

Comparative analysis of fatigue resistance, fracture strength, and fracture patterns in ceramic crowns with zirconia and direct metal laser-sintered cores - An *in vitro* study

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Abstract

Purpose: Core materials in metal-ceramic crowns have metal, and all-ceramic crowns may have a zirconia substructure. These core materials are used to reinforce the strength of the prosthesis. The various metal substructures were compared to study the fracture strength and bond failure between the core structure and the layered ceramic. Digital metal laser-sintered (DMLS) substructures can be fabricated to thinner sections of up to 0.3mm. In conditions where there is a need for lesser reduction of tooth structure, the DMLS structures can be a viable alternative to zirconia substructures. The conducted study was intended to evaluate the fracture strength in ceramic crowns with DMLS and zirconia cores. **Materials and Methods:** A prepared tooth with standardized dimensions was generated using computer-aided design software and milled in metal. Impression of die was made, and 40 epoxy resin dies were prepared. Then, 20 DMLS substructures (Group I) and 20 Zirconia substructures (Group II) were made following in which ceramic veneering was done. Group I is divided into Group I(A) (10 crowns for the load to fracture) and Group I(B) (10 crowns for fatigue test). Group II is divided into Group II(A) (10 crowns for the load to fracture) and Group II(B) (10 crowns for fatigue test). All crowns were cemented to their respective dies using Type I glass ionomer luting cement. All crowns were subjected to thermocycling (5000 cycles) and Group I(A) & Group II(A) crowns were tested for load to fracture, and observational analysis of fracture pattern was carried out. The data were analyzed using SPSS software. Mean and standard deviation were estimated from the samples of each test group. Descriptive statistics was used to find the mean and standard deviation variables. Levene's test was used to test the equality of variances for independent "t" test. **Results and Conclusion:** The amount of load to fracture for Group I(A) was high with 3163.96 ± 525.27 and that for Group II(A) was 2077.1 ± 388.97 . The difference between the mean was found statistically significant ($P=0.005$). Both DMLS crowns group I(B) and Zirconia crowns group II(B) showed good fatigue resistance on observational examination and there is no evidence of no cracks or fracture at the end of fatigue test. Hence, crowns from both groups expected to resist crack propagation when used clinically. Hence, it may be concluded that mean load to fracture between Groups I(A) and Group II(A) significantly differs.

Introduction

Metals and alloys have been used in dentistry for fixed partial dentures in teeth replacement based on their strength, longevity, castability, and biocompatibility. Three types of metals were used in dental crowns and bridges, namely precious metals, semi-precious metals, and non-precious metals.^[1] Precious metals are gold, platinum, and palladium alloys, of which percentage of gold

would be more than the others. In semi-precious metals, there will be more silver content than gold, which would be around 25%. Non-precious metals like cobalt (Co), chromium (Cr), nickel (Ni), and beryllium were commonly used in dentistry.^[1] Co-Cr replaced Ni-Cr as Co-Cr exhibited material properties considered suitable for dental reconstructions with high strength, high modulus of elasticity and high corrosion resistance, less

density, easy finishing, and excellent biocompatibility.^[2] Direct metal laser sintering is a computer-aided design (CAD)-computer-aided manufacturing (CAM)-based technique, in which metal substructure can be designed and fabricated using Co–Cr. This process builds up each substructure in a series of successive thin layers (0.020 mm). A high power laser beam is focused on to a bed of powdered metal and these areas fuse into thin solid layer, and another layer of powder is laid down over this and the next slice of substructure is fused to the previous layer until the substructure is completed. It is a promising new technology which may replace conventional casting of base metal alloys. The advantages of direct metal laser sintering system as claimed by the manufacturer is the ease of use, ability to manufacture up to 90 units of metal substructure or core in a single operation, full density objects with complex geometries can be produced, accuracy of the substructure without much retained porosity, simplified post-processing procedures and improved physicochemical characteristics.^[3] Nowadays, Co–Cr has been used increasingly in recent years due to CAD/CAM techniques such as milling (subtractive) and direct metal laser sintering (additive) which has increased the precision and strength of the material.^[2,4] The fracture strength and fatigue resistance of these materials are important for prolonged clinical use. From an esthetics stand-point, the metallic framework, sometimes, limits their use in the esthetically visible areas even with the porcelain veneers because PFM systems are translucent with monochromatic and exhibit metal shine through in the gingival one third. The quest for a more esthetic restorative material coupled with the cost factor has hastened the introduction of all-ceramic restorations. Metal-ceramic restoration is a combination of strength and accurate fit of cast restorations, along with an esthetic effect of a ceramic crown. When compared to all-ceramic restorations, metal-ceramic restorations possess greater strength. The major advantage of metal-ceramic restoration is their high resistance to fracture. Metal-ceramic restorations are still the most widely used type of indirect restorative system and have been used with great success. Porcelain remains the material of choice for the esthetic veneering of teeth (laminates), metal (PFMs), or high-strength ceramic substructure (all ceramics). Advantages of all-ceramic over metal-ceramics include color resemblance of the teeth and translucency of enamel. The main drawback is their reduced load-bearing capacity when compared to metals because of that they have been used in areas where lesser occlusal forces are acting. Nowadays, various kinds of ceramics are available for use in dentistry. A recent review has reported an increased use of all-ceramic materials for the fabrication of crowns, and fixed dental prosthesis has been reported owing to the development of new ceramic systems.^[5] High-strength ceramic zirconia can be used as an alternative material to metal for the fabrication of frameworks for posterior FPDs as zirconia exhibits fracture strength and toughness superior to those of all other ceramics and base metal alloys.^[5]

