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Effect of Stiffness of Cement on Stress Distribution in Ceramic Crowns

Xu Dong DONG[1], Hao Ran WANG[2], Brian W DARVELL[3], Sai Huen LO[4]

Objective: *To analyse the stress distribution in monolithic- and bilayer-structured ceramic crowns by means of the finite element method (FEM), as a function of elastic modulus of the core ceramic, Ecor, and that of the cement used to lute the crown, Ecem, with a view to identifying an ideal stiffness for the cement.*

Methods: *A two-dimensional axisymmetric FEM model was created to represent tooth structure with a cemented ceramic crown in place. The value of Ecor was set at 70, 100, 150 and 200 GPa representative of the range of commercially available materials. For the veneer, Even, it was set at 70 GPa, while that of the cement, Ecem, was varied from 0.2 to 200 GPa, in a 1-2-5 sequence. The tensile stress along the x-direction was calculated as an indication of the local sensitivity of the model to failure at a given load.*

Results: *The stiffness of both the core ceramic and of the cement strongly affected the tensile stress distribution. With an increase in Ecor, the stress was increased for low Ecem. Also, the stress in the cement tended to increase with an increase in Ecem. However, the stress in the dentine varied little over the ranges studied here. For Ecor > Ecem, the stress in the core for low Ecem was higher than for high Ecem.*

Conclusion: *It is suggested that the modulus of elasticity for the cement used to lute the ceramic crown plays a critical role in improving the fracture resistance of ceramic restorations.*

Key words: *cement, ceramic crown, finite element method, modulus of elasticity,*
Chin J Dent Res 2016;19(4):217–223; doi: 10.3290/j.cjdr.a37146

Full-ceramic restorations can exhibit superior tooth mimicry compared with metal-ceramic devices. However, they have a crucial weakness: high failure rate for crowns in clinical service, especially in premolar and molar sites. To improve strength, bilayer-structured restorations have been developed[1,2]. The load bearing capacity of such ceramic restorations is more dependent on the strength and design of the core material. Therefore, it is appropriate to investigate the stress distribution in bilayer full-ceramic crowns to understand their behaviour and thus potentially improve their design.

The purpose of the present study was to analyse the stress distribution in monolithic- and bilayer-structured ceramic crowns by means of the finite element method (FEM), as a function of the elastic modulus of the core ceramic, Ecor, and that of the cement used to lute the crown, Ecem, with a view to identifying an ideal stiffness for the cement. The stress distribution, magnitude and orientation throughout a loaded structure depends not only on the loading configuration but also on the geometry of the structure and the properties of its materials. One of the advantages of FEM is the ability to investigate the influence of property variation to gain a fundamental understanding of the relations amongst factors under consideration. The stiffness of the cement and its effect on the stress in the ceramic are of particular interest.

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Materials and methods

In creating FEM models of crowns and tooth structure, simplification of their structure is made. Notably, the three-dimensional asymmetric tooth structure is often modelled by using a two-dimensional axisymmetric representation instead[2]. Furthermore, Huiskes et al[3] pointed out that, evidently, an inaccurate 3D model is less useful in obtaining positive results than using an accurate 2D model. They remarked that parametric analyses do not necessarily need to be carried out with an expensive anatomic model, but can often be limited to a simplified, general representation. In this study, therefore, an axisymmetric FEM model was developed for a second mandibular molar restored by a full-ceramic crown. The model conditions and assumptions were:

- Enamel tissue was completely removed and replaced by a full coverage ceramic crown with a variable stiffness core. The occlusal thickness of the crown was set at 2.0 mm, and the veneer and core were of equal thickness.
- The ceramic crown was luted on to sound dentine.
- A uniform cement layer was set at 0.1 mm thickness, perfectly bonding the ceramic to the dentine.
- The influence of the periodontal ligaments were assumed to be negligible.
- The ceramic, cement and dentine were assumed to be homogeneous, linearly elastic and isotropic.

