Fracture resistance of zirconia-composite veneered crowns in comparison with zirconia-porcelain crowns

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The objectives were to evaluate the fracture resistance and stress concentration in zirconia/composite veneered crowns in comparison to zirconia/porcelain crowns using occlusal fracture resistance and by stress analysis using finite element analysis method. Zirconia substructures were divided into two groups based on the veneering material. A static load was applied occlusally using a ball indenter and the load to fracture was recorded in Newtons (N). The same crown design was used to create 3D crown models and evaluated using FEA. The zirconia/composite crowns subjected to static occlusal load showed comparable results to the zirconia/porcelain crowns. Zirconia/composite crowns showed higher stress on the zirconia substructure at 63.6 and 50.9 MPa on the zirconia substructure veneered with porcelain. In conclusion, zirconia/composite crowns withstood high occlusal loads similar to zirconia/porcelain crowns with no significant difference. However, the zirconia/composite crowns showed higher stress values than the zirconia/porcelain crowns at the zirconia substructure.

Keywords: Zirconia, Composite veneer, Porcelain veneer, Bi-layered crowns, Fracture resistance

INTRODUCTION

Ceramics are widely used as restorative materials due to their favorable properties such as strength, biocompatibility and esthetics[1)]. Yttria partially stabilized tetragonal zirconia (Y-TZP) is one of the most used ceramic in dentistry for fabricating substructures due to its favorable mechanical and optical properties[2)]. All-ceramic bi-layered crowns consist of a high strength ceramic substructure such as zirconia or alumina veneered with ceramic or dental porcelain such as feldspathic porcelain. Although the resultant restorations have excellent esthetic properties, they are prone to failure such as chipping of the veneering ceramic[3,4)]. Ceramic veneers cannot withstand high tensile stresses that eventually cause the ceramic to fracture[5)]. Ceramic restorations are also abrasive and may cause wear of the opposing teeth[6)]. A possible solution for repairing a fractured ceramic veneer is to bond composite resin intra-orally, but this is considered a compromised solution due to strength reduction, bond failure and potential color mismatch of the material over time[7)].

Strategies intended to improve the performance of all-ceramic dental restorations and their veneering material have been reported which aim to optimize and improve the: a) coefficient of thermal expansion (CTE) match between the veneer and substructure[8)], b) firing time when building the porcelain veneer[9)], c) veneer pressing technique[10)] and d) CAD/CAM milling of the ceramic veneer[11)]. An alternative approach is to eliminate the veneer and produce a full contour monolithic zirconia crown[12)]. While monolithic zirconia crowns have recently become popular, there are still concerns regarding the wear they could cause to natural opposing teeth[13,14)]. Further the possible decrease in strength associated with a phenomenon known as low temperature aging or degradation (LTD) that could be induced in the aqueous environment[15,16)]. A possible way to overcome this phenomenon is by ensuring protection of the zirconia restoration from direct exposure to the oral cavity by full coverage with ceramic veneer[17)].

In comparison to metal-ceramic restorations, ceramic veneer chipping rates are higher with a zirconia substructure than those recorded with metal frameworks[18)]. This cohesive chipping has been reported in clinical follow up studies; a systematic review by Heintze and Rousson[19)] looked at zirconia and metal-ceramic restorations showing that veneer chipping over approximately three years was about 54% for zirconia based crowns and 34% for metal-ceramic restorations. A review by Triwatana *et al.*[20)] involving 14 studies stated that 11 reported veneer chipping of zirconia-based restorations, which varied between 13, 15 and 25%.

An alternative may be to consider veneering with composite. Composite resins are widely used for direct restorations due to their excellent physical, optical, mechanical properties, ease of handling and ability to be bonded to the tooth structure[21)]. A study by Walton *et al.*[22)] revealed that composite veneered metal crowns showed the greatest longevity (13.9 years) against other types of crowns, such as metal-ceramic crowns (6.5 years). Therefore would composite veneered zirconia have a similar longevity?