A search continues for a material which can sustain high stresses at a minimum thickness to reduce tooth reduction

and requires minimal interocclusal clearance. The strength and other mechanical properties of zirconia core with full contoured ceramic crowns and other crowns have been compared. Most of the studies conducted by Nazirkar and Meshram,^[6] Pelaez *et al.*,^[7] Sailer *et al.*,^[8] and Zahran *et al.*^[9] compared the mechanical behavior between all-ceramic crowns, and few studies compared the mechanical behavior between all-ceramic crowns and metal-ceramic crowns which is made of conventional casting technique. The mechanical behavior of ceramic crowns with digital metal laser sintered (DMLS) substructure and zirconia core is not compared for their fatigue resistance and fracture strength which has led to the study. Research question tested in this study is “Do ceramic crowns with metal laser sintered core resist fracture more than crowns with zirconia core?” and the null hypothesis is that “there is no significant difference of fracture strength between ceramic crowns cored with zirconia and metal laser sintered substructure.

Materials and Methods

Materials and specifications used in this study are mentioned in Table 1

Equipment and instrument used

DMLS machine

EOSINT M270 manufactured in Germany was used in the fabrication of direct metal laser-sintered Co–Cr substructures.

Zirconia milling unit

Zirkonzahn M5 milling unit connected to a computer where there will be modeling software (Zirkonzahn. Modellier software) was used in the fabrication zirconia substructure.

Table 1: Materials and specifications used in this study

Materials	Dimensions and ratios
Ice Zirkon zirconia blocks for substructure and vita VMK 9 for ceramic veneering	Substructure thickness 0.6mm with marginal collar of 2.0 mm width and veneering thickness of 1.0 mm from central fossa of substructure
EOS cobalt chrome SP2 DMLS substructure material and vita VMK Master ceramic layering material	Substructure thickness 0.6 mm with marginal collar of 2.0 mm width and veneering thickness of 1.0 mm from central fossa of substructure
Tri dynamics tri-epoxy resin, keystone industries, USA	Die dimensions - cylindrical in shape Diameter - 15 mm Height 15 mm from finish line to base
Resin Hardener - Aradur HY 951, Huntsman advanced material, Mumbai	Resin hardener ratio 6:1

DMLS: Digital metal laser sintered

Universal testing machine

The universal testing machine (Instron 3345, capacity 5KN, model no 2519-107, serial number – 64512, USA) was used to test the load to fracture (fracture strength) of the samples used in this study. The load cell can be calibrated in the Bluehill software installed in a system connected to the universal testing machine.

Fatigue testing machine

MTS Acumen (Electro Dynamic Test System, capacity-3KN, serial number-502349, Version 5, USA) was used for fatigue testing in this study.

