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ORIGINAL ARTICLE

# Influence of the supporting die structures on the fracture strength of all-ceramic materials

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**Abstract** This study investigated the influence of the elastic modulus of supporting dies on the fracture strengths of all-ceramic materials used in dental crowns. Four different types of supporting die materials (dentin, epoxy resin, brass, and stainless steel) (24 per group) were prepared using a milling machine to simulate a mandibular molar all-ceramic core preparation. A total number of 96 zirconia cores were fabricated using a CAD/CAM system. The specimens were divided into two groups. In the first group, cores were cemented to substructures using a dual-cure resin cement. In the second group, cores were not cemented to the supporting dies. The specimens were loaded using a universal testing machine at a crosshead speed of 0.5 mm/min until fracture occurred. Data were statistically analyzed using two-way analysis of variance and Tukey HSD tests ($\alpha$=0.05). The geometric models of cores and supporting die materials were developed using finite element method to obtain the stress distribution of the forces. Cemented groups showed statistically higher fracture strength values than non-cemented groups. While ceramic cores on stainless steel dies showed the highest fracture strength values, ceramic cores on dentin dies showed the lowest fracture strength values among the groups. The elastic modulus of the supporting die structure is a significant factor in determining the fracture resistance of all-ceramic crowns. Using supporting die structures that have a low elastic modulus may be suitable for fracture strength tests, in order to accurately reflect clinical conditions.

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## Introduction

With an increased demand for esthetics and concerns about toxic and allergic reactions to dental alloys, full coverage all-ceramic crowns have become very popular with both patients and clinicians because of their highly esthetic results and biocompatibility [1]. However, the fracture resistance of all-ceramic crowns remains a concern for clinical success [2]. Ceramics are brittle and have low tensile strength and fracture toughness due to the presence of inherent flaws within the material. Numerous techniques have been developed in an attempt to overcome this problem and allow the use of all-ceramic restorations on posterior teeth [3, 4].

Fracture strength is one of the most important criteria for long-term success of dental restorations [5]. It is obvious, from the different studies in relation to the fracture strength of all-ceramic systems, that the values reported are highly variable [4, 6–10]. Fracture strength depends on the modulus of elasticity of the supporting substructure, properties of the luting agent, tooth preparation design, surface roughness, residual stress, and restoration thickness [9, 11–16]. Resin bonding of ceramic restorations to the supporting tooth structure increases the fracture resistance of the restored tooth and the restoration itself [9, 17, 18]. Many studies have evaluated the fracture strength of all-ceramic crowns [4, 19–31] using metal [4, 21, 23, 25], brass [19, 26], acrylic resin [20], epoxy resin [24, 27], and dentin [22] as supporting die materials. Increasing the elastic modulus of the supporting die material has been suggested as a means to increase the fracture resistance of all-ceramic posterior crowns [11].

The finite element method (FEM) is a technique for strength determination that has been used extensively in industrial applications [32]. The 3-D finite element approach consists of dividing a geometric model into a finite number of elements in which the variables of interest are approximated using mathematical functions [33]. The use of FEM for analysis of biological structures was first reported by Brekelmans et al. [34]. This method has been used in dental applications to study fracture mechanics, implants and dental restorative devices, and dental materials [35–38].

The purpose of this in vitro study was to investigate the influence of the elastic modulus of the supporting die structures on the fracture strength of ceramic dental materials.

## Materials and methods

### Die production and core fabrication

A series of 24 freshly extracted carious-free and crack-free human mandibular molars were embedded in chemically cured acrylic resin. Brass, stainless steel (chromium–nickel), epoxy resin (bisphenol A–epichlorohydrin resin, propanetriol, glycidyl ethers), and tooth (24 per group) were prepared to simulate a mandibular molar all-ceramic core preparation (Fig. 1). Cores were prepared using a computer numerical control (CNC) milling machine (SL-35, John Ford Roundtop Machinery Industries Co., Taiwan) to the following dimensions: 5 mm vertical height, 90°, 1 mm shoulder with a total convergence taper of 16°. A total of 96 zirconia (Zirkonzahn, Ahrntal, Italy) cores were fabricated using a CAD/CAM system (Dental Wings, Montreal, Canada). Each core had a 0.6-mm occlusal and circumferential wall thickness and 30-µm cement gap thickness. The specimens were divided into two groups. In the first group, zirconia cores were cemented. In the second group, cores were not cemented to the dies.