Assessing the capabilities of different material combinations in pre-clinical trials is challenging as it is

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Received Aug 30, 2016: Accepted Oct 5, 2016
doi:10.4012/dmj.2016-298 JOI JST.JSTAGE/dmj/2016-298

difficult to produce a test that accurately simulates the oral environment. Although occlusal fracture resistance evaluation allows the restoration to be constructed and compared to like designs, the limitations of the data have been discussed as being not applicable to real life situations[23]. This is primarily due to the test failing to reproduce crown failure as observed clinically, *i.e.* the mode of fracture differs and loads exceeding maximum recording bite forces are often observed[24]. Such forces vary considerably depending on gender and age, but overall the molar region has a higher force[25]. The test is useful in carrying out pre-clinical trials of novel materials or designs that are being investigated for future use. Using the material processed into the definitive crown shape and bonded to the appropriate substructure, unlike the uniform samples in laboratory mechanical testing, is suggested as reason enough to employ such testing, rather than relying purely on standard strength tests[26]. The fact that the material used to produce the crown for testing has been through a production process, is asymmetrical in shape and made out of more than one material and bonded to a tooth may have an impact on the test results of crown samples compared with standard, evenly shaped samples[5]. Similarly the restoration strength may be affected by variables such as veneer thickness, substructure design, cement thickness, properties of the underlying abutment[27]. Mimicking the oral environment with a comprehensive *in-vitro* test environment is difficult to achieve, but primary evaluations such as the occlusal fracture resistance can contribute to developing new techniques and materials[28].

Finite element analysis (FEA) has been increasingly used to analyze the stress of different materials and designs saving time and resources and giving initial results for new products or explaining weak points in current ones. In dentistry, FEA has been used to investigate how different materials and restoration shapes interact with the oral cavity in a non-damaging or time consuming way and also overcomes ethical issues of *in-vivo* testing of new materials[29-31].

This study assessed zirconia substructure crowns with both composite and ceramic veneers. The structural integrity of the crowns was assessed by subjecting them to static load and comparing their load at fracture. FEA was also carried out to assess the stresses generated on the underlying substructure.

MATERIALS AND METHODS

Fracture resistance

1. Samples fabrication

Using the CEREC® CAD/CAM system (CEREC inLab, Sirona Dental Systems, Bensheim, Germany), a zirconia substructure (0.7 mm thick) was designed using a cutback technique and from the opposing dentition. The substructure was then milled from zirconia blocks (In-Ceram YZ®, VITA Zahnfabrik, Bad Säckingen, Germany) and sintered following the manufacturers instructions. Zirconia substructures were divided into two groups (n=10) based on the veneering material to: zirconia/composite YZ/LC (VITA VM LC®, VITA Zahnfabrik) and zirconia/porcelain YZ/VM9 (VITA VM9®, VITA Zahnfabrik). A list of the materials used and their lot numbers are detailed in Table 1.

For the YZ/LC group, a light-cured composite veneer was added after the substructures had been shot-blasted with 50 µm Al_2O_3 and coated using universal primer (Monobond® Plus, Ivoclar Vivadent, Schaan, Liechtenstein). The YZ/VM9 veneers were produced following the manufacturer's guidelines. A silicone matrix (Provil Novo Putty Soft Regular Set, Heraeus Kulzer, Hanau, Germany) was used to produce the veneer overlay in order to make the crowns as consistent as possible. Crowns in both groups were finished and polished to a clinical standard thickness of 1.2 mm. The crowns were then cemented with Pavavia 21 (Kuraray Noritake Dental, Kurashiki, Okayama, Japan) on stone (Dentona esthetic-base® gold, Dentona, Dortmund, Germany) models before being subjected to load (Fig. 1).

2. Fracture resistance

A universal testing machine (Lloyd LRX universal testing machine, Lloyd Instruments, West Sussex, UK) was used to apply a load through a 4.2 mm diameter steel ball indenter at a crosshead speed of 1 mm/min occlusally in the middle of the crown (fossa) and the maximum load causing crown failure was recorded.

Table 1 Materials used in making crown samples for the occlusal fracture resistance test

Type	Brand name	Lot no.
Zirconia	In-Ceram YZ®, VITA Zahnfabrik, Bad Säckingen, Germany	10921
Composite	Vita VM LC®, VITA Zahnfabrik	14991
Porcelain	VITA VM9®, VITA Zahnfabrik	26610
Die stone	Dentona esthetic-base® gold, Dentona, Dortmund, Germany	81020300
Primer	Monobond® Plus, Ivoclar Vivadent, Schaan, Liechtenstein	N45336
Cement	Pavavia 21, Kuraray Noritake Dental, Kurashiki, Okayama, Japan	041111

1) Statistical analysis
Results were compared using Levene's test for equal variance followed by Welch's *t*-test at significant level ($p<0.05$) using statistical data analyzing software IBM SPSS version 23 (IBM, Armonk, NY, USA).