Preparation and fabrication of dies

Epoxy resin dies [Figure 1] were made by designing classic tooth preparation specifications using CAD software (CATIA V5) [Figure 1] and transferring the STL file data [Figure 1] into a milling machine, and a master Co-Cr metal die is milled [Figure 1]. The design specification of dies included 6° taper mesiodistally and 6° taper buccolingually with a circumferential shoulder of 1.0 mm and height of 5 mm. The occlusal reduction was 1.5 mm, measured in the deepest point of the main fissure and axial reduction of 1 mm.^[9] The die base was flat and cylindrical in shape with diameter of 10 mm and height of about 15 mm from the finish line to the base, and 40 impressions of the metal die were made using elastomeric impression material (Condensation Silicone, Speedex, Coltene Whaledent, Switzerland). Dental grade epoxy resin (Tri-dynamics Tri Epoxy Resin, Keystone Industries, Cherry Hill, New Jersey, USA), 40 dies were used to pour by mixing the resin with a hardener (Aradur HY 951, Huntsman advanced materials, Mumbai) in the proportion of 6 ml resin and 1 ml hardener in a plastic cup with a wooden stick uniformly without creating air bubbles and poured

into the impressions which were placed over a vibrator. After the curing time of the resin of 45 min, the dies were separated from the impressions.

Fabrication of ceramic crowns with Zirconia and DMLS substructure

40 epoxy resin dies were numbered and scanned in 3M ESPE optical scanner (S600 ARTI, Zirkozahn, Italy), data were transferred to the Zirkozahn.Modellier software (Zirkozahn, Italy) and DMLS software from the transferred data, 20 crowns with Co-Cr metal substructure (EOS cobalt chrome SP2, Germany) were made using EOSINT, M 270, Germany, CAD-CAM technology of uniform thickness of 0.6 mm,^[10] and another 20 crowns with Zirconia substructure using zirconia blanks (Ice Zirkon) following cuspal configuration were milled using CAD-CAM milling unit (CAD/CAM M5 Milling unit, Zirkozahn, Italy) to a uniform thickness of 0.6mm^[10] evenly with collar of 2.0 mm width^[11] and were fabricated in a dental laboratory [Prime Dental Lab, Chennai]. All DMLS substructure is sandblasted subsequently with 125 µm aluminum oxide for 5 s at a pressure of 3 bar and were cleaned with acetone in an ultrasonic cleaner for 10 min as per manufacturer instructions. Then, oxidation was performed according to metal to manufacturer instructions, then substructure was refinished, and steam cleaned.^[1] Following standard protocols by a single operator, veneering of DMLS and zirconia substructures was made resembling the size and anatomy to each other as closely as possible using layering and sintering technique maintaining the minimum and maximum dimensions of the layered material. The veneering thickness should be 1.0 mm, and the total thickness of veneered restoration including substructure and veneering should be 1.5 mm at central

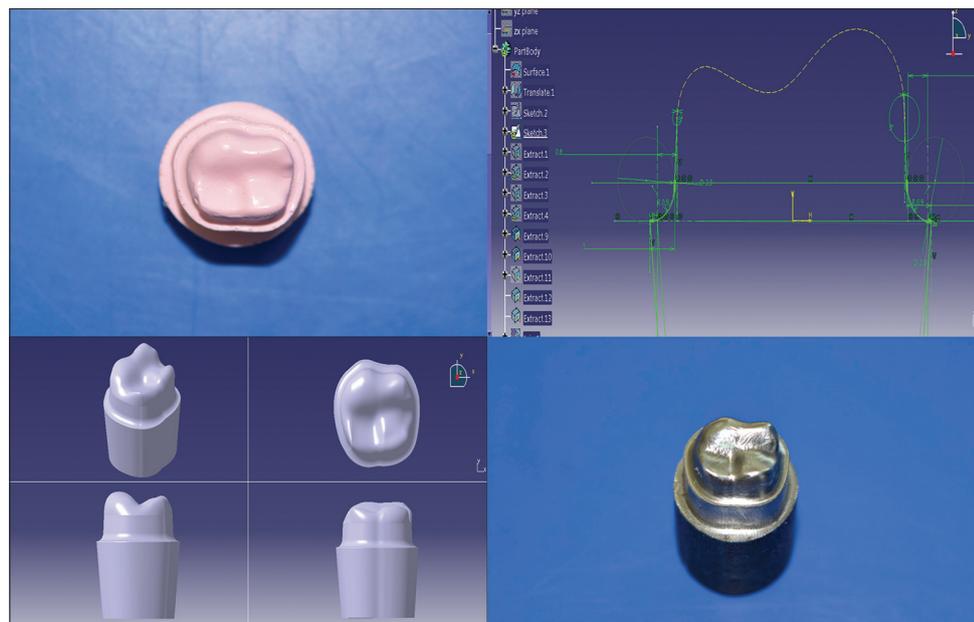


Figure 1: Epoxy resin die, Design of the Die - CATIA V5 software, completed design STL file, Milled Metal Die - cobalt-chromium

fossa region.^[12] Sintering of the veneered porcelain was done with ceramic furnace (Zirkonofen 600) following the standard protocol. Two groups named as Group I (direct metal laser-sintered crowns) and Group II (all-ceramic crowns). Group I is divided into I(A) (10 crowns for the load to fracture test) and I(B) (10 crowns for fatigue test). Group II is divided into II(A) (10 crowns for load to fracture test) and II(B) (10 crowns for fatigue test). Allocation of samples to their respective groups is done by simple randomization.

