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Mixed mode fracture of dental interfaces

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Abstract

This paper presents the results of a combined experimental and computational study of mixed mode fracture in glass/cement and zirconia/cement interfaces that are relevant to dental restorations. The interfacial fracture is investigated using Brazil-nut specimens. The kinking in-and-out of the interface that occurs between glass/cement and zirconia/cement interfaces, is also shown to be consistent with predictions from a microstructure-based finite element model. The predictions later verified using focused ion beam and scanning electron microscopy images.

Keywords: Ceramic crown; Fracture; Interfacial fracture toughness; Glass; Zirconia; Dental cement; Crack path

1. Introduction

Recently, resin cements have been increasingly used in all ceramic crowns [1]. The structure of these dental restorations is composed of a ceramic layer which is adhered to dentin with a dental join material (Fig. 1). However, such a structure produces two extra interfaces, and the possibility of interfacial failure due to contact loads [2–4]. Knowledge of the adhesion between the ceramic and the cement is essential in failure analysis and design of the dental crowns. Glass and zirconia are chosen as typical ceramic materials which are extensively used in structure of the all ceramic dental crowns. Therefore, the main purpose of this paper is to study the interfacial toughness between glass/cement and zirconia/cement interfaces.

In recent years, fracture mechanics approaches have been used to study the interfacial fracture that can occur between interfaces that are relevant to dental multilayers, [5,6]. The early work in this area was done using Double Cleavage Drilled Compression (DCDC) specimens that provide a simple way of studying interfaces subjected to loading configurations that are close to mode I, [5]. However, since the actual occlusal loading scenarios are not just limited to near mode I conditions, more recent efforts have tried to utilize Brazil disk specimen geometries, [7], that can be used to apply the full range of mode mixities between pure mode I and pure mode II, [6]. Although Brazil disk specimens have enabled the improved understanding of interfacial fracture mechanisms in dental interfaces, the current understanding is still not at a level that can be used to predict crack paths within and beyond interfaces that are relevant to dental multilayers.

Motivated by the approach of Lawn et al. [8], who used elastically similar transparent sodalime glass layers to idealize the behavior of dental crowns, this paper explores the effects of mode mixity on the mixed mode fracture of glass, and the interfacial fracture that can occur between glass and methyl-methacrylate based cements that are used to cement dental ceramic crowns to dentin or ceramic-filled polymer foundation that are relevant to dental restorations. Four-point shear and Brazil specimen geometries are used, respectively, to study, matrix and interfacial fracture between glass and an methyl-methacrylate based dental cement over a wide range of mode mixities. The underlying crack growth directions are also shown to be consistent with predictions from fracture mechanics models.

This paper is organized as follows: in Section 2, the experimental techniques are presented for the study of sodalime glass mixed mode fracture and the interfacial fracture between borosilicate glass (henceforth referred to as glass) and an methyl-methacrylate based dental cement (henceforth referred to as cement). This is followed by Section 3 in which the background

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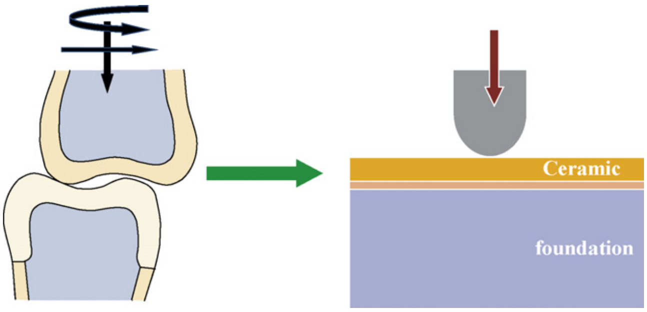

Fig. 1. Idealized trilayer dental restorations.

theory and analytical/computational models are described. Subsequently, the results and discussion are presented in Section 4 before summarizing the salient conclusions from this work in Section 5.

2. Experimental methods

Two set of experiments were used to investigate the dependence of glass/cement and zirconia/cement interfacial fracture toughness on mode mixity. The first set involved glass/cement interface, while the second set investigated zirconia/cement interfaces. Brazil nut specimens were used to measure the interfacial fracture toughness over a wide range of mode mixities between pure model I and pure mode II. The experimental details are presented in the following subsections.

2.1. Glass/cement and zirconia/cement interfaces

The Brazil-nut sandwich sample and the mechanical testing set-up that were used in this experiment is shown schematically in Fig. 2. Two half-circle glass disks were bonded together using dental cement with a thickness $\sim 100\,\mu$m.

