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# Design maps for failure of all-ceramic layer structures in concentrated cyclic loading

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**Abstract**

A study is made of the competition between failure modes in ceramic-based bilayer structures joined to polymer-based substrates, in simulation of dental crown-like structures with a functional but weak "veneer" layer bonded onto a strong "core" layer. Cyclic contact fatigue tests are conducted in water on model flat systems consisting of glass plates joined to glass, sapphire, alumina or zirconia support layers glued onto polycarbonate bases. Critical numbers of cycles to take each crack mode to failure are plotted as a function of peak contact load on failure maps showing regions in which each fracture mode dominates. In low-cycle conditions, radial and outer cone cracks are competitive in specimens with alumina cores, whereas outer cone cracks prevail in specimens with zirconia cores; in high-cycle conditions, inner cone cracks prevail in all cases. The roles of other factors, e.g. substrate modulus, layer thickness, indenter radius and residual stresses from specimen preparation, are briefly considered.
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*Keywords:* Multilayers; Fracture; Fatigue

## 1. Introduction

Considerable recent work has been done on the way brittle layer structures consisting of a weak and relatively compliant "veneer" joined to a strong and stiff "core" and glued to a polymeric base fail in contact loading with spheres [1–17]. Such configurations are representative of occlusal loading of all-ceramic veneer/core dental crowns fixed to tooth dentin [18–21]. They are also of general applicability to a broad range of engineering laminate structures where coating or glazing layers are used to provide functional (mechanical, thermal, aesthetic) protection for soft, compliant bulk substrates [6,22–28]. Several fracture modes may operate under different conditions, but the most dominant are those indicated in Fig. 1: radial (R) cracking at the bottom surface of the core layer, where flexural tensile stresses concentrate; and outer (O) and inner (I) cone cracks at the top surface of the veneer layer, in the near-contact field. All of these cracks grow steadily with time in the presence of moisture due to the action of slow crack growth [29–31], but in the case of I cracks there is an additional "hydraulic pumping" effect from pressure-induced intrusion of water during cyclic loading [32,33]. Both radial and cone cracks can penetrate to the veneer/core interface in prolonged loading. At this point the structure is effectively compromised and so we designate it here as "failure", although strictly it may remain intact and sustain further damage with prolonged loading.

The key question that we pose here is: which of the fracture modes in Fig. 1 dominates under any given set of conditions? Only by answering this question can we lay a sound foundation for optimizing all-ceramic layer systems for maximum resistance to failure. Several such influential conditions may be identified: crack evolution – the stability of fracture between initiation and failure; material

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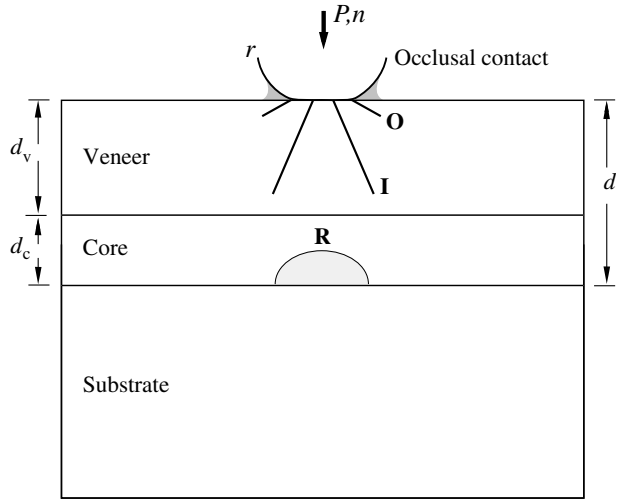


Fig. 1. Schematic showing competing outer (O) and inner (I) cone cracks in the veneer and radial cracks (R) in the core, net layer thickness $d = d_v + d_c$, bonded to a compliant support base. The specimen is loaded with spheres of radius $r$ at load $P$ for number of cycles $n$ in water (shaded).

properties (modulus, strength, toughness) – role of core properties in determining the mechanics of fracture in both core and veneer; loading mode – single-cycle overload vs. prolonged cycling; geometrical variables – role of layer thicknesses and cuspal curvature; residual stresses – role of coefficient of thermal expansion (CTE) mismatch or other specimen preparation stresses.

