criterion predicts that the yield stresses measured in uniaxial tension and compression will be equal. Both dental hard tissues and restorative materials are brittle materials that present a higher strength in compression than in tension. Accordingly, a specific failure criterion for brittle types of materials must be used, ie, the

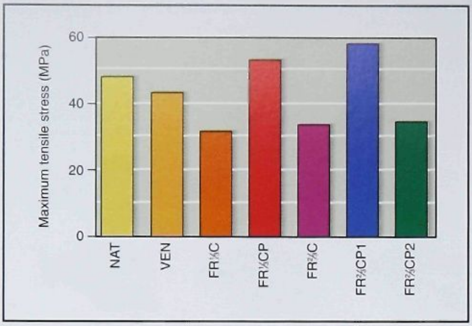

Fig 4 Maximum tensile stresses found in the incisal half of the crown facial surface for each experimental design.

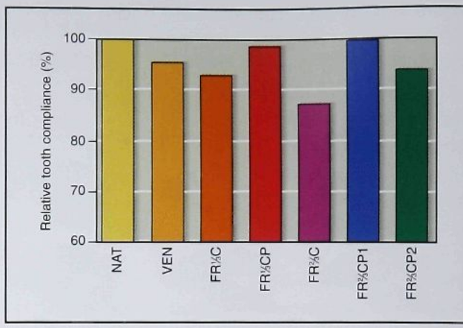

Fig 5 Relative tooth compliance or flexibility (as a percentage of the compliance of the intact tooth, NAT) calculated from the maximum horizontal displacement (x displacement) at the most incisal node of the enamel surface.

mVM criterion[23]: it incorporates the so-called strength differential effect, namely the ratio between compressive strength and tensile strength. For all test conditions very low mVM stresses were detected in the palatal half of the tooth (mainly subjected to compressive forces), whereas significant mVM stress concentrations were found on the facial side (mainly subjected to tensile forces).

The pattern of surface tangential stresses was similar for all test conditions: values were always positive except in the area of the load point where, as expected, it was highly negative. The tooth can be analyzed in 3 portions:

- The most cervical part of the tooth, especially the dentinoenamel junction, exhibited high levels of stress.
- The cervical half of the crown was always the most quiescent area, with stresses on all restored teeth being substantially lower than the intact enamel. This can be explained by the cervical overcontour of the veneer, the ceramic layer at this level being actually thicker than the preexisting enamel. The reasons for this design were justified above.
- In the incisal half of the crown, another maximum of tensile stresses was always present (Fig 3). This value is reported in Fig 4 for each restorative design. It is mainly this part of the tooth that exhibited major differences between test conditions. The maximum stresses at the surface of the ceramic were here generally lower when compared to the surface of intact enamel (49 MPa), except for FR⅓CP (54 MPa) and FR⅔CP1 (59 MPa). Test condition VEN showed a pattern of stresses similar to the intact tooth (Fig 3), as did fractured teeth restored with minimal veneers and a dentin-like composite buildup (FR⅓CP and FR⅔CP1). The lowest stresses were observed for

fractured teeth restored without composite buildup (FR⅓C and FR⅔C).

The relative tooth compliances (rated as a percentage of the compliance of the intact tooth, NAT) are presented in Fig 5. All experimental designs showed a loss of resilience when compared to the intact tooth (100%), FR⅔C being the stiffest, with a relative compliance of 87%. Compliances close to the original tooth were found for FR⅓CP and FR⅔CP1 (relative values of 99.0% and 99.9%, respectively), corresponding again to fractured teeth restored with minimal veneers and a composite buildup that substituted for the loss of dentin.

Discussion

Relevance of 2-D FE model

When it comes to the analysis of the tooth crown portion, the accuracy of 2-D plane-strain FE analyses considered in a buccolingual cross section was demonstrated on several occasions and validated by experimental strain measurement.[24-26] Three-dimensional models, although more realistic, present coarser meshes that would not allow the fine representation of thin layers such as the luting composite or preparation details such as marginal chamfers.[27] Two-dimensional FE models with plane-strain conditions are therefore commendable because of their improved performance in terms of element and simulation quality. In the present study, the assumption was that force causing traumatic impact travels in the 2-D sagittal plane.