The dimensions of the model were selected to be consistent with the values identified by Wheeler for an average molar crown[4]. A uniformly-distributed load of 600 N was applied normally to the occlusal surface of the crown on the central axis over a 1.0 mm radius circle. The individual areas of contact between opposing teeth (wear facets) have been reported[5] to be in the range of 1 to 4 mm^2. The loaded area here was 3.14 mm^2. The values for the modulus of elasticity of the ceramic components were set at 70 GPa for the veneer porcelain, Even, and 70, 100, 150 and 200 GPa for Ecor. These values were broadly representative of the range of values for commercially available ceramics. Ecem was varied from 0.2 to 200 GPa in a 1-2-5 sequence, although the values for known cements available do not usually exceed 20 GPa. The elastic modulus of dentine was set at 10 GPa according to Scherrer's investigation[6]. The Poisson ratios of the ceramic, cement and dentine used were set at 0.25, 0.30 and 0.31, respectively. These data are listed in Table 1.

The FEM analysis was carried out using software (FACILE, version 3.0, Civil Engineering Department, The University of Hong Kong) on a workstation (IBM 6091/90, IBM Corporation, Texas, USA), under the UNIX operating system. The code included four modules for 1) establishing and meshing the FEM model; 2) input parameter values and setting the load as well as boundary conditions; 3) calculating the solution; and 4) graphical output of contours and the vector field for the model[7].

For a good approximation of the structure under the assumed simplified conditions, the most important factors are element mesh density and element type. The model here was composed of 2453 triangular elements with a total of 5052 nodes (Fig 1). The adaptive meshing capability of the code was employed to minimise the error associated with a lack of convergence of the nodal stress. By this technique, the mesh density was progressively increased until sufficient accuracy for the stresses was obtained[8,9]. All normal, shear and principal stresses were calculated. The boundary conditions were to fix the y-axis (i.e. the load axis) at the central axis of the model with a free x-axis at the bottom of the model.

The magnitude of the stress gives an indication of the local sensitivity of the model to failure at a given load. The results were focused on the stress state in the ceramics, with variation in stiffness and structure as a function of the elastic modulus of the cement. The most probable site of failure initiation lies on the

Table 1 Elastic moduli and poisson ratios used in the FEM calculation.

Material	Modulus of elasticity / GPa	Poisson ratio
Dentine	10	0.31
Veneer	70	0.25
Core	70, 100, 150, 200	0.25
Cement	0.2, 0.5, 1, 1.5, 2, 5, 10, 15, 20, 50, 100, 150, 200	0.30

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cementation surface of the ceramic, directly beneath the applied load, although stress concentrations may occur around the corners of the FEM model of the crown[10]. Accordingly, the magnitude of the x-direction tensile stress along the central axis was examined in detail, as this represented the path of the steepest descent for this stress, in the various components of the structure. This choice was made on the basis that failure of ceramic restorations is strongly associated with tensile stress.

Results

According to the FEM solutions, the stiffness of the core strongly affected the stress distribution. For the bilayer structures, Ecor had a strong effect, with an increase in this value, the tensile stress was increased using low Ecem, but tended to decrease gradually with an increase in Ecem (Fig 2).

The value of Ecem strongly influenced the stress distribution, not only in the ceramic but also in the cement itself. However, the tensile stress in the dentine varied little for the ranges studied here. In the bilayer structures, the stress in the ceramic tended to vary smoothly with an increase in Ecem. Using Even = Ecor as a reference condition, i.e. a monolithic structure, as the value of Ecem approached Ecor the stress in the ceramic decreased (Fig 3).

With Ecor > Ecem, the stress for low Ecem was higher than for high Ecem. But for Ecem > Ecor, the peak stress in the cement became very high, although the stress in the ceramic tended to be reduced (Fig 3). However, it was surprising to see that no stress concentration occurred at the veneer-core interface with an increase in Ecor (Figs 2 and 3).