This study seeks to address the key question of dominant fracture mode by conducting experiments on model flat trilayer systems [8,14,16]. Glass veneer plates are simply joined with an interlayer of epoxy resin to alumina or zirconia (Y-TZP) core plates. Glass has similar mechanical properties to dental porcelain, while alumina and zirconia are basic dental core ceramics. We chose epoxy adhesive as the preferred method of joining because it is cured at room temperature and therefore avoids CTE mismatch stresses [16]. It can also be applied in a sufficiently thin interlayer that the mechanics of the primary fracture modes are not significantly affected, and is sufficiently strong that delamination does not constitute a primary mode of failure. The ensuing all-ceramic bilayers are bonded to a compliant polycarbonate base, using the same epoxy adhesive, to simulate placement of a crown onto tooth dentin. The specimens are then loaded at their top surfaces with hard spheres in cyclic loading in a water environment, representing occlusal function in the mouth. The evolution of fractures is observed in situ using video cameras [8,34]. The numbers of cycles needed to initiate radial cracks in the core and cone cracks in the veneer, and to propagate these cracks through the respective layers to the core/veneer interface, are measured. We demonstrate that both radial and cone crack modes can lead to failure, and that each can dominate in different material structures under different circumstances. Implications concerning the design of longer lifetime all-ceramic layer systems are discussed.

## 2. Materials and methods

The materials used to fabricate the trilayer structures depicted in Fig. 1 are indicated in Table 1 [16]. For the veneers, microscope soda-lime glass slides of thickness $d_v = 1.0$ mm (Daigger, Wheeling, IL) were etched at their faces (10% HF, 30 s) to remove large flaws and polished at their edges for side viewing. For the cores, plates of polycrystalline alumina (AD995, CoorsTek, Golden, CO) and Y-TZP zirconia (Lava Frame, 3M ESPE, Morrow, GA) were diamond polished at their top and bottom faces to thickness $d_c = 0.5$ mm. The combined net thickness $d = 1.5$ mm of the glass veneer and ceramic core layers is typical of dental crowns. A few polished monocrystalline sapphire plates (Goodfellow Ltd., Cambridge, England) and glass plates of thickness $d_c = 0.5$ mm were also used as cores to facilitate in situ side viewing of radial cracks, the sapphire as a "transparent alumina" and the glass as a reference material.

In one set of specimens, the bottom surfaces of both the glass veneer and the core ceramic were abraded (600 SiC grit) to introduce microcrack flaws, to ensure preferential radial cracking in the core in subsequent testing. Conversely, in another set of specimens, the top surfaces of the glass veneer and core ceramic were abraded to ensure cone cracking in the veneer. Abrasion of the surfaces immediately adjacent to the epoxy adhesive was included to test whether cracks in any one layer could penetrate into the other layer. The 1.0 mm glass plates were joined to the ceramic cores with epoxy resin (Harcos Chemicals, Bellesville, NJ) to form bilayers. After applying the adhesive, the plates were clamped and the epoxy allowed to cure for 2 days at room temperature, resulting in an adhesive interlayer <20 μm thick. The core bases of the resulting bilayers were then glued to polycarbonate slabs 12.5 mm thick (Hyzod, AlN Plastics, Norfolk, VA) with the same epoxy, which was allowed to cure under the same conditions.

The finished trilayers were loaded at their top surfaces with a WC indenter of radius $r = 5.0$ mm, an intermediate value within the occlusal function range [35]. The choice of WC was simply to enable repeated testing without the need to replace the indenter. (Comparable tests with glass indenters show virtually no shift in failure data [35].) A drop of water was placed at the indenter contact at the top surface and was constantly replenished during testing. Cyclic loading was conducted sinusoidally between a minimum load 2 N (to prevent the indenter wandering at the top surface) and maximum loads $P_m$ up to 1300 N, at a frequency

Table 1
Parameters for materials in this study

| Material | $E$ (GPa) | $S$ (MPa) | $T$ (MPa m$^{1/2}$) | $N$ |
|---|---|---|---|---|
| Glass | 73 | 120 | 0.6 | 17.9 |
| Y-TZP | 210 | 1300 | 4.0 | 25 |
| $Al_2O_3$ | 372 | 465 | 3.0 | 26 |
| Polycarbonate | 2.35 | | | |