Relevance of selected boundary conditions

Fixed displacement. Generally speaking, when local stress distributions in a crown are studied, fixation of the model is prescribed along the cross section of the root. Because the model is 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. In addition, the enamel surface at the crown-root junction shows a distinct stress peak. This can be explained by the thin enamel as well as the change of material properties (enamel-dentin transition). Such subtle details would require a more precise model definition and further study. Owing to the abovementioned reasons, no conclusions can be drawn from the high levels of tensile stresses encountered in the root portion of the crown.

Load application. The setup of the present study corresponds to a challenging situation for a veneered maxillary incisor. As demonstrated by the mVM stresses (Fig 3), the simulation of a facial impact was chosen because it generates harmful tensile stresses at the surface of the veneer. A palatal load or a vertical load on the incisal edge would have produced compressive stresses on most of the restoration, thereby reducing the ability of the present analysis to discriminate between different restorative designs.

The biomimetic principle

The modest results of the present study may constitute a supplementary link between restorative dentistry and a newly emerging interdisciplinary material science called "biomimetics."[28] This modern concept involves investigation of both structures and physical functions of biologic "composites" and the designing of new and improved substitutes. In restorative dentistry, biomimetics starts with the understanding of hard tissue arrangement and related stress distribution within the intact tooth.[26] Enamel and dentin form a composite structure that provides a tooth with unique characteristics[29]: on one hand, the hardness of enamel protects the soft underlying dentin, yet the crack-arresting effect of dentin and of the thick collagen fibers at the dentinoenamel junction[30] compensate for the inherently brittle nature of enamel. This structural and physical interrelationship between an extremely hard tissue and a more pliable softer tissue provides the natural tooth with its unique ability to withstand masticatory and thermal loads during a lifetime. Because of the improvement of adhesive procedures and the development of restorative materials, the behavior of the enamel-dentin complex can be partially mimicked. In this context it seems reasonable to conclude that new restorative approaches should not aim to create the strongest restoration, but rather a restoration that is compatible with the mechanical and biologic properties of underlying dental tissues—the biomimetic principle. The dramatic consequences of the "biomechanical mismatch" between tooth and restoration can be found in the literature. A simulated impact study by Stokes and Hood[15] showed the problematic root fracture pattern generated with stiff restorations (gold crowns, metal ceramics), whereas teeth veneered with bonded porcelain performed similar to intact teeth. Certain types of veneers, however, can be very sturdy: Andreasen et al[11] showed the excessive resistance of bonded porcelain veneers when it comes to the restoration of crown-fractured incisors.

Optimization of restorative design: Low stress versus high compliance

The present study comes as a valuable complement to the previous works of Andreasen and coworkers[10,11] and Stokes and Hood.[15] It shows, using stress distribution and resilience as indicators, how optimal intermediate performance can be obtained by modulating the restorative design. In the present work, a correlation logically emerges between the maximum stresses and the tooth compliance, with the most strained structures showing the most elevated stresses. Restorative designs demonstrating a stress pattern similar to the tooth also happened to have almost the same compliance (FR⅓CP, FR⅔CP2). The latter constitutes an essential quality in any structure; otherwise it would be unable to absorb the energy of a traumatic blow. In other words, a compliant restoration will cushion a sudden blow by bending elastically under the load. Up to a point, the more resilient a structure the better.[31] In our model the natural tooth gave the highest compliance. In this context it is interesting to note the findings of Stokes and Hood,[15] who showed that in an impact situation the intact tooth absorbs the highest energy of fracture when compared to teeth restored with veneers or different types of crowns. The compliance of the intact tooth was therefore taken as the biomimetic reference for the calculation of the relative compliance of our experimental models.

High-compliance designs

Among modern dental materials, ceramics best feature the physicomechanical characteristics of enamel in terms of elastic modulus, fracture strength, hardness, and thermal expansion. Stiffness and hardness of dentin are much lower and more likely to be simulated by composite resin materials. Because of their elastic modulus, composites alone are not able to restore the loss of stiffness following tooth preparation and the related loss of enamel.[16] It is therefore logical that there should be similarities in the stress pattern and compliance of intact teeth and restored teeth incorporating ceramic and composite as enamel and dentin substitutes, respectively (FR⅓CP and FR⅔CP2). The configuration of the veneer could still be optimized to fit exactly the stress distribution of the tooth by increasing ceramic thickness at the incisal level and removing the cervical overcontour. Even though the combination of composite and ceramic seems best to reproduce the behavior of the intact tooth, one may still criticize the high thermal expansion of certain composite resins. The latter proved to have a significant influence in the development of ceramic postbonding flaws, even when used only as a thick luting agent.[32–34]

