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Effects of design parameters on fracture resistance of glass simulated dental crowns

Zhongpu Zhang[a], Tanapon Sornsuwan[b], Chaiy Rungsiyakull[c], Wei Li[a], Qing Li[a], Michael V. Swain[d,*]

[a] School of Aerospace, Mechanical and Mechatronic Engineering, Faculty of Engineering, The University of Sydney, NSW 2006, Australia
[b] Department of Restorative Dentistry, Faculty of Dentistry, Naresuan University, Phitsanulok, Thailand
[c] Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, Thailand
[d] Disciplines of Biomaterials, Faculty of Dentistry, The University of Sydney, NSW 2010, Australia

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ABSTRACT

Objective. This study aimed to individually quantify the effects of various design parameters, including margin thickness, convergence angle of abutment, and bonding conditions on fracture resistance of resin bonded glass dental crown systems (namely, glass simulated crown).

Materials and methods. An *in vitro* experimental test and an *in silico* computational eXtended Finite Element Method (XFEM) were adopted to explore crack initiation and propagation in glass simulated crown models with the margin thickness ranging from 0.8 to 1.2 mm, convergence angle from 6° to 12°, and three different bonding conditions, namely non-bonded (NB), partially bonded (PB), fully bonded (FB).

Results. The XFEM modeling results of cracking initiation loads and subsequent growth in the glass simulated crown models were correlated with the experimental results. It was found that the margin thickness has a more significant effect on the fracture resistance than the convergence angle. The adhesively bonded state has the highest fracture resistance among these three different bonding conditions.

Conclusion. Crowns with thicker margins, smaller convergence angle and fully bonded are recommended for increasing fracture resistance of all-ceramic crowns. This numerical modeling study, supported by the experimental tests, provides more thorough mechanical insight into the role of margin design parameters, thereby forming a novel basis for clinical guidance as to preparation of tapered abutments for all-ceramic dental crowns.

* *Corresponding author at*: Disciplines of Biomaterials, Faculty of Dentistry, The University of Sydney, Sydney Dental Hospital, 2 Chalmers ST, Surry Hills, Sydney, NSW 2010, Australia. Tel.: +61 2 9351 8375.

E-mail addresses: leo.zhang@sydney.edu.au (Z. Zhang), tsor7523@uni.sydney.edu.au (T. Sornsuwan), chaiy@eng.cmu.ac.th (C. Rungsiyakull), wei.li@sydney.edu.au (W. Li), qing.li@sydney.edu.au (Q. Li), mswain@mail.usyd.edu.au (M.V. Swain).

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1. Introduction

All-ceramic dental crowns have become more and more popular attributable to their excellent esthetics, inertness and biocompatibility [1,2]. However, clinical failure rates of all-ceramic prostheses are still substantially higher than metal–ceramic counterparts particularly for molar teeth [3,4]. Based on clinical guidelines for preparing all-ceramic crowns, greater attention needs to be paid to geometric features. Margin thickness [5], degree of convergence angle [6,7], cusp angles [8,9], configurations of margin [10,11], *etc.* are some typical clinically relevant geometric parameters. Of these, margin design appears to be most important, being of a profound effect on fracture resistance of all-ceramic crowns, which can largely determine the extent of removal of sound tooth tissue during preparation of taper abutment for achieving adequate esthetic outcomes and structural integrity of tooth-crown system. On the other hand, not only does minimal preparation, by preserving as much sound tooth tissue surrounding the cervical area (ferrule effect) as possible, increase long term prognosis of the tooth, but also helps preserve pulp vitality, thereby maintaining health status of the host abutment tooth [12]. The concern remains on how these design parameters affect the structural strength of the crown against mechanical loading. To address this issue, both experimental and numerical studies have been conducted to identify an effective design for all-ceramic crowns, especially for those in the posterior region where the occlusal forces are more demanding [13,14].