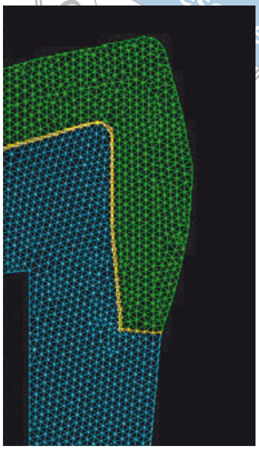

Fig 1 FEA meshing model (from the screen capture of the program display).

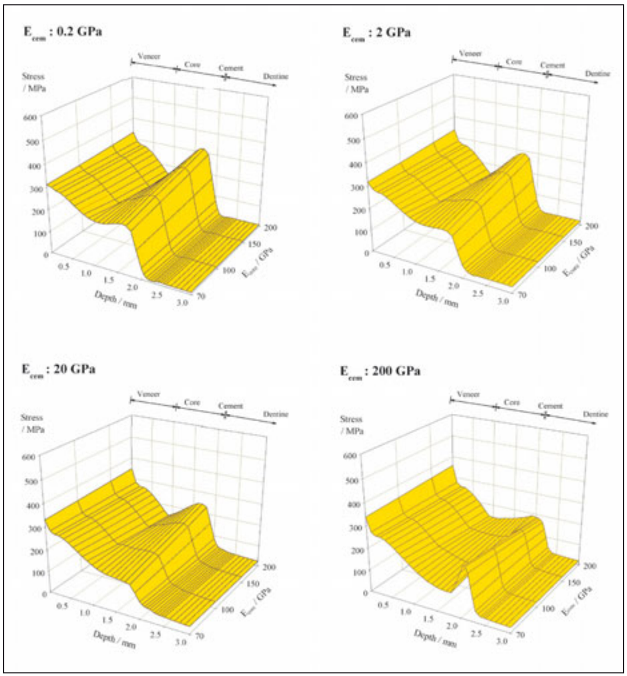

Fig 2 Variation in the x-direction tensile stress with depth on the central axis vs the elastic modulus of the core ceramic for four values of Ecem: 0.2, 2, 20 and 200 GPa. The front boundary of the results surface represents the monolithic structure, the remainder is bilayer.

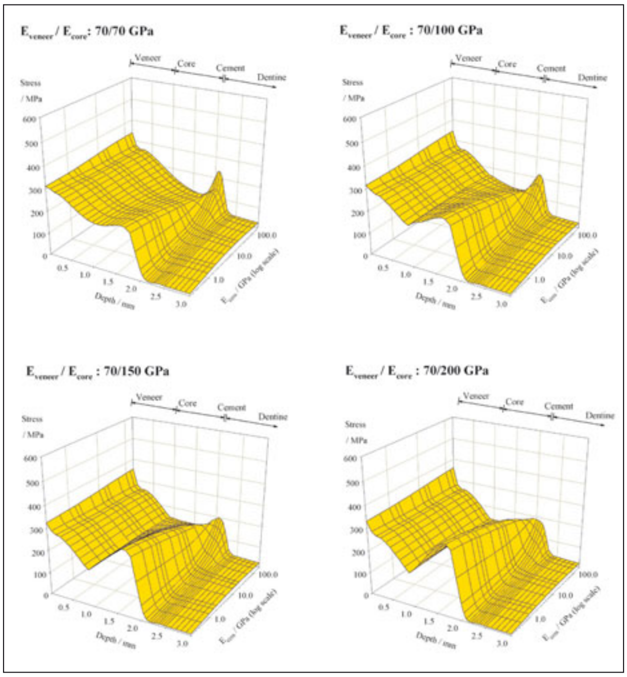

Fig 3 Variation in the x-direction tensile stress with depth on the central axis vs the elastic modulus of the cement for four values of Ecor: 70, 100, 150 and 200 GPa. Even was set at 70 GPa, hence for Ecor = 70 GPa, the model represents a monolithic structure, where the other three were a bilayer.