Low-stress designs

From Figs 4 and 5 it can be concluded that the maximum tensile stress reached its lowest value in the restorative designs showing the lowest relative compliance (FR⅓C, FR⅔C, and FR⅔CP2). These restored teeth had extensive ceramic thickness taking the place of preexisting dentin. This simplified design is often preferred by clinicians because it is straightforward and features optimal esthetic results (Fig 1). The dental technician can use specific porcelains to accurately reproduce the anatomy and optical characteristics of dentin, ie, opaque dentin for adequate translucence and fluorescent stains for an adequate luminescence. Most composite resins do not allow such precise characterization.

It seems obvious that a low surface stress might be preferred in a restoration since this might reduce the risk of localized fracture. However, with regard to biomimetics, ceramic-only designs (FR⅓C and FR⅔C) may present an excessive strength. In the case of recurrent trauma this could generate a fatal root fracture or at least the loss of an additional portion of the tooth. These assumptions now require experimental validation using the latest generation of dentin adhesives, as the dentin bond proves to be an essential determinant in the fracture pattern and fracture mechanics of the tooth.[35]

Conclusions

The treatment of crown-fractured incisors was investigated using different designs of facial porcelain veneers with and without underlying composite buildup. A 2-D FE model simulating an incisal impact situation was used to calculate the stress distributions and tooth resilience.

- Tensile stresses were generated on the facial surface of the porcelain laminates with a similar pattern for all test conditions, the cervical part of the crown being the most quiescent area.
- Substantial differences appeared in the incisal half of the crown. Fractured teeth restored with ceramic and a dentin-like composite buildup showed stress patterns similar to the intact tooth. The lowest stresses were observed for extensively fractured teeth restored without composite buildup (ceramic only).
- The natural tooth showed the highest tooth compliance or flexibility and all restorative designs featured increased tooth stiffness. However, the original tooth compliance was almost recovered when composite was used to replace the missing dentin, with the porcelain acting only as a facial and incisal enamel substitute.

When restoring crown-fractured incisors, the use of ceramic alone generates low stress concentrations but also less compliant restored teeth. Tooth resilience and stress distribution can be modulated by the combination of composite resins and ceramics. Optimized configurations can be reached to reproduce the original biomechanical behavior of the intact tooth.

Acknowledgments

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References

1. Calamia JR. Clinical evaluation of etched porcelain veneers. Am J Dent 1989;2:9–15.
2. Calamia JR. The current status of etched porcelain veneer restorations. J Indiana Dent Assoc 1993;72:10–15.
3. Rucker LM, Richter W, MacEntee M, Richardson A. Porcelain and resin veneers clinically evaluated: 2-year results. J Am Dent Assoc 1990;121:594–596.
4. Kourtkouta S, Walsh TT, Davis LG. The effect of porcelain laminate veneers on gingival health and bacterial plaque characteristics. J Clin Periodontol 1994;21:638–640.
5. Peumans M, Van Meerbeek B, Lambrechts P, Vuylsteke-Wauters M, Vanherle G. Five-year clinical performance of porcelain veneers. Quintessence Int 1998;29:211–221.
6. Fradeani M. Six-year follow-up with Empress veneers. Int J Periodontics Restorative Dent 1998;18:216–225.
7. Van Gogswaardt DC, Van Thoor W, Lampert F. Clinical assessment of adhesively placed ceramic veneers after 9 years (abstract 1,178). J Dent Res 1998;77:779.
8. Magne P, Magne M, Belser U. Natural and restorative oral esthetics. Part II: Esthetic treatment modalities. J Esthet Dent 1993;5:239–246.
9. Belser U, Magne P, Magne M. Ceramic laminate veneers: Continuous evolution of indications. J Esthet Dent 1997;9:209–219.
10. Andreasen FM, Daugaard-Jensen J, Munksgaard EC. Reinforcement of bonded crown fractured incisors with porcelain veneers. Endod Dent Traumatol 1991;7:78–83.
11. Andreasen FM, Flugge E, Daugaard-Jensen J, Munksgaard EC. Treatment of crown fractured incisors with laminate veneer restorations. An experimental study. Endod Dent Traumatol 1992;8:30–35.