### Cementation and loading procedure

Before cementation, each core was seated on its substructure to check its marginal fit. A measuring microscope (Leica IC-3D, Leica Microsystems, Heerbrugg, Switzerland) was used to determine the marginal gap at four points on each surface. It was planned to reject any core with a mean marginal gap exceeding 100 µm; none of the cores was rejected. After airborne-particle abrasion (50-µm aluminum oxide particles at 0.28 MPa for 13 s at a distance of 10 mm), each core was cemented on its respective die. Dual-cure resin cement (Multilink Automix, Ivoclar Vivadent, Schaan, Liechtenstein) was applied according to the manufacturer's instructions. The cement was applied to the internal surface of the cores, and cores were positioned on the substructure. Zirconia cores were seated on the substructures with finger pressure and sustained with a 22-N load for 5 min [39]. Excess material was removed, and cemented cores were light cured for 40 s each at 5 mm distance from the occlusal, buccal, and lingual sides (light intensity of 650 mW/cm$^2$) (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein). Cemented cores on dies were stored at 37°C in distilled water for 24 h. In the second group, cores were not cemented. Fracture strength testing was carried out using a universal testing machine at a crosshead speed of 0.5 mm/min. The load was applied vertically on the center of the occlusal surface of the coping using an instrument 2 mm in diameter (Fig. 2). The minimum force required to produce fracture was recorded in newtons.

### Statistical analysis

Two-way analysis of variance and Tukey HSD tests were performed using the SPSS program (version 15.0, SPSS Inc., Chicago, IL) to evaluate the data ($\alpha$=0.05).

### Finite element analysis

The study used a 3-D FE method and the Solidworks 2007 9.0.3 structural analysis program (SolidWorks Corporation, USA). Three-dimensional FEA mathematical models were created to simulate the fracture strength test. The model contained the crown and die structure. Initially, cross sections of structures included in the mathematical model were sketched on the front plane separately for each unit in the computer environment on the basis of the geometry of

