DENTAL MATERIALS 30 (2014) 902–909

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.intl.elsevierhealth.com/journals/dema

Biaxial flexure strength determination of endodontically accessed ceramic restorations

R.D. Kelly[a], *G.J.P. Fleming*[b], *P. Hooi*[b], *W.M. Palin*[a], *O. Addison*[a,*]

[a] *Biomaterials Unit, University of Birmingham School of Dentistry, College of Medical and Dental Sciences, St Chad's Queensway, Birmingham B4 6NN, UK*
[b] *Materials Science Unit, Division of Oral Biosciences, Dublin Dental University Hospital, Trinity College Dublin, Lincoln Place, Dublin 2, Ireland*

ARTICLE INFO

Article history:
Received 22 September 2013
Received in revised form
26 April 2014
Accepted 21 May 2014

Keywords:
Biaxial flexure strength
Dental ceramic
Endodontic access
Finite element analysis
Analytical solutions

ABSTRACT

Objectives. To report analytic solutions capable of identifying failure stresses from the biaxial flexure testing of geometries representative of endodontic access cavities prepared through dental restorative materials.

Methods. The ring-on-ring biaxial flexure strength of annular discs with a central circular hole supported peripherally by a knife-edge support and loaded evenly at the upper edge of the central hole were solved using general expressions of deformations, moments and shears for flat plates of a constant thickness. To validate the solutions, finite element analyses were performed. A three-dimensional one-quarter model of the test was generated using a linear P-code FEA software and the boundary conditions represented the experimental test configuration whereby symmetry planes defined the full model. To enable comparison of the maximum principal stresses with experimental derived data, three groups of nominally identical feldspathic ceramic disks ($n = 30$) were fabricated. Specimens from Group A received a 4 mm diameter representative endodontic access cavity and were tested in ring-on-ring. Group B and C specimens remained intact and were tested in ring-on-ring and ball-on-ring, respectively, to give insight into strength scaling effects. Fractography was used to confirm failure origins, and statistical analysis of fracture strength data was performed using one-way ANOVAs ($P < 0.05$) and a Weibull approach.

Results. The developed analytical solutions were demonstrated to deviate <1% from the finite element prediction in the configuration studied. Fractography confirmed the failure origin of tested samples to coincide with the predicted stress maxima and the area where fracture is observed to originate clinically. Specimens from the three experimental groups A–C exhibited different strengths which correlated with the volume scaling effects on measured strength.

Significance. The solutions provided will enable geometric and materials variables to be systematically studied and remove the need for load-to-failure 'crunch the crown' testing.

* *Corresponding author at*: Biomaterials Unit, University of Birmingham School of Dentistry, College of Medical and Dental Sciences, St Chad's Queensway, Birmingham B4 6NN, UK. Tel.: +44 121 466 5506; fax: +44 121 466 5503.
E-mail address: o.addison@bham.ac.uk (O. Addison).

http://dx.doi.org/10.1016/j.dental.2014.05.024
0109-5641/

1. Introduction

Clinical studies have demonstrated that the loss of pulpal vitality leading to a need for endodontic treatment is amongst the most common complications for teeth that have received indirect extra-coronal restorations [1,2]. As a consequence, clinicians are faced with the challenge of accessing the root canal anatomy by either removing or machining through the indirect restoration to complete endodontic therapy. Currently there is little robust evidence to inform clinicians regarding the need to replace dental crowns with access cavities machined through the restorative material. A significant contributory factor to the lack of clinical evidence is the deficiency of in vitro testing methodologies to robustly model the material behavior in such clinical situations as they arise.