Sample preparation and thermocycling

All crowns were luted to their respective dies using resin-modified glass ionomer luting cement under a static load of 22N for 5 min. 1 h after cementation, all crowns with dies were stored in 37°C distilled water for 1 week. Then, all the crowns underwent 5000 thermocycles in a Thermo-cycler (Wiley Tec Thermo-cycler with cooling system HAAKE EK, Thermo-electron Corporation, Germany) before the pre-loading procedure with two water baths at 5°C and 55°C. Each cycle lasted for 60 s, 20 s in each bath, and 10 s to complete the transfer between the baths.^[1]

Fatigue test

The specimens from Groups I(B) and II(B) were placed for mounting on the lower stage of a fatigue testing machine. Fixture of 3-mm diameter was fixed to the lower end of the testing machine styli as the antagonist for fatigue loading. The specimens mounted in a fatigue testing machine were loaded for 50,000 cycles using a load (50N–600N maximum) at a frequency of 2 Hz (MTS Acumen Electro Dynamic Test System, capacity-3KN, version 5, USA). After the cycles were completed, the samples were checked for survival and examined for veneer chipping, cracks, or bulk fracture.

Fracture test

The fracture test was based on the maximum force leading to final (significant load drop) fracture. Since all crowns were the same size and shape and were loaded in an axial direction on the same contact points, the term strength is used to describe the fracture properties. The cemented crowns from Groups I(A) and II(A) were placed in the Instron Universal Testing Device (Instron 3345, capacity 5kn, USA) and a compressive load applied to failure at a crosshead speed of 1 mm/min, using a 3 mm diameter stainless steel ball which is fabricated separately according to the dimensions of the universal testing machine fixture [Figure 2]. The crowns were centrally positioned under the ball indenter attached to the universal testing machine. The initial failure, namely veneer chipping, and final failure of substructure fracture were recorded. Initial fracture was determined by the sequence of a maximum load followed by a direct vertical drop in the stress-strain curve relationship. Data on load to fracture were obtained from the Instron machine software (Bluehill-3, version 3.42), and the units of measurement were noted in Newton (N) [Figure 2].

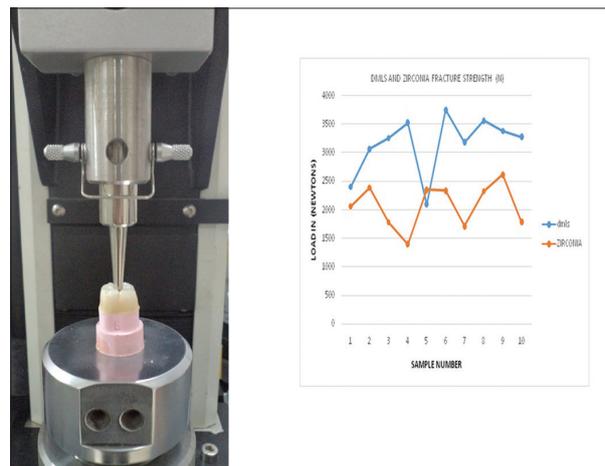


Figure 2: Fracture test in UTM, Shows fracture to load plotting points of DMLS and zirconia substructure with veneered ceramic crowns

Results

Fracture pattern analysis

After fatigue test (50,000 cycles), all crowns from Groups I(B) and II(B)) survived without any evidence of fractures or cracks. Based on the examination of the zirconia ceramic and metal-ceramic (DMLS) crowns, after fracture to the load test, the following observations are made. In case of all-ceramic crowns from Group II(A), it was observed that there was fracture of both substructure and veneering ceramic, indicating cohesive failure in all the samples. In case of metal ceramic, there is only fracture of the veneering porcelain, but none of the crowns showed fracture of the substructure in Group I(A) indicating adhesive failure. Most of the fracture patterns were observed originating from the central fossa and transmitted to the buccal/lingual surface of the crown.