Finite element analysis
The program ANSYS 11.0 (ANSYS, Canonsburg, PA, USA) was used to create a 3D crown and subjected to virtual loading to identify where the stresses were distributed in the crown. The CAD/CAM zirconia substructure designed previously was used as a guide when drawing the crown. The veneer was schematically drawn to replicate actual clinical designs. Different layers were configured and assigned their characteristics according to Table 2[32-36].

Force was applied occlusally on a 4.2 mm diameter radius in the middle fossa to simulate the applied force in the fracture resistance test. A load value of 500 N was distributed equally at the loading point. Maximum first principal stress was chosen to determine the stress distribution in the structure after applying a virtual load to it, with the color guide showing the stress values in MPa.

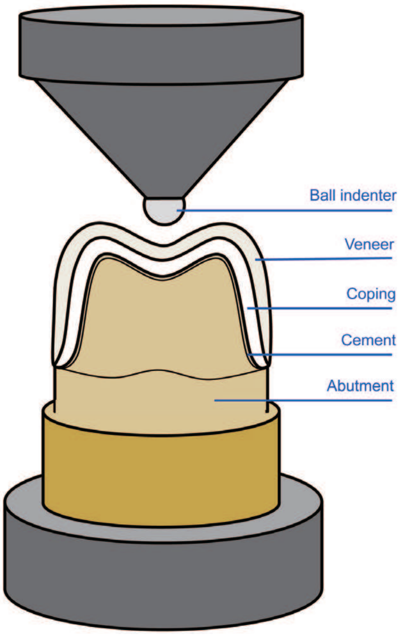

Fig. 1 Illustration of the occlusal fracture resistance test.

RESULTS

Fracture resistance
The occlusal fracture resistance of both groups can be seen in Fig. 2. All samples were tested to failure and the composite veneered zirconia crowns showed an average load at failure of 1,465 N (±350). Although minor veneer chips were observed prior to fracture, in all sample the composite veneer remained bonded to the underlying zirconia substructure The porcelain veneered zirconia crowns showed slightly higher resistance to fracture 1,576 N (±289.2) but with no evidence of a significant difference in the variances ($F=0.301$, $p=0.590$) and therefore we performed the Welch's *t*-test ($p=0.449$) which suggests no evidence of difference in means between tested groups.

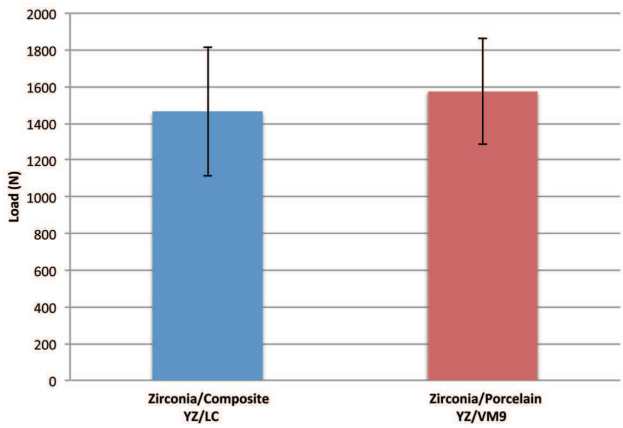

Fig. 2 Occlusal fracture resistance of Zirconia/Composite and Zirconia/Porcelain crowns.

Table 2 Elastic moduli and Poisson's ratios for each material used for the FEA

Material	Elastic modulus GPa	Poisson's ratio
Zirconia	209.3[32]	0.32[32]
Porcelain	66.5[32]	0.21[32]
Composite	4.5[33]	0.3[34]
Die (dentine)	18.6[35]	0.31[35]
Cement	18.6[36]	0.28[36]

Superscript numbers indicate references.