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Discussion

According to Anusavice et al[11], the fracture resistance of full-ceramic restorations is strongly dependent on crown thickness, cement, crown configuration and the elastic modulus of the supporting tooth substrate or other materials. Furthermore, it has been suggested that ceramic and cement thickness, ceramic and cement modulus, and load position should be taken into account for the restoration design to minimise clinical failure[12]. The present results extend from outcomes of those reports to include the relative values of the elastic moduli of the components.

The stiffness of the cement certainly affected the stress distribution in the crown, but since such ceramic restorations are usually constructed by a layering technique, for example, as a veneer and core, attention needs to be given to this aspect as well. However, the present results suggest that no unexpected effects occur at the interface, even when the modulus mismatch between the veneer and core is large (Fig 2). Nevertheless, the stress in the core reduced as the cement became stiffer (Fig 3).

The purpose of the cement is primarily one of retention, keeping the crown in place. However, while the cement transfers stress from ceramic to dentine, it may also form a ‘sandwich’ structure for the whole restored tooth in the sense that it creates an integrated object that behaves as one entity[13]. The stress transfer is influenced by the adhesion of the cement at both interfaces. In practice, the cement thickness under a crown is commonly observed to be about 0.1 mm, although the acceptable thickness of cement is claimed by Scherrer et al[14] and others to be approximately 0.03 mm. However, Liu et al[15] were of the view that cement thickness is not very important to stress distribution in ceramics, in comparison with the influence of loading conditions or the cement modulus. However, for an FEM model, the thickness of the cement should be consistent with the clinical observation[16]. Hence, here the thickness of the cement was set at 0.1 mm, as used in FEM calculations by Dérand and Herø[17]. Also, a special computer code is required to mesh such a thin layer in an FEM model for sufficient accuracy, as was employed here[18].

In Figure 3, it can be seen that the tensile stress is concentrated at the cement layer if Ecem is increased beyond Ecor (Fig 3). However, this stress concentration is unlikely to occur in practice because no known cement is stiff enough to meet that condition. Even so, Ecem slightly reduced the stress in the core ceramic as Ecem was increased, consistent with results reported by Dérand and Herø[17].

Three classes of cement are commonly used for bonding ceramic restorations clinically, i.e. zinc phosphate, glass ionomer and resin-based cements (the misnaming of the resin-based materials as cements for simplicity was ignored as they are not cements in the strict sense), with elastic moduli ranging from 1 to 20 GPa, but calculations for the values of Ecem up to 200 GPa were made here, in order to better observe the effect of the stiffness of the lute on the stress distribution. However, it has to be said that zinc phosphate is rarely used for bonding full-ceramic restorations in practice because of a high risk of failure due its poorer adaptation[19-23]. Similarly, there is a high risk of failure with the glass ionomer, which has been suggested to be due in part to high setting expansion, and thus is also not appropriate for such restorations[22]. Subsequent expansion due to water absorption is also a known problem.

According to the present results, high stiffness cement is able to reduce the stresses in the core (Fig 2). The stress curve in the ceramic with a high stiffness core became smooth when the stiffness of the cement was matched with the core. However, it is probably more important that these results indicate that the magnitude of the stress in the lute increases with an increase in its elastic modulus. When high shear stresses arise in the cement layer, the cement film may have pulverised, and the restoration would have both decreased support and reduced retention to the dentine. If this happened, such full ceramic crowns would have a high risk of failure[24]. Hence, a luting cement with a high modulus of elasticity and low bonding strength, such as zinc phosphate, cannot be recommended in this application.