Observational analysis of fracture

Group I(A) samples (DMLS Core) after load to fracture test showed adhesive fracture pattern of veneering ceramic, and there was no change in the morphology of the substructure material. Group II(A) sample milled zirconia core after load to fracture test showed cohesive fracture pattern of veneering ceramic along with the fracture of the core zirconia substructure material [Figure 3].

Statistical analysis

The data were analyzed using the SPSS software. Mean and standard deviation were estimated from the samples of each test group. Descriptive statistics was used to find the mean and standard deviation variables. Levene's test was used to test the equality of variances for independent *t*-test [Table 2].



Figure 3: Load to fracture tested digital metal laser sintered samples, load to fracture tested zirconia samples

Table 2: Mean and standard deviation of Group I and Group II, with “t” value, degrees of difference (df) and “P” value

Group I (A) DMLS Mean±SD (n=10)	Group II (A) Zirconia Mean±SD (n=10)	(t) value	(df) Degrees of difference	P value
3163.96±525.27	2077.1±388.97	5.258	18	0.005

DMLS: Digital metal laser sintered

Discussion

Metal-ceramic technology was used for the fabrication of dental crowns, and with a continuous evolution in the method of substructure fabrication from lost wax technique, electroformed crowns and DMLS system. Metal-ceramic crowns had advantages of strength and disadvantage of esthetics which was overcome with the evolution of materials and techniques. Evolution of all-ceramic crowns was initially not well accepted due to failure rates. With technological and material advances in zirconia core, all-ceramic crowns were demonstrated comparable mechanical properties to that of metal ceramic crowns in 2012^[7] and 2009.^[8] However, recently, there is the introduction of all-ceramic crowns for better esthetic purposes. It is proven by various studies that metal-ceramic restoration is more resistant to fracture than all-ceramic crowns. However, recent study quoted that the clinical survival rate of metal ceramic fixed partial denture is similar to that of the zirconia-fixed dental prosthesis.^[7] According to that study, both metal-ceramic and all-ceramic provide same survival rate clinically in 4 years' follow-up. Most commonly, *in vitro* studies are done to find the fracture strength and other mechanical properties of metal-ceramic and all-ceramic restorations. Kelly recommended few guidelines for a clinically relevant *in vitro* load-to-failure test protocol for all-ceramic restorations which was followed in this study.^[13] This includes using a die material for fabricating crowns with elastic modulus similar to human dentin, designing the prepared teeth dimensions according to the clinical guidelines and clinically relevant dimensions of all-ceramic

crowns and cementing the crowns with reliable and most commonly used luting cement. In this study, epoxy resin was used as modulus of elasticity of epoxy resin was similar to human dentin^[14] and the die preparation was carried out according to clinical guidelines of mandibular molar with 6° taper, CATIA v5 software was used to design the die dimension for the accuracy of the dimensions, and the taper, if tooth preparation is done in a typodont model exact taper, cannot be prepared manually, so die was designed in a software. The crowns were cemented using type I glass ionomer luting cement which is the most common luting cement used for the cementation of the crowns. To mimic the aging of restorations in oral conditions, thermocycling of all dental crowns was carried out.^[1] In this study, zirconia substructure was made with a 2.0-mm marginal collar width to increase the fracture strength of the veneering porcelain and functional longevity of the crowns.^[12] Clinically, all-ceramic and metal-ceramic crowns commonly fail due to crack propagation, resulting from fatigue caused by masticatory stresses. The crowns in this study were subjected to fatigue forces similar to which the crowns in the molar region might get encountered. The crowns were subjected to 50,000 cycles. Vertical forces were given in cyclic loading machine, and the result of this study should be limited to the vertical loading situation in clinical implication. In a study done by Zahran *et al.*^[9] cyclic loading test was done using frequency of 20 Hz and 5,00,000 cycles. Which is higher comparing the frequency of 1 to 2 Hz seen in chewing cycles. This high frequency may lead to more heat generation and may not give a time for stress relaxation compared to 1–2 Hz frequency. In this study, frequency of 2 Hz for 50,000 cycles was used to mimic the clinical scenario. Studies have been carried out to assess the fracture strength and fatigue resistance of materials like In-Ceram YZ, Vita Mark II, and Lava, Digident crowns. On testing and comparing the above materials, it was concluded that the performance of VMII crowns was superior to YZ crowns in the fatigue test, and Lava crowns showed a complete fracture of both the veneering porcelain and the core, whereas the Digident crowns showed fracture only of the veneering porcelain.^[15] Kwon *et al.*^[15] conducted a study where they compared the fracture strengths of two CAD/CAM zirconia crown systems that is Lava and Digident. Zahran *et al.*^[9] in their study compared fracture strength and fatigue resistance of In-Ceram YZ crowns and feldspathic all-ceramic crowns made with CAD/CAM. However, none of the studies compared the fracture strength and fatigue resistance between zirconia crowns and metal crowns, and there is no study evaluated the Ice Zirkon zirconia substructure. Hence, fracture and fatigue resistance of zirconia crown systems were compared with the DMLS metal substructure with veneered ceramic. Ice Zirkon (Zirkonzahn, Italy) is one of the available yttrium-oxide partially-stabilized zirconium oxide ceramics and machined using a CAD/CAM device. According to the manufacturer's product information, the material has a flexural strength of 1400 MPa and a fracture toughness of 5.9 MPa/m^{-1/2}. Therefore, dental restorations made using these zirconium oxide systems were found to resist fracture better than traditional all-ceramic restorations, especially in areas where high occlusal loads