12. Walls AW. The use of adhesively retained all-porcelain veneers during the management of fractured and worn anterior teeth: Part 1. Clinical technique. Br Dent J 1995;178:333–336.
13. Walls AW. The use of adhesively retained all-porcelain veneers during the management of fractured and worn anterior teeth: Part 2. Clinical results after 5 years of follow-up. Br Dent J 1995;178:337–340.
14. Munksgaard EC, Hojtved L, Jorgensen EH, Andreasen JO, Andreasen FM. Enamel-dentin crown fractures bonded with various bonding agents. Endod Dent Traumatol 1991;7:73–77.
15. Stokes AAN, Hood JAA. Impact fracture characteristics of intact and crowned human central incisors. J Oral Rehabil 1993;20:89–95.
16. Reeh ES, Ross GK. Tooth stiffness with composite veneers: A strain gauge and finite element evaluation. Dent Mater 1994;10:247–252.
17. Highton R, Caputo AA, Matyas J. A photoelastic study of stress on porcelain laminate preparations. J Prosthet Dent 1987;58:157–161.
18. Craig RG. Restorative Dental Materials, ed 6. St Louis: Mosby, 1980:76.
19. Anusavice KJ, Hojjatie B. Influence of incisal length of ceramic and loading orientation on stress distribution in ceramic crowns. J Dent Res 1988;67:1,371–1,375.
20. Watts DC, El Mowafy OM, Grant AA. Temperature-dependance of compressive properties of human dentin. J Dent Res 1987;66:29–32.
21. Sorensen JA, Avera SP, Materdomini D. Marginal fidelity and microleakage of porcelain veneers made by two techniques. J Prosthet Dent 1992;67:16–22.
22. Gere JM, Timoshenko SP. Analysis of stress and strain. In: Gere JM, Timoshenko SP (eds). Mechanics of Materials, ed 3. Boston: PWS, 1990:378–460.
23. De Groot R, Peters MCRB, De Haan YM, Dop GJ, Plasschaert AJM. Failure stress criteria for composite resin. J Dent Res 1987;66:1,748–1,752.
24. Morin DL, Cross M, Voller VR, Douglas WH, DeLong R. Biophysical stress analysis of restored teeth: Modeling and analysis. Dent Mater 1988;4:77–84.
25. Morin DL, Cross M, Voller VR, Douglas WH, DeLong R. Biophysical stress analysis of restored teeth: Experimental strain measurement. Dent Mater 1988;4:41–48.
26. Magne P, Versluis A, Douglas WH. Rationalization of incisor shape: Experimental-numerical analysis. J Prosthet Dent 1999;81:345–355.
27. Korioth TWP, Versluis A. Modeling the mechanical behavior of the jaws and their related structures by finite element (FE) analysis. Crit Rev Oral Biol Med 1997;8:90–104.
28. Sarikaya M. An introduction to biomimetics: A structural viewpoint. Microsc Res Tech 1994;27:360–375.
29. Kraus BS, Jordan RE, Abrams L. Histology of the teeth and their investing structures. In: Kraus BS, Jordan RE, Abrams L (eds). Dental Anatomy and Occlusion. Baltimore: Williams & Wilkins, 1969:135.
30. Lin CP, Douglas WH. Structure-property relations and crack resistance at the bovine dentin-enamel junction. J Dent Res 1994;73:1,072–1,078.
31. Gordon JE. Strain energy and modern fracture mechanics. In: Gordon JE (ed). Structures: Or Why Things Don't Fall Down. New York: DaCapo, 1978:70–109.
32. Barghi N, Berry TG. Post-bonding crack formation in porcelain veneers. J Esthet Dent 1997;9:51–54.
33. Magne P, Kwon KR, Belser U, Hodges JS, Douglas WH. Crack propensity of porcelain laminate veneers: A simulated operatory evaluation. J Prosthet Dent 1999;81:327–334.
34. Magne P, Versluis A, Douglas WH. Effect of luting composite shrinkage and thermal loads on the stress distribution in porcelain laminate veneers. J Prosthet Dent 1999;81:335–344.
35. Versluis A, Tantbirojn D, Douglas WH. Why do shear bond tests pull out dentin? J Dent Res 1997;76:1,298–1,307.