The effect of various cements on the fracture resistance of ceramic crowns have been investigated[11,14,21] and it was pointed out that the load at the fracture of a resin-luted crown was significantly greater than for other cements[25-28]. Scherrer et al[14] reported that the fracture strength of ceramic discs bonded with resin-based cement was approximately 75% higher than when zinc phosphate cement was used. According to Heintze et al[29], the average longevity of ceramic crowns adhesively luted with resin-based cement was appropriately three times as long as with zinc phosphate cement. The implication of this is that strong adhesion to the abutment teeth is more important than ceramic strength for survivability[29,30]. Furthermore, it has been found that etching the ceramic and then polymer-coating its tension surface can also significantly improve the strength[31]. Anusavice et al[10] investigated the cement effect on the tensile stress in the occlusal surface of ceramic crowns using FEM and reported that the stress decreased when Ecem was high, consistent with results

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reported by Farah et al[32]. However, high fracture resistance was demonstrated for crowns luted by resin-based cement with low Ecem. There was speculation that the resin material enhanced the transfer of stress away from the ceramic crown better than other cements[10,33].

The type of cement affects the fracture resistance of bonded ceramics and has been demonstrated in many experiments[21,22,34-38]. Some cements can increase fracture resistance but others are detrimental, for example, a fluoride-releasing resin caused fracture during 2-month storage[22]. Other work has demonstrated that resin-based cement used with an acid-etching process was able to increase fracture resistance[21,34-37].

A 1.3% overall failure rate at 2 years for 143 anterior and 254 posterior glass-ceramic crowns luted with a light-activated resin has been reported[39], while at 4 years the failure rate reached 2.9%[40]. In contrast, 3-year failure rates for molar, premolar and anterior glass-ceramic crowns bonded with zinc phosphate cement were 35.3%, 11.8% and 3.5%, respectively[41]. Malament et al found that survival of glass-ceramic crowns at 14 years was improved significantly with resin-based luting cements[20]. Burke et al have demonstrated that bonding systems provide higher bonding strength than plain cementation, which does not involve such bonding agents[34,36], so a luting cement accompanied by a dentine bonding system may produce a beneficial synergistic effect for ceramic restorations. It would appear that the luting cement plays a substantial role in the achievement of high fracture resistance for ceramic restorations[42-44].

The possible mechanisms of this phenomenon have been proposed as follows:

- The bonding agent and resin lute transfer stress better than zinc phosphate cement, perhaps because of the poorer penetration of the latter into flaw tips[10]. The maximum tensile stress in the ceramic is reduced by a bonded lute[45-47].
- Acid-etching the ceramic may increase the radius of curvature of crack tips so as to decrease stress concentration there[10].
- Resin cement decreases the shear strain along the internal surface as a result of chemical bonding between ceramic, cement and dentine[10].
- Acid-etching increases surface roughness and the number of undercuts, thereby increasing the surface area for mechanical retention[48].
- Crack-bridging may improve the clinical performance of ceramic crowns luted with resin. Rosenstiel et al suggested the bonding cement itself reinforces the ceramic [31]. They supposed that the filling of cracks by silane molecules and to the bonding of resin across the mouths of cracks was effectively fusing flaws and thus improving fracture resistance.
- In addition to the effect of chemical bonding between resin and ceramic phases, silane also promoted wetting and enabled the resin to flow easily and fill the undercuts of the bonded ceramic surface[48].

A cement adaptation theory was proposed by Thompson et al[23]. They indicated that transfer of stress was better accomplished by a material with a high modulus of elasticity. Furthermore, good adaptation between the restoration, luting cement, and the underlying tooth or the restored abutment core is critical for the success of a ceramic restoration. However, if the lute failed in a cohesive manner, this adaptation would not be a factor in restoration success. Their findings thus support the idea that using resin-based cement on an acid-etched ceramic surface is the preferred technique. It can be seen that the wetting and flow properties of the luting cement may be the key factors controlling cement adaptation on the ceramic surface. Cement adaptation (Af) has been defined as the fractional portion of the total length of the cement-ceramic interface, in which intimate physical contact between the cement and ceramic could be observed under SEM[23]. It was clear that the gap between the ceramic and a cement with low adaptability was significantly larger than otherwise. Thus for resin-based (RB), glass ionomer (GI) and zinc phosphate (ZP) cements, the rank order of the values of Af was RB > GI > ZP. This mechanism may explain why ZP, despite having higher Ecem cannot transfer stress well, while RB, despite lower Ecem, is better. In addition, strong cement is also important. ZP has higher Ecem but lower compressive strength than RB. ZP has lower plasticity (0.1% to 0.2%) compared with RB (5%)[49], and, as indicated by White et al[50], the strengths of the cements are also ranked RB > GI > ZP. The FEM solutions of the present study (Fig 3) showed that the stress in the cement layer indeed increases with Ecem. Hence, using RB to bond ceramic restorations may give lower stress and lower risk of failure in the cement layer than other cements. Dérand and Herø[17] pointed out that loading *in vivo* may induce stresses that result in a break in the cement layer, and that such failure may reduce the support and fixation of the restoration. Therefore, for successful ceramic restorations, it is crucial to achieve greater interfacial bond strength. From the results of Scherrer et al[51] and Lin et al[52], it is suggested that increasing this bond strength may be more advantageous than increasing the flexural strength of the ceramic.