are anticipated. However, zirconium oxide ceramics are not transparent and cannot be stained to create good esthetic results. They must, therefore, be veneered with suitable veneering porcelain to enhance the esthetic results. Unfortunately, this multilayer arrangement increases the complexity of stress distribution within the restoration, making it difficult to predict its performance in clinical situations. Hence, the *in vitro* study was carried out to evaluate the fracture strength and fatigue resistance of machinable zirconia material and comparing it with the metal-ceramic crowns fabricated by DMLS technology. DMLS substructure is made from the most commonly used EOS machine, Germany, and as per the manufacturer instructions, SP2 Co-Cr powder is used for manufacturing metal substructure. Comparing to the clinical contact pressure, the use of a small ball increased the contact pressure in the crowns.^[13] It is influenced by the ratio of elastic modulus of loading fixture to the elastic modulus of the dental porcelain and by the radius of the loading fixture. Alternative methods could have included the use of a loading ball with a modulus of elasticity lower than that of the stainless steel ball, a tin sheet between the load applicator and crown as stress breaker, or a stainless steel loading piston with its end machined to a curvature equivalent to 40–50 mm diameter to reproduce clinical contact pressure.^[13] In this study, both the materials were subjected to the same contact pressure and same load frequency. The fracture strength data should be considered relative, not as absolute values, and comparing of these *in vitro* strength data to the clinical performance must be considered cautiously as it possess within the limitation of any *in vitro* study.^[16] In a study done by Zahran *et al.*,^[9] result shows that the mean fracture loads of YZ crowns were 1459 N and 1272 for VMII crowns. In this study, the mean fracture load of zirconia group is 2077 N and mean fracture strength of the metal (DMLS) group is 3163 N which is twice than that of the YZ crowns. There is a statistical difference present between the two compared groups in this study. All zirconia-ceramic crowns showed catastrophic cohesive fracture involving the whole thickness of the ceramic crown. This is the expected mode of fracture for all-ceramic crowns.^[17] None of the zirconia and DMLS crowns subjected to cyclic loading demonstrated any evidence of cracking or fracture which is similar to study conducted elsewhere.^[17] None of the crowns which underwent fatigue loads reported to have any fractures or cracks. Limitations do exist, which is a component of any *in vitro* study. The minimal sample size without affecting the power of the study fulfilling statistical requirement was chosen. Although realistic frequency of 2 Hz during fatigue testing was chosen, the study was conducted with 50,000 cycles which was mentioned in the literature. Increasing to 500,000 cycles may or may not affect the results of the study. *In vitro* studies perform loading in controlled conditions which do not exist in oral environment. Type I GIC was the luting agent which was used in the current study. The influence of luting cement was beyond the relevance to aims and objectives of the study. However, clinical follow-up studies on the performance of the two categories of crowns mentioned would yield results which are realistic and can be translated readily for reference.

Conclusion

Within the limitations of this *in vitro* study, the following conclusions can be drawn:

1. There is statistically significant difference between the mean fracture loads of the DMLS crowns and Zirconia crowns.
2. The mean fracture loads of DMLS crowns were higher compared to the zirconia crowns.
3. Both DMLS crowns and zirconia crowns showed good fatigue resistance (100% survival) during observational examination.
4. There is no evidence of any cracks or fracture after fatigue test.
5. DMLS and zirconia crowns showed different fracture modes. All zirconia crowns showed total crown fracture involving the whole crown thickness, while all DMLS crowns had their fractures in the veneering layer. The addition of the veneer layer to the core is the weak link in the DMLS crowns, and attention is needed to improve the bond between core and veneer.

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