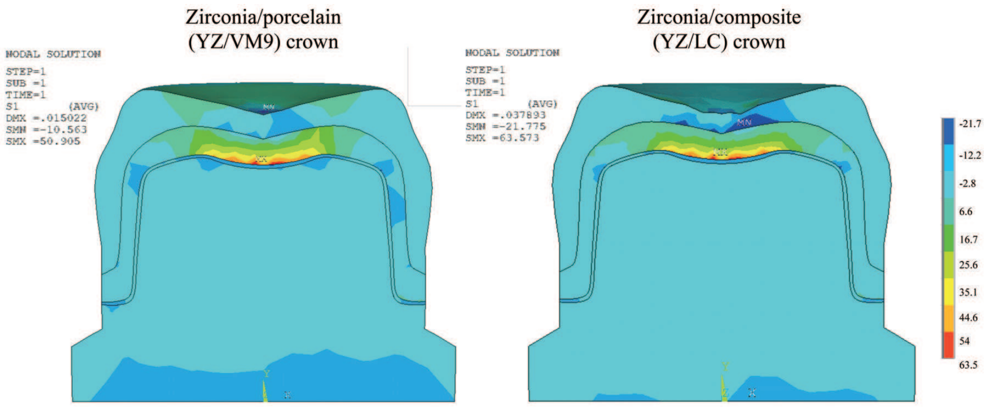

Fig. 3 Cross sectional view of stress (MPa) distribution of the zirconia/composite and the zirconia/porcelain veneered crowns and sphere after applying a virtual load of 500 N.

Finite element analysis

Colored deformed structures representing YZ/LC and YZ/VM9 crowns are shown in Fig. 3. The color key shows the highest and lowest stress generated in the 3D crown model after being subjected to virtual load.

When a load of 500 N was applied occlusally in the middle fossa, the crown veneered with a 4.5 GPa stiff composite showed the highest tension point under the loading area in the bottom of the zirconia substructure in the range of 63.6 MPa, peaking at around −21.8 MPa in the composite veneer under the loading area as a compressive stress. These conditions were repeated for the stiffer (65 GPa) ceramic veneered crown, resulting in high tension in the bottom of zirconia at around 50.9 MPa and compressive stress peaking at about −10.6 MPa at the porcelain veneer and cement under the loading zone.

DISCUSSION

In this study, a zirconia-based crown veneered with composite was proposed to overcome some of the drawbacks associated with porcelain veneered zirconia crowns. Such crowns are made with a zirconia substructure and veneered with indirect light cured composite. The benefits of this system include biocompatibility and strength of the zirconia substructure and a less abrasive composite veneer that allows ease of handling and intra-oral repair. Properties of zirconia and composites have been investigated in many studies[37-42], but few studies were found that tested the performance of composite veneered zirconia crowns[43-45].

One method to investigate the structural integrity of such structures is the occlusal fracture resistance or load-to-failure test, which takes into account the complexity of the crown's anatomy and its different component layers. Such test configurations and fabrication processes differ between studies, *e.g.* using a ball or a bar to apply load[5] or the type of the underlying abutment[46]. Consequently there is a variation in results between different investigations[47]. Further variables with this testing result from the design and reproducibility of samples. It has been stated that the structure and thickness of the substructure and veneer may affect the fracture resistance of the crowns independent of the mechanical properties of the materials[48]. Standardizing of samples for this test was achieved by machining the substructure using CAD/CAM and using an index to aid the production of the hand-built outer veneer. The crowns were measured on all sides to confirm they had been fabricated to the expected full contour before being cemented to the die. The results obtained from an *in-vitro* laboratory based test cannot be directly applied to the oral environment since there are differences in magnitude and direction of load and surrounding environment. More attention is indicated to produce a test which creates conditions closer to the oral cavity, such as: mimicking the periodontal ligament[49], using abutment materials with elastic moduli close to dentine[50], and using rubber sheet under the indenter to even the stress on the crown[51].

The results were measured in Newtons and all tested crowns withstood static loads exceeding 1,000 N without showing any signs of damage or chipping of the composite and porcelain veneers. The composite veneered crowns failed at 1,465.3 N compared to 1,576.4 N for the porcelain veneered crowns with no significant difference. This finding is in accordance with other studies that have concluded that the fracture resistance of indirect composite zirconia restorations showed comparable results to the porcelain veneered zirconia restorations[43-45]. These figures significantly exceed the maximum bite force recorded in the mouth.