In the literature, the response of a restored tooth to a single load to failure test is often adopted in the laboratory for its simplicity in evaluating the complex stress state of dental materials loaded onto biological hard tissues [15,16]. For assessing all-ceramic crowns, typically, an axial load is applied on anatomical crown by controlling some factors of interest to identify how these factors affect the catastrophic fracture loads that the crown can resist [1,13]. While simple, such a test is considered realistic in order to quantify the effects of various factors on the failure load for different designs and dental materials. However, the test often has several major limitations, such as the scatter of recorded failure loads and the different fracture origins compared with what happens with clinically failed crowns, making the test somewhat less reliable clinical guide for structural design and material selection [17]. The other key limitation is that from such a simple test it is difficult to reveal the fractographic details such as crack initiation and propagation.

To restrict the attention onto the aforementioned critical design parameters, some simplified structural system, *e.g.* the glass simulated crowns to be used in this study, have proven effective, helping determine the critical conditions for marginal failure of complex ceramic crowns under given loading. There have been a number of studies reported in the literature on use of glass specimens to explore fracture behavior of brittle all-ceramic crowns [2,18]. It must be pointed out that the fracture behavior of glass and ceramics are slightly different. Glass fracture usually initiates from surface flaws, whereas dental porcelain may start from both surface flaws and internal defects. However, glass specimens have significant benefits for laboratory studies [19], such as elastic modulus close to that of tooth enamel and dental porcelain, clearer fractographic features, easier visualization of internal cracks and less complexity of fabrication [19]. In the tests, bonding with dental resin has been shown to increase the fracture resistance [14,20]. Again such tests are limited to the effectiveness of capturing fracture initiation in the specimens [21].

As one of the most powerful simulation techniques, the finite element method (FEM) has been widely employed to explore detailed stress distributions in all-ceramic crowns, to a certain extent reducing the need for time-consuming and expensive specimen preparation and experimental testing [22]. For example, Qasim et al. [19] conducted a FE study for determining the basic stress states in dome-like polymer-filled thin walled glass structures, and they found a shift in maximum tensile stress from the near-contact apex area to dome edges as a consequence of localized ball contact *versus* more uniform apex loading with a soft material. As a result, the location of maximum tensile stress changed from the apex contact area to the margins. Ford et al.'s FE study [23] explored the stress fields for assessing contact driven damage in ceramic prostheses; but unfortunately formation of the potential crack was not modeled. Kamposiora et al.'s FE study [24] identified the effects of margin design, cement materials, cement thickness, loading direction and magnitude on stress levels and distributions within luting cement. Nevertheless, there have been limited studies available simulating crack formation in crown-like dental restorations to date [25].

XFEM has proven to be a promising method to simulate crack initiation and propagation [26–29]. In comparison with the conventional finite element method (FEM), XFEM offers significant advantages for modeling crack initiation and propagation along an arbitrary, mesh-independent and solution-dependent path, with more flexibility and versatility [28–30] than other numerical techniques available, such as continuum-to-discrete element approach [25,31–34]. Therefore, XFEM, instead of standard FEM, was employed to explore the fracture behavior of glass simulated crown models in this study.

In our previous experimental study on single load to failure [35], it was found that the margin thickness becomes less influential in the tests for the adhesively bonded glass crown-like specimens. In addition, no clear difference was observed in the failure loads of two different margin thicknesses, *i.e.* 0.8 or 1.2 mm, with different surface treatments [35]. Simple analytical models were also developed to identify the stress concentration at the crowns' margin. However, the effects of margin design parameters, especially the supporting roles of the margin and adhesion, were not adequately addressed in the previous analysis. An important hypothesis tested was whether the crown design parameters, specifically the degree of convergence, marginal thickness and bonding conditions, play an equal role in contributing to the fracture strength. This study will provide an *in vitro* experimental and an *in silico* numerical study for quantifying the effects of these design parameters on the fracture behavior, thereby establishing a mechanical basis for clinical application.