Morris et al[53] also pointed out that the mechanism generating the tensile stresses at the cementation

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surface was elastic modulus mismatch between the ceramic and cement, not the bending of the ceramic. The present results support this, but since the modulus of elasticity of the resin-based materials is low, the mechanism, where they confer improved fracture resistance on ceramic crowns will need further investigation.

Conclusions

It is concluded that ceramic crowns with a high elastic modulus core need to be bonded with high elastic modulus cement to reduce the risk of failure. From a clinical viewpoint, although this is likely to decrease the stress in the core, stress-related problems would occur in the cement itself and should not be ignored; damage to the cement layer risks ceramic failure. This crucial role needs to be recognised in selecting a cement for clinical use, although compromise is required in that adaptation, bonding and strength as well as stiffness are needed. The differences in elastic moduli of the current veneer and core ceramics do not appear to present a problem with respect to stress concentration at their interface.

Conflicts of interest

The authors reported no conflicts of interest related to this study.

Author contribution

Dr Xudong Dong for the experimental design, operation and data analysis, and writing of the manuscript; Dr Haoran Wang for editing and checking the computer program, and the data analysis; Dr Brain W Darvell and Dr Saihuen Lo for their supervision, data analysis and manuscript revision.

(Received July 01, 2016, accepted Sep 25, 2016)