Ceramic restorations that have been perforated to allow endodontic access have been observed to fracture and the fracture origin may occur at the periphery of the access cavity [3,4]. Unfortunately, no comprehensive fractographic study has been performed but anecdotal reporting from 751 clinicians has strongly demonstrated a perceived association between endodontic access and subsequent restoration fracture for many all-ceramic restorative materials [5]. The anatomical considerations of endodontic access require the machined access cavity to be located in the regions of subsequent concentrated masticatory loading – namely at the cingulum or on the occlusal surface of the anterior and posterior teeth, respectively [3]. Previous investigations into the mechanical behavior of endodontically accessed restorations have almost exclusively used load-to-failure testing of 'clinically representative' geometries [4,6,7]. These are most commonly reported as series of crowns prepared with access cavities – the so called 'crunch-the-crown' tests [4,6,7]. However, such load-to-failure methods have problems with both reproducibility and validity and do not represent the common stress patterns in ordinary masticatory cycles [8]. To provide useful guidance for clinicians, in vitro mechanical testing of dental materials should mimic the clinical failure mode [8]. All-ceramic restorations routinely fail from the extension of pre-existing defects resident on the inner 'fit' surface(s) of the restoration in contrast to failure originating at the loaded surface. Load-to-failure testing methodologies involve loading morphologically realistic restorations with flat or spherical indenters [4,6–11]. However, the forces required to initiate failure greatly exceed both the masticatory [12] and parafunctional forces and result in exaggerated contact stresses [13]. Furthermore, failures observed clinically are associated with the production of a low number of fracture fragments (most commonly two) whereas 'crunch-the-crown' testing methodologies produce a large number of fragments which is indicative of the considerable energy stored prior to failure. The application of stress solutions to such complex structures is also not possible [8] and therefore only the load bearing capacity of the system can be reported [14,15]. As a result, there has been an increased use of finite element analyses (FEA) within the dental literature [16–18]. However, FEA models used in isolation are unable to predict the stability and statistical distribution of the surface defect population which accounts for the variability in the fracture strength of brittle systems [19]. Therefore, in vitro load to failure mechanical testing methodologies that enable the stress calculation, at the clinically relevant point of failure are required.

The tensile strength of dental ceramics has previously been determined from indirect tensile, pure tension and flexure testing [20]. Of these techniques, flexure testing is favored as it creates a pure state of tension on one aspect of the specimen [21]. Flexure testing is most commonly performed utilizing rectangular beam-shaped specimens in uniaxial flexure or discs-shaped specimens in biaxial flexure [20]. Biaxial flexure testing is considered advantageous over uniaxial testing as the specimens are considered to be easier to prepare and closely match the size (volume and thickness) of clinical restorations [20]. Under loading a greater volume of the specimen is tested when compared with the uniaxial bending of beams resulting in a searching examination of the strength limitations of the specimen [22].

Failure stresses for disk-shaped specimens loaded in biaxial flexure in a ball-on-ring or ring-on-ring configuration can be derived from analytical solutions for stress distributions in isotropic bodies described initially by Timoshenko's analyses of thin plates [23]. Timoshenko's analyses have been extensively applied within the dental literature to calculate the failure stresses for monolithic ceramic specimens loaded under biaxial flexure in different geometries [24,25]. However, to study more complex geometries such as plates with central holes the development of closed-form solutions are necessary. The aim of this study is to report analytic solutions capable of identifying failure stresses from the biaxial flexure testing of geometries representative of endodontic access cavities prepared through dental restorative materials.

2. Materials and methods

2.1. *Test specimen preparation*

Disk-shaped ceramic specimens (14 mm diameter, 0.85 mm thickness) were prepared from a feldspathic ceramic advocated for use in dentin-bonded crowns (DBCs). To ensure reproducible specimen geometry, composition and surface condition, accurately proportioned dentin porcelain powder and modeling liquid were condensed into a ring-mold assembly prior to controlled firing. Vita Modeling Liquid (0.2 mL; batch no. 29990; Vita Bad Sackingen, Germany) was added to 0.6 g of VitaVM7 Base Dentin powder (batch no. 25660; Vita Bad Sackingen, Germany) to produce a thick slurry consistency. The entire slurry was transferred to a ring-mold which was firmly secured to an aluminum base plate which possessed a mirror-like finish. The assembly was centered on a vibrating table and the excess liquid was removed with an absorbent tissue over 60 s. The overfilled mold was leveled carefully with a razor blade and following disassembly of the ring-mold, the condensed specimens were placed with a consistent orientation on a clean silicon nitride firing slab and fired in a VITA Vacumat 40 T vacuum furnace (Vita Zahnfabrik H. Rauter GmbH & Co. KG, Bad Säckingen, Germany) according to the manufacturers' recommended cycle. Following firing, the resultant specimens possessed a "glaze-like" surface from firing against the silicon nitride firing slab and a "fit"