A study by Casson *et al.*[5] tested the fracture load of 10 human extracted teeth mounted in die stone loaded using a bar with crosshead speed of 1 mm/min and recorded an average of 754 N with a standard deviation of 150 N. Taking into account the natural teeth tested in the previous study in a manner similar to the test done in this study, the composite veneered crowns withstood loads exceeding the natural teeth average of 754 N. A similar study by Zahran *et al.*[52] that tested the fracture resistance of all-ceramic crowns made out of yttrium-stabilized zirconium oxide and feldspathic ceramic gave comparable results this research. In their test, a 1.5 mm thick crowns of a 0.7 mm zirconia substructure veneered with VM9 feldspathic porcelain (n=10) gave an average fracture resistance to a ball indenter in a crosshead speed of 1 mm/min of 1,459 N (±492) and average of about 1,270 N (±109) for the other tested group of feldespathic crowns (VITA mark II, Vita Zahnfabrik) with a thickness of 1.5 mm. When comparing the Zahran *et al.* results it can be seen that the composite veneered zirconia crowns withstood higher loads than VITA mark II crowns. Sorrentino *et al.* evaluated monolithic zirconia molar crowns, and the groups with 1.5 and 1.0 mm thicknesses showed a fracture resistance of 1,554 N (±366.3) and 1,655 N (±314.6) respectively[53]. These studies show that porcelain veneered zirconia and monolithic zirconia crowns exhibited fracture resistance exceeding the highest recorded bite forces and ranging between 1,400–1,600 N and with a common cohesive mode of fracture.

The finding of this research shows that the light-cured composite zirconia veneered crowns showed comparable results to other zirconia based crowns but with the advantage of being repairable with the same material.

Intra-oral repair of cohesively fractured ceramic crowns with resin composite can be considered a cost and time effective method with the advantage of maintaining the restoration substructure and therefore protecting the underlying tooth[54,55]. The alternative is to replace the crown, removal of which is a difficult process, and producing an aesthetic replacement. There are some disadvantages associated with repairing ceramic restorations with resin composite, such as possible reduction in both mechanical and optical properties[7]. Repairing a fractured composite veneer intraorally with the same material would be less challenging with optimal esthetics when repaired with the same material and shade.

Studies have demonstrated that the maximum bite force was 500 N[56] and recommended that any restoration in the molar area should be able to sustain an occlusal load of about 500 N[57] Therefore, when evaluating crowns *in-vitro*, it is thought that posterior metal-free restorations should withstand an occlusal force of at least 1,000 N, with the assumption that the mastication forces in the moist oral environment may weaken the restoration by up to half its known fracture resistance force[58,59].

FEA has been used to imitate the occlusal fracture resistance test done in this study to show stress points after applying load on those structures. The virtual schematic crowns do not necessarily reflect the actual samples due to the fabrication process involving different stages mainly by hand[60]. It was assumed for this evaluation that there is a good bond between the different layers in the virtual veneered crowns, regardless of any faults that probably exist in clinical cases. Checking the stress zones is essential in most application fields since the stress, even if below failure point, is considered as a major cause of crack propagation and hence of system failure[36]. After applying the load to the designed structure, the result can be seen in different ways depending on the type of material and the user's investigation. For this study, the intention was to observe the stress generated on the crowns during testing. This virtual test can reveal compressive stress and tensile stress, which are among the causes of ceramic restoration failure[61]. With the ceramic veneer, stress was distributed across different levels, the stress being highest under the point where the load was applied. When replaced by composite, higher stresses were generated at the base of zirconia based crowns under the same occlusal load. This observation matches findings by other studies that low stiffness veneers pass the load to the substructure material, causing a higher tensile stress in the core that eventually can initiate crack growth through the veneer layer[29,60]. This is also in accordance with the results from the fracture resistance test as the composite veneered zirconia crowns fractured at lower loads than the porcelain veneered group. In this study, the composite veneered zirconia crowns showed promising results when compared to the same substructure veneered with porcelain. Further evaluation could be carried out on composite veneers when bonded to structures other than zirconia, preferably with elasticity closer to the composite and dentine to reduce the stress inducing zones between different layers of the crowns. High performance polymers such as PEEK and PEKK could be used for this purpose[62].

Further testing should be carried out in conditions that simulate the oral environment, *e.g.* thermal cyclic loading tests and using chewing simulators, before the results can be considered for clinical application. Also, different composites with different properties could be evaluated along with the bond between the zirconia and composite veneer.

CONCLUSIONS

From this study, the following conclusions can be drawn:

1. Crowns constructed from a zirconia coping and veneered using light-cured composite gave results similar to those veneered with feldspathic porcelain and showed no statistically significant difference.
2. FEA with the assumption of a good bond between the different crown layers, showed high tensile stress located at the base of zirconia copings under the area of load with ceramic veneered models and even higher levels with composite veneered models.

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