References

1. Carrier DD, Kelly JR. In-Ceram failure behavior and core-veneer interface quality as influenced by residual infiltration glass. J Prosthodont 1995;4:237–242.
2. Pospiech P, Rountree P, Rammelsberg P, Unsold F. In vitro investigations on the fracture strength of all-ceramic posterior bridges of Empress 2. J Dent Res 1999;78:307 Abstr.
3. Huiskes R, Chao EY. A survey of finite element analysis in orthopedic biomechanics: the first decade. J Biomech 1983;16:385–409.
4. Wheeler R. A Textbook of Dental Anatomy and Physiology. Philadephia: W.B. Saunders, 1964.
5. Kelly JR. Ceramics in restorative and prosthetic dentistry. Ann Rev Mater Sci 1997;27:443–468.
6. Scherrer SS, de Rijk WG. The fracture resistance of all-ceramic crowns on supporting structures with different elastic moduli. Int J Prosthodont 1993;6:462–467.
7. Cheung YK, Lo SH, Leung AYT. Finite Element Implementation. Oxford: Blackwell Science, 1996.
8. Lee CK, Lo SH. An automatic adaptive refinement finite element procedure for 2D elastostatic analysis. Int J Numer Methods Eng 1992;35:1967–1989.
9. Lee CK, Lo SH. An automatic adaptive refinement finite element procedure for 3D stress analysis. Finite Elem Anal Des 1997;25:135–166.
10. Anusavice KJ, Hojjatie B. Tensile stress in glass-ceramic crowns: effect of flaws and cement voids. Int J Prosthodont 1992;5:351–358.
11. Anusavice KJ, Tsai YL. Stress distribution in ceramic crown forms as a function of thickness, elastic modulus, and supporting substrate. In: Bumgardner JD, Puckett AD (eds). Proceedings of 16th Southern Biomedical Engineering Conference. Piscataway, Institute of Electrical and Electronics Engineers, 1997:264–267.
12. Rafferty BT, Janal MN, Zavanelli RA, et al. Design features of a three-dimensional molar crown and related maximum principal stress. A finite element model study. Dent Mater 2010;26:156–163.
13. Yucel MT, Yondem I, Aykent F, Eraslan O. Influence of the supporting die structures on the fracture strength of all-ceramic materials. Clin Oral Investig 2012;16:1105–1110.
14. Scherrer SS, de Rijk WG, Belser UC, Meyer JM. Effect of cement film thickness on the fracture resistance of a machinable glass-ceramic. Dent Mater 1994;10:172–177.
15. Liu B, Lu C, Wu Y, Zhang X, Arola D, Zhang D. The effects of adhesive type and thickness on stress distribution in molars restored with all-ceramic crowns. J Prosthodont 2011;20:35–44.
16. Fu G, Deng F, Wang L, Ren A. The three-dimension finite element analysis of stress in posterior tooth residual root restored with postcore crown. Dent Traumatol 2010;26:64–69.
17. Dérand T, Herø H. Bond strength of porcelain on cast vs. wrought titanium. Scand J Dent Res 1992;100:184–188.
18. Shahrbaf S, vanNoort R, Mirzakouchaki B, Ghassemieh E, Martin N. Effect of the crown design and interface lute parameters on the stress-state of a machined crown-tooth system: a finite element analysis. Dent Mater 2013;29:e123–e131.
19. Grossman DG, Nelson JW. The bonded Dicor crown. J Dent Res 1987;66:206 Abstr.
20. Malament KA, Socransky SS. Survival of Dicor glass-ceramic dental restorations over 14 years: Part I. Survival of Dicor complete coverage restorations and effect of internal surface acid etching, tooth position, gender and age. J Prosthet Dent 1999;81:23–32.
21. Groten M, Probster L. The influence of different cementation models on the fracture resistance of feldspathic ceramic crowns. Int J Prosthodont 1997;10:169–177.
22. Leevailoj C, Platt JA, Cochran MA, Moore BK. In vitro study of fracture incidence and compressive fracture load of all-ceramic crowns cemented with resin-modified glass ionomer and other luting agents. J Prosthet Dent 1998;80:699–707.
23. Thompson JY, Rapp MM, Parker AJ. Microscopic and energy dispersive X-ray analysis of surface adaptation of dental cements to dental ceramic surfaces. J Prosthet Dent 1998;79:378–383.
24. Dejak B, Mlotkowski A, Langot C. Three-dimensional finite element analysis of molars with thin-walled prosthetic crowns made of various materials. Dent Mater 2012;28:433–441.
25. Freitas AC Jr, Rocha EP, dos Santos PH, de Almeida EO, Anchieta RB. All-ceramic crowns over single implant zircon abutment. Influence of Young‘s modulus on mechanics. Implant Dent 2010;19:539–548.
26. Kelly JR, Rungruanganunt P, Hunter B, Vailati F. Development of a clinically validated bulk failure test for ceramic crowns. J Prosthet Dent 2010;104:228–238.