An elliptical slot was introduced into the center of the upper half-circle disk, with radius of $r = 5.5$ mm, to serve as an initial notch. The slot was $2a = 2.0$ mm long, i.e. $a = 1.0$ mm, and the notch-root radius, R, was ~ 1.0 mm. The glass substrate was designated as material 1, while the dental cement interlayer was designated as material 2.

The same setup was used to study the zirconia/cement interface. An elliptical slot was introduced into the center of the upper half-circle zirconia disk, with radius of $r = 9.0$ mm, to serve as an initial notch. The slot was $2a = 3.0$ mm long, i.e. $a = 1.5$ mm, and the notch-root radius, R, was ~ 1.0 mm. The zirconia substrate was designated as material 1, while the dental cement interlayer was designated as material 2.

A 3M-ESPE RelyX$^{\mathrm{TM}}$Adhesive Resin Cement paste (3M ESPE, St. Paul, MN) was used in the experiments. The major compositions of the dental cement are Bis-GMA, TEGDMA, dimethacrylate polymer, zirconia/silica glass (67.5 wt%), chemical and photoninitiators. Before bonding the two half-circle glass disks with dental cement, 8% hydrofluoric acid (HF) was applied to the glass surface for 2 min. The surfaces ware washed thoroughly for 1 min under tap water, and dried under dry nitrogen. The surfaces were then further treated using a silane primer

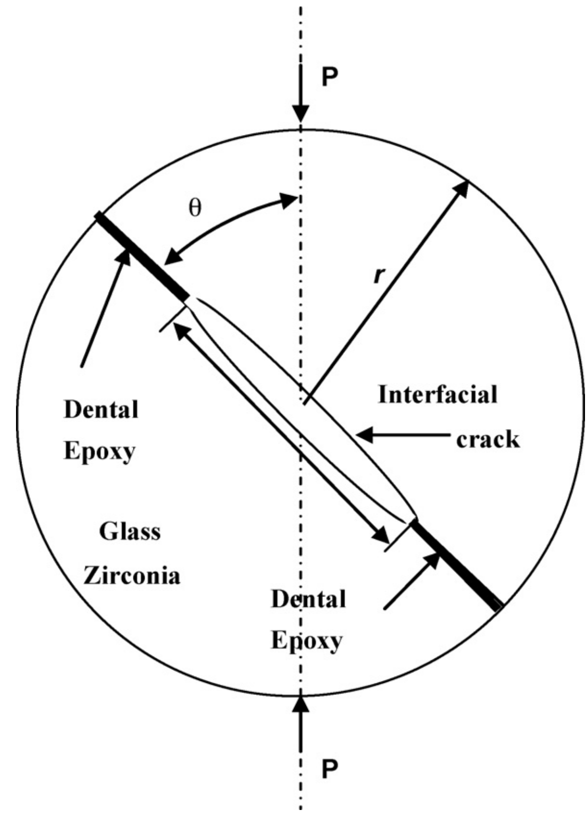

Fig. 2. Schematic of the Brazil-nut experiment.

Monobond-s (Vivadent, Liechtenstein). This was done for 60s before air drying. The preparation of the zirconia half disks was the same as the glass half disks.

Interfacial fracture testing was conducted in an Instron 8872 servo-hydraulic testing machine (Instron, Canton, MA), equipped with a 5 kN load cell. Testing was performed under displacement-control at a ramp rate of 0.005 mm/s. Both load and displacement data were recorded using a computer. Critical loads corresponding to specimen failure were used for the calculation of the loading phase and energy release rate. The Brazil-nut sandwich specimens failed by two mechanisms: glass substrate failure and interfacial failure. The tests were only considered valid when the initial crack extension occurred along the interfaces. The corresponding data were then analyzed to determine the interfacial fracture toughness values (energy release rate) and mode mixities.

In the Brazil-nut sandwich experiment, loading phase is controlled by the compression angle, θ. The monolithic base specimen in the absence of the interlayer is in mode I when $\theta = 0°$ and is in mode II when $\theta = 25°$. The conventional stress intensity factors are,

$$K_{\mathrm{I}} = f_{\mathrm{I}} P a^{-1/2}, \quad K_{\mathrm{II}} = \pm f_{\mathrm{II}} P a^{-1/2} \tag{1}$$

where the plus sign and negative sign are for the two crack tips, respectively. The non-dimensional calibration factors, f_{I} and f_{II}, are functions of the loading angle, θ, and relative crack length, l/a. They are available in fitting polynomial forms in [7]. The