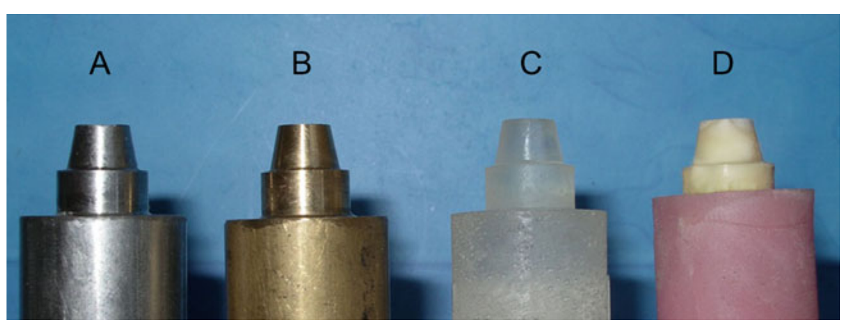


**Fig. 1** Supporting die materials; **a** stainless steel, **b** brass, **c** epoxy resin, **d** dentin

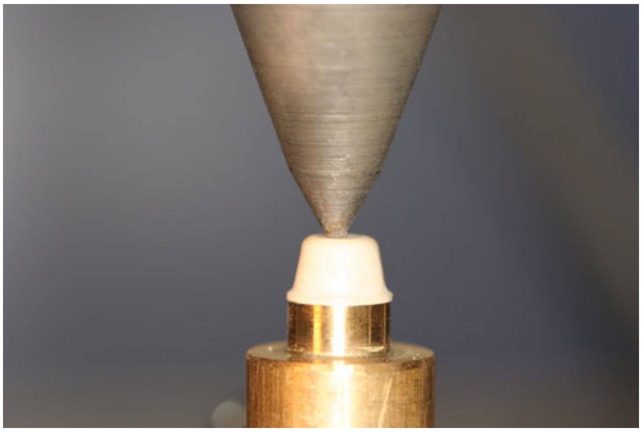

**Fig. 2** Zirconia framework under fracture strength test

fracture strength test specimens. Revolving the sketch at 360° defined the final geometry of the FE model. The geometric models were meshed with tetrahedral quadratic elements. Each mathematical model included approximately 11,200 nodes and 7,400 solid elements. The bottom exterior nodes of the die structure in the FEM models were fixed in all directions as the boundary condition. A 100-N static vertical occlusal load was applied to the nodes at the center of the upper surface of the crown to calculate stress distributions.

Materials used in the study were assumed to be homogenous and isotropic. The elastic properties of the materials (Young's modulus, $E$, and Poisson's ratio, $\mu$) were determined from the literature and are given in Table 1.

## Results

Before cementation, the mean fracture strengths and the standard deviations for core materials on the epoxy resin dies were 296.22±14.25 and 282.24±16.95 N on the dentin dies, 336.66±14.4 N on the brass dies, and 346.34±22.72 N on the steel dies. After cementation, the mean fracture strengths and the standard deviations for core materials on the epoxy resin dies were 497.86±17.18 and 479.56±17 N on the dentin dies, 890.24±25.44 N on the brass dies, and 955.64±36.78 N on the steel dies (Fig. 3).

The cemented group showed significantly higher fracture strength than the non-cemented group ($p<0.05$). Ceramic cores on stainless steel dies showed the highest fracture strength values among the groups. No significant difference was found in the fracture strength between dentin and epoxy resin structures in both cemented and non-cemented groups. While there were no significant differences between metal and brass dies in the non-cemented group, a significant difference was found between the cemented groups.

**Table 1** Mechanical properties of the investigated materials

| Material | Elastic modulus (GPa) | Poisson's ratio ($\mu$) |
|---|---|---|
| Zirconia core [43] | 210 | 0.30 |
| Dentin [44] | 18.6 | 0.31 |
| Filled epoxy [45] | 11.8 | 0.30 |
| Stainless steel[a] | 200 | 0.28 |
| Brass[a] | 100 | 0.33 |

[a] Acquired from SolidWorks material library

### Finite element analysis

The FEM results are presented as stresses distributed in the investigated structures. These stresses may occur as tensile, compressive, shear, or a stress combination known as equivalent von Mises stresses. Since the compressive strength of porcelain is much higher than the tensile strength, tensile stress values were chosen to evaluate the stress distributions. Calculated numerical data were transformed into color graphics to better visualize mechanical phenomena in the models. A 3-D cross-sectional view of the models was presented for each condition. All stress values were indicated in megapascals. A narrower stress indicator range was used to better visualize the stress distribution differences (0 to 10 MPa).

Analysis of the tensile stress values revealed that maximum stress concentrations were located at the occlusal surface, close to loading areas, for all models. Maximum tensile stress values were 79 MPa for epoxy, 62 MPa for dentin, 18 MPa for stainless steel, and 17 MPa for the brass model. Both stress distribution patterns and values were similar for dentin and epoxy resin die materials (Fig. 4).

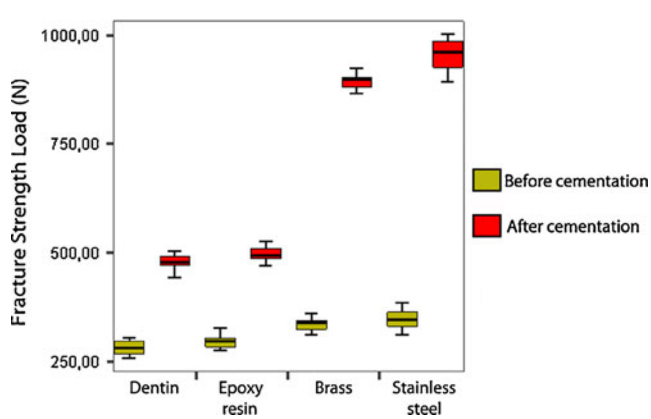


**Fig. 3** The mean fracture strengths and the standard deviations for zirconia core materials on the supporting die materials

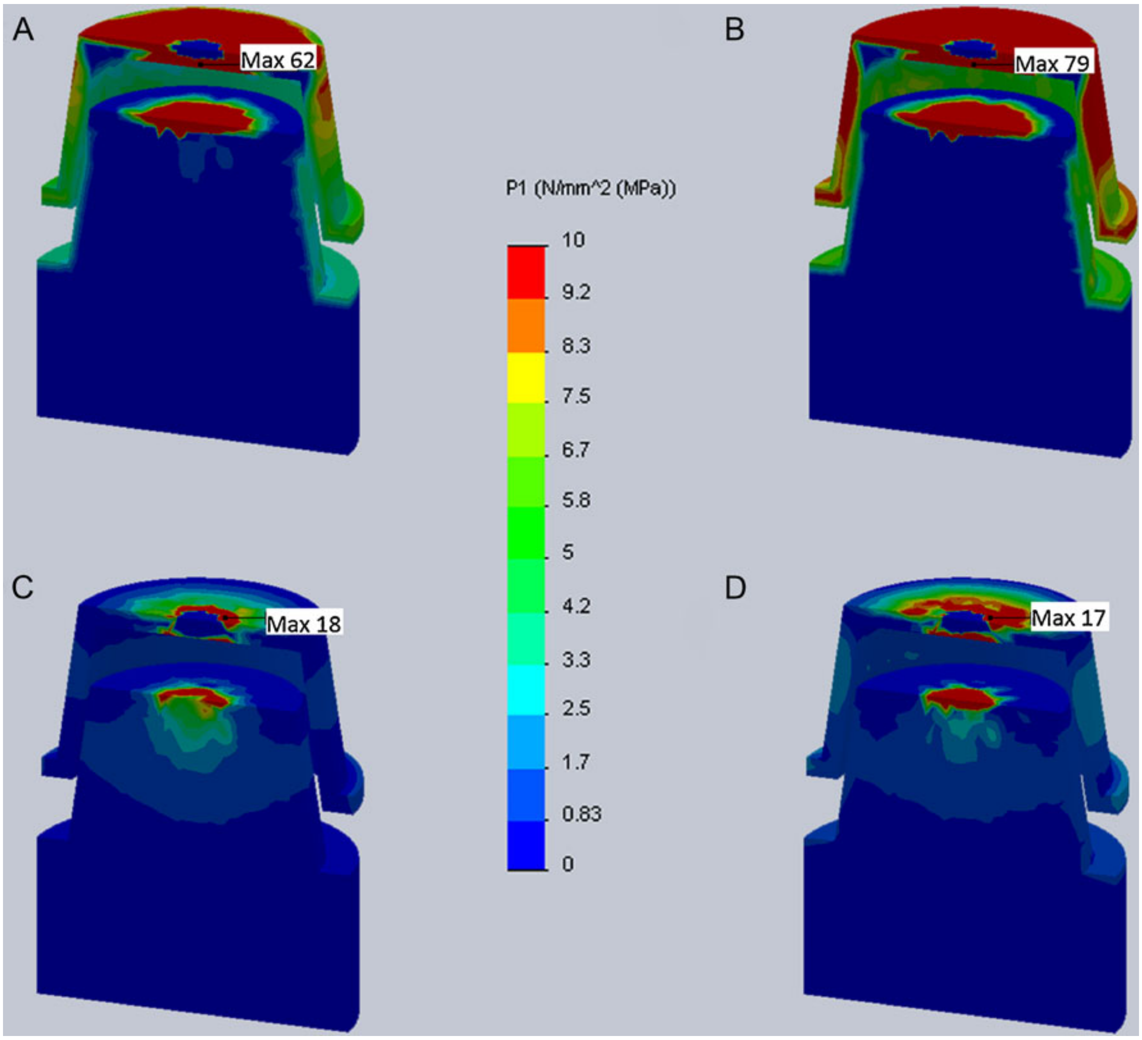


**Fig. 4** Distribution of tensile stresses (megapascals) at cross-sectional view of the whole model; **a** dentin, **b** epoxy resin, **c** stainless steel, and **d** brass die material. *Blue* to *red colors* represent stress values from lower to higher, respectively

## Discussion

The results of this study suggest that the elastic modulus of the supporting die material has a significant influence on the fracture strength of zirconia cores. The elastic modulus is a measure of the stiffness or the rigidity of a material within the elastic range; the higher the elastic modulus value, the stiffer the material is, and the less it deforms under a given load [40]. Therefore, the elastic modulus could be used as a measure of the supporting ability of the core material and possibly its ability to prevent failure of a brittle restoration [19].

Failure in a porcelain restoration usually results from the tensile stress component. Porcelain has a tensile strength that is lower than its compressive strength, and its limited capacity to deform plastically during structural deformation leads to failure at a critical strain of the order of 0.1% [40, 41]. During function, forces are transferred through the porcelain crown to the underlying supporting cement layer and the core material, inducing stresses and deformation in these structures [19]. In the present study, zirconia cores on dentin and epoxy resin dies showed lower fracture strength values than brass and steel dies. Metal dies are very rigid and have a higher elastic modulus than dentin and epoxy resin, so that these dies deform less, resulting in a lower shear stress at the inner crown surface. In the FEM analysis, widespread stress distribution of zirconia cores on dentin and epoxy resin dies may explain the situation. This result is in agreement with the observation of Scherrer and de Rijk, who found that the fracture loads of all-ceramic crowns increased with the elastic modulus of the supporting structure [11].

In this study, only one ceramic material was manufactured using CAD/CAM technology. All cores were fabricated to the same shape and size for the purposes of standardization. All supporting structures were manufactured using a CNC milling machine for the same reason. Veneering material was not applied to the zirconia cores for eliminating co-factors because use of veneering material can cause delamination and may affect the purpose of the study.

This study suggests that the modulus of elasticity of the supporting die structures may have a significant effect on the ability of the model to accurately reflect clinical conditions. For fracture testing, an epoxy resin die might be used rather than a metal die to obtain realistic fracture strength values.

The finite element method showed different stress distributions between groups, which supports our fracture strength test results. The FEM showed that ceramic cores on dentin and epoxy resin dies were subject to similar stress distributions. Likewise, stainless steel and brass dies showed similar stress distributions. The results clearly demonstrated that the stress distributions of dentin and epoxy resin die models were different from those of stainless steel and brass die models.

The fracture strength test values after cementation were significantly higher than those of groups with non-cemented cores. The significant increase in fracture load data for ceramic cores with cementation may be related to both the higher mechanical properties of the resin cementation material and the adhesion established at the interfaces between the ceramic, cementation material, and abutment [20].

Abutment tooth material appears to have a great influence on stresses in loaded restorations, so it is of crucial importance to consider this behavior when experimentally simulating the in vivo situation. There are some disadvantages to using natural abutment teeth for in vitro studies: the tooth may fracture under high loads during fracture testing, and there are some restrictions in the reproducibility and comparability between natural teeth specimens [42]. To avoid these disadvantages, materials with a lower elasticity modulus might be used as a supporting structure for fracture strength tests in order to simulate clinical conditions.

## Conclusions

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

> The elastic modulus of the supporting die structure is a significant factor in determining the fracture resistance of all-ceramic crowns.
>
> When investigating the fracture strength of ceramic dental materials, supporting die structures that have an elastic modulus similar to teeth may be used to achieve results that are closer to clinical conditions.

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