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27. Cui C, Sun J. Optimizing the design of bio-inspired functionally graded material (FGM) layer in all-ceramic dental restorations. Dent Mater J 2014;33:173–178.
28. Duan Y, Griggs JA. Effect of elasticity on stress distribution in CAD/CAM dental crowns: Glass ceramic vs. polymer-matrix composite. J Dent 2015;43:742–749.
29. Heintze SD, Rousson V. Fracture rates of IPS Empress all-ceramic crowns--a systematic review. Int J Prosthodont 2010;23:129–133.
30. Beier US, Kapferer I, Dumfahrt H. Clinical long-term evaluation and failure characteristics of 1,335 all-ceramic restorations. Int J Prosthodont 2012;25:70–78.
31. Rosenstiel SF, Gupta PK, Van der Sluys RA, Zimmerman MH. Strength of a dental glass-ceramic after surface coating. Dent Mater 1993;9:274–279.
32. Farah JW, Powers JM, Dennison JB, Craig RG, Spencer J. Effects of cement bases on the stresses and deflections in composite restorations. J Dent Res 1976;55:115–120.
33. Sen S, Guler MS, Guler C. Stress distributions on crown-luting cement-substrate system with finite element method. J Central South University 2012;19:2115–2124.
34. Burke FJ. The effect of variations in bonding procedure on fracture resistance of dentin-bonded all-ceramic crowns. Quintessence Int 1995;26:293–300.
35. Burke FJ, Qualtrough AJ, Hale RW. The dentine-bonded ceramic crown: an ideal restoration? Br Dent J 1995;179:58–63.
36. Burke FJ, Watts DC. Effect of differing resin luting systems on fracture resistance of teeth restored with dentine-bonded crowns. Quintessence Int 1998;29:21–27.
37. Burke FJ, Qualtrough AJ, Wilson NH. A retrospective evaluation of a series of dentin-bonded ceramic crowns. Quintessence Int 1998;29:103–106.
38. Burke FJ. Maximising the fracture resistance of dentine-bonded all-ceramic crowns. J Dent 1999;27:169–173.
39. Malament KA, Grossman DG. Clinical application of bonded Dicor crown: a two years report. J Dent Res 1990;69:299 Abstr.
40. Malament KA, Grossman DG. Bonded vs. nonbonded Dicor Crowns: four-year report. J Dent Res 1992;71:321 Abstr.
41. Moffa JP, Lugassy AA, Ellison JA. Clinical evaluation of dental restorative materials: three year study. J Dent Res 1988;67:118 Abstr.
42. Magne P, Schlichting LH, Paranhos MP. Risk of onlay fracture during pre-cementation functional occlusal tapping. Dent Mater 2011;27:942–947.
43. Salameh Z, Ounsi HF, Aboushelib MN, Sadig W, Ferrari M. Fracture resistance and failure patterns of endodontically treated mandibular molars with and without glass fiber post in combination with a zirconia-ceramic crown. J Dent 2008;36:513–519.
44. Addison O, Marquis PM, Fleming GJ. Adhesive luting of all-ceramic restorations--the impact of cementation variables and short-term water storage on the strength of a feldspathic dental ceramic. J Adhes Dent 2008;10:285–293.
45. Kelly JR. Clinically relevant approach to failure testing of all-ceramic restorations. J Prosthet Dent 1999;81:652–661.
46. Campos RE, Soares PV, Versluis A, de O Junior OB, Ambrosano GM, Nunes IF. Crown fracture: Failure load, stress distribution, and fractographic analysis. J Prosthet Dent 2015;114:447–455.
47. Ha SR. Biomechanical three-dimensional finite element analysis of monolithic zirconia crown with different cement type. J Adv Prosthodont 2015;7:475–483.
48. Lu R, Harcourt JK, Tyas MJ, Alexander B. An investigation of the composite resin/porcelain interface. Aust Dent J 1992;37:12–19.
49. Olio G, Espevik S. Stress/strain behavior of some dental luting cements. Acta Odontol Scand 1978;36:45–49.
50. White SN, Yu Z. Compressive and diametral tensile strengths of current adhesive luting agents. J Prosthet Dent 1993;69:568–572.
51. Scherrer SS, de Rijk WG, Belser UC. Fracture resistance of human enamel and three all-ceramic crown systems on extracted teeth. Int J Prosthodont 1996;9:580–585.
52. Lin CP, Douglas WH. Structure-property relations and crack resistance at the bovine dentine-enamel junction. J Dent Res 1994;73:1072–1078.
53. Morris DR, Kelly JR. Failure loads of bonded ceramics influenced by hydrostatic compressive stresses. J Dent Res 1995;74